An Objective Climatology, Classification Scheme, and Assessment of Sensible Weather Impacts for Appalachian Cold-Air Damming

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ABSTRACT

The geostrophic adjustment process for a rotating, stratified atmosphere in the presence of an orographic barrier may be manifest as a phenomenon known as “cold-air damming” (CAD). The degree of blocking by an orographic barrier, and therefore CAD intensity, is related to the static stability of the upstream air mass. When precipitation falls into dry near-surface air, differential evaporational cooling can increase static stability, and strengthen or initiate CAD. The sheltering effect of clouds can also maintain surface-based stability. Therefore, the ability of numerical forecast models to accurately predict CAD requires adequate representation of cloud and precipitation processes. Operational forecasters in the Appalachian damming region have previously developed a subjective classification scheme that distinguishes those CAD events that are heavily influenced by diabatic processes from those that are dominated by synoptic-scale forcing. In this study the subjective scheme is formalized in order to elucidate distinct synoptic-scale patterns associated with different CAD types. Knowledge of CAD types will enable forecasters to interpret and adjust numerical model forecasts, and reinforce understanding of atmospheric processes during CAD. An objective CAD-identification algorithm, based on hourly surface reports in and around the Appalachian damming region, was used to construct a 12-yr climatology of CAD events of varying intensity. Between the years 1984 and 1995, 353 CAD events were identified. The annual frequency of strong CAD events is consistent with previous studies. However, the overall frequency of CAD reveals a large number of weak warm-season events, with maximum overall frequency in September. A CAD-classification algorithm, based on the aforementioned subjective operational scheme, was used to quantify differences in synoptic setting and sensible weather impacts between CAD types. Analysis of the climatological CAD sample reveals that despite similar patterns in the sea level isobars, some CAD events exert strong influences on sensible weather parameters while others do not. The climatological departure of the maximum temperature at Greensboro, North Carolina, was used to define “high impact” and “low impact” CAD events. Composites of high-impact cases reveal a coupled jet signature at the 250-mb level similar to that accompanying some East Coast cyclones. The low-impact composite exhibits much more pronounced ridging west of the damming region at the 500-mb level relative to the high-impact composite. These results support the interpretation that CAD is not a monolithic phenomenon.

1. Introduction

a. CAD as a geostrophic adjustment process

Consider the hypothetical scenario depicted in Fig. 1, in which higher pressure is located to the north with sea level isobars oriented perpendicular to a midlatitude mountain barrier. The ambient atmosphere is assumed to be stably stratified. As air parcels approach the barrier from the east, their westward momentum is reduced.1

As the northward-directed component of the Coriolis force weakens, the air parcel motion turns toward the

1 It is the development of an “upwind high,” due to adiabatic cooling and mass convergence upwind of the barrier, that is responsible for the deceleration (Smith 1982).
south in response to the unbalanced pressure gradient force (PGF). A similar circumstance would apply west of the barrier, except there the deceleration would be in response to the development of lower pressure to the east (a lee trough). As ageostrophic northerly flow develops on either side of the barrier, Coriolis deflection turns parcels located east of the barrier to the right of the motion (toward the barrier), resulting in mass accumulation and pressure increases (Fig. 1b). West of the barrier, the Coriolis deflection of ageostrophic northerly flow also deflects parcels to the right of the motion (toward the west), except here the result is depletion of mass adjacent to the barrier and the development of an inverted trough pattern. The flow has undergone geostrophic adjustment in the sense that the force balance in the cross-barrier direction (force components normal to the barrier) exhibits a higher degree of geostrophy than it would in the absence of the ridge–trough couplet (Bell and Bosart 1988; Lackmann and Overland 1989; Xu 1990).

Unlike the idealized situation depicted in Fig. 1, the ridge to the east of the barrier is often more pronounced than the trough to the west. When a cold, stable anticyclone is located to the north of the region as in Fig. 1, lower-tropospheric cold advection is favored in the northerly ageostrophic flow, resulting in increased static stability and enhanced hydrostatic pressure rises (Xu et al. 1996). This advection pattern preferentially strengthens the ridge while weakening the trough west of the barrier. The pronounced ridge and accompanying cool, stable air mass are often referred to as “cold-air damming,” or CAD. Earlier studies focused on the dynamics of the ridge to the east of the barrier and the important sensible weather impacts found there, which may include freezing rain, sleet, low visibility, and generally much below average maximum temperatures (e.g., Richwien 1980; Forbes et al. 1987; Fritsch et al. 1992). Geostrophic adjustment scenarios of the type described here have been identified previously in various locations throughout the world (e.g., Smith 1982; Overland 1984; Dunn 1987; Lackmann and Overland 1989; Bond and Macklin 1993).

The onset of Appalachian CAD is typically associated with a strong surface anticyclone (dubbed the “parent high”) centered to the north of the “damming region,” which for the purposes of this study is defined as Virginia, the Carolinas, and northeastern Georgia. Due to geostrophic adjustment processes of the type described above, the characteristic U-shaped “wedge” of high pressure is reflected in the sea level or lower-tropospheric isobar pattern (Richwien 1980). Processes contributing to the development of this ridge during a non-precipitating CAD event include (i) along-barrier advection of cold, dense air from the parent high to the north; (ii) adiabatic cooling resulting from orographic ascent; and (iii) the accumulation of mass adjacent to the barrier stemming from the Coriolis deflection of the ageostrophic along-barrier flow. The lower-tropospheric along-barrier cold advection contributes to increased static stability, further enhancing the blocking effect,
adiabatic upshele cooling, and hydrostatic pressure increase. The occurrence of CAD in coastal locations (with a flat lower boundary) such as southwestern Alaska, southeastern coastal Australia, and the U.S. west coast confirm that near-surface adiabatic upshele cooling is not required to produce the characteristic U-shaped isobar pattern associated with CAD (e.g., Colquhoun et al. 1985; Mass and Albright 1987; Lackmann and Overland 1989).

b. Diabatic processes and forecasting implications

The extent to which the flow is blocked by an orographic barrier can be anticipated through consideration of the Froude number (e.g., Manins and Sawford 1982):

\[ \text{Fr} = \frac{U}{N H} \]

where \( U \) is the component of the flow normal to the barrier, \( N \) is the Brunt–Väisälä frequency, and \( H \) is the barrier height. Large static stability is consistent with a small Froude number\(^4\) and stronger blocking. If dry air is present near the surface, the occurrence of precipitation and the resulting differential evaporational cooling can serve to increase the static stability, reduce Fr, and enhance or initiate CAD (Bell and Bosart 1988; Fritsch et al. 1992). For example, Bell and Bosart (1988) determined that evaporation contributed up to 30% of local cooling during a CAD event from March 1985. Fritsch et al. (1992) investigated both the direct and indirect influences of diabatic subcloud processes during CAD. They estimated that solar sheltering and evaporational cooling during a precipitating CAD event contributed approximately 2 mb to the surface pressure increase in the CAD ridge, and they documented precipitation–CAD feedbacks that could explain the rapid southward progression of a CAD ridge.

The prominent role of diabatic processes in CAD initiation and maintenance during some events suggests that forecast accuracy requires adequate numerical model representation of diabatic processes in these cases. For example, consider a situation in which numerical weather prediction (NWP) models predict widespread precipitation and the onset of CAD, while in reality precipitation is lighter and highly limited in spatial extent. The model atmosphere, stabilized by abundant widespread precipitation, would depict a significant CAD event, complete with signatures recognized by forecasters such as the characteristic U-shaped sea level isobars in the damming region, evidence of a pronounced lower-tropospheric inversion in forecast soundings, and northeasterly near-surface winds in model forecasts. Corresponding forecasts of maximum temperature, cloud cover, wind direction, and other parameters would reflect the expected onset of CAD. In reality, clear skies and near-average temperatures are observed at the surface in the damming region. A nonevent of this type occurred during the Genesis of Atlantic Lows Experiment (GALE) and was studied by Oravec and Bosart (1990). In this case, CAD was predicted by numerical models but did not materialize. Their results confirm that the synoptic environment and precipitation forecasts are critical to the accurate prediction of a CAD event; the lack of precipitation in the case they presented likely contributed to the lack of CAD. In other cases, model underestimates of cloud and precipitation may result in forecast biases in the opposite sense of those described above.

Operational forecasters in the Appalachian damming region are well aware of the challenges provided by CAD (e.g., Keeter et al. 1995). The phenomenon occurs frequently along and east of the Appalachians [Bell and Bosart (1988) cited three to five events per month on average during winter], and can produce a myriad of difficulties in forecasting elements such as temperature and precipitation type (e.g., Forbes et al. 1987). The idealized CAD scenario, characterized by a strong parent high, can be referred to as “classical” CAD, as it is governed by relatively strong synoptic-scale features and processes at the surface and aloft (e.g., Richwien 1980; Forbes et al. 1987; Bell and Bosart 1988). For classical events that are not strongly influenced by precipitation, operational NWP models often accurately depict the onset of damming. However, forecasters recognize that CAD events can vary widely in terms of duration, forcing mechanisms, and impacts on sensible weather, and that their evolution can depart significantly from the classical example. Experience has shown that diabatically forced and small-scale CAD events are often not accurately handled by NWP models (Stauffer and Warner 1987; Forbes et al. 1987; Bell and Bosart 1988). These nonclassical CAD types can have dramatic ramifications for sensible weather, producing strong temperature and dewpoint gradients on the CAD periphery, sometimes resulting in enhanced low-level vertical wind shear and strong rotating convection along the edge of the cold dome (e.g., Businger et al. 1991). Furthermore, the eastern periphery of the cold dome is often manifest as a coastal front (Riordan 1990; Appel et al. 2002, manuscript submitted to Wea. Forecasting), which can serve as a site for coastal cyclogenesis (e.g., Bosart 1981; Stauffer and Warner 1987; O’Handley and Bosart 1996). Even high-resolution mesoscale models exhibit difficulty with small-scale CAD phenomena (e.g., Kramer 1997).

c. The CAD “spectrum”

Variability in the role of diabatic processes and spatial scales of CAD phenomena, and recognition of the need for forecasters to expand their view of CAD beyond the

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\(^4\) Here, \( N^2 \) is proportional to \( \gamma_d - \gamma \), where \( \gamma_d \) and \( \gamma \) are the dry and environmental lapse rates, respectively. As the atmosphere becomes more stable, the value of \( N \) increases, and the Froude number decreases.
basic recognition of a ridge in the sea level pressure field, led to the development of a CAD “spectrum” (G. Hartfield et al., NWS, 1996, unpublished manuscript; Kramer 1997; Hartfield 1998). The three major components of this scheme serve to distinguish CAD events by scale variations and by the relative roles of synoptic-scale forcing and diabatic processes. This subjective CAD classification scheme consisted of 1) classical CAD, chiefly initiated by synoptic-scale features, including a cold surface high with a central pressure 1030 mb or greater, centered north of 40°N but with minimal contribution from diabatic processes; 2) “in situ” CAD, during which diabatic processes play a dominant role as precipitation falls into low-level dry air, eventually resulting in an ageostrophic wind adjustment; and 3) “hybrid” CAD, in which both synoptic-scale forcing (from a weaker or less than optimally positioned anticyclone) and diabatic processes contribute to damming development (Fig. 2a). This classification scheme has undergone minor refinement in recent years based on continuing investigation of CAD cases as they occur. National Weather Service (NWS) forecasters throughout the damming region have utilized this classification system to assist them with CAD forecasting and interoffice coordination.

Owing to the fact that the forecaster cannot rely solely on NWP models for correct CAD solutions, a sound meteorological foundation of CAD processes and knowledge of existing conceptual models and typical patterns are imperative for those forecasting CAD. In an effort to help quantify the subjective CAD classification outlined above and to further improve forecasters’ understanding and recognition of the various CAD types, an objective climatology of CAD has been developed for the Appalachian region. Composites of several meteorological fields based on this climatology were created, centered on the onset, peak, and demise of the various CAD types. The climatology revealed further important distinctions both at the surface and aloft among and within the CAD types contained in the original spectrum. These differences resulted in an updated CAD spectrum, with subdivisions of the original CAD types (Fig. 2b). The composites have already been utilized to a limited extent as a real-time forecast tool in an operational environment.

2. Data and methodology

a. CAD-detection algorithm

In order to identify a broad spectrum of events for use in the climatological study, an objective CAD-detection algorithm was designed to identify the characteristic pressure ridge, cold dome, and ageostrophic northeasterly flow typically associated with CAD. The algorithm utilizes hourly surface data to identify these CAD features. Vertical soundings were not used in the algorithm despite their obvious utility because (i) the

![Diagram](Image)

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Diabatic Processes

Dry Synoptic Processes

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Diabatic Processes

Dry Synoptic Processes

Fig. 2. The CAD spectrum defined with respect to event intensity and the relative contribution of diabatic processes to synoptic-scale forcing: (a) original scheme and (b) revised scheme.

temporal and spatial resolution afforded by the rawinsonde network would preclude detection of weak, localized, and short-lived events, and (ii) the potential operational application of the algorithm necessitates a simple and versatile design.

The Laplacian of sea level pressure or potential temperature in the mountain-normal direction provides a quantitative measure of the intensity of a pressure ridge or cold dome (Bell and Bosart 1988). The detection algorithm is based upon Laplacians evaluated for three mountain-normal lines constructed from surface observations in and around the damming region (Fig. 3). Each line consists of three stations, with the center station in

We recognize that departures from linearity render the computations outlined here to be approximations of the actual Laplacian value; nevertheless, these computations effectively serve the intended purpose.
Fig. 3. Surface stations and lines used in the objective CAD-detection algorithm. The numbers 1–3 in line A correspond to Eq. (2) in the text.

The core of the damming region, and one station on either side in a direction approximately perpendicular to the Appalachian Mountains. Line A consists of Charleston, West Virginia (CRW); Lynchburg, Virginia (LYH); and Norfolk, Virginia (ORF). Bristol, Tennessee (TRI); Greensboro, North Carolina (GSO); and Wilmington, North Carolina (ILM), make up line B. Line C includes Knoxville, Tennessee (TYS); Greenville–Spartanburg, South Carolina (GSP); and Charleston, South Carolina (CHS). Along all three lines, Laplacians ($\nabla^2 x$) were calculated using

$$\nabla^2 x = \frac{x_1 - x_2 - x_2 - x_1}{d_{2,3} - d_{1,2}},$$

where $x$ denotes either sea level pressure or potential temperature ($\theta$) and the subscripts 1–3 denote stations running from west to east along the line (e.g., see line A in Fig. 3). In (2), $d_{1,2}$ is the distance between stations 1 and 2, and $d_{2,3}$ is the distance between stations 2 and 3. Negative values of $\nabla^2 p$ are typically associated with pressure maxima at the center station, while positive values of $\nabla^2 \theta$ usually correspond to colder temperatures in the center of the section. However, it is possible for $\nabla^2 p$ values to be negative even without higher pressure at the center station. To account for these cases, and to eliminate ephemeral events, the pressure at the center station was required to be greater than the pressure at the two endpoint stations for at least 6 h at the onset of an event. To allow the algorithm to capture CAD decay, this requirement was relaxed after 6 h. In addition, the mean and standard deviation of all negative $\nabla^2 p$ values for each line were calculated for the entire study period and used as a threshold. The mountain-normal $\nabla^2 p$ must be negative in excess of one standard deviation below the average of all negative $\nabla^2 p$ in order for the algorithm to trigger. Although this criterion may eliminate some very weak CAD events, it also served to eliminate numerous weak ridging events that were not accompanied by CAD.

A fourth line (line D), parallel to the mountain barrier, was included as a surrogate representation of ageostrophic northeasterly flow. Stations in this line include GSP, GSO, and Richmond, Virginia (RIC). The PGF is oriented parallel to the mountain range toward the southwest during a typical CAD event (Forbes et al. 1987; Bell and Bosart 1988). The algorithm requires that either the GSP–GSO or GSO–RIC pressure difference exceed 1.5 mb, with higher values to the northeast. This threshold value was selected based on examination of wind and pressure readings during several CAD cases. After 6 h, this requirement was relaxed in order to capture the demise of an event. The following is a summary of the CAD detection criteria used in the algorithm:

- The mountain-normal Laplacian of sea level pressure must be negative and exceed in magnitude one standard deviation of the average of all the negative mountain-normal Laplacian values in the dataset.
- The mountain-normal Laplacian for potential temperature must be greater than zero.
- Sea level pressure must be greater at the center station relative to the end stations.
- The difference in the pressure along line D must be greater than 1.5 mb between either GSP and GSO or GSO and RIC, with higher values to the northeast.
- All requirements must be met for at least six consecutive hours on at least one of the mountain-normal lines (A–C).

In order to confirm that the events identified by the detection algorithm were consistent with those that operational forecasters would recognize as CAD, the output from the algorithm was compared against subjective CAD identification for real-time events undertaken by personnel at the NWS Forecast Office (NWSFO) in Raleigh. Owing to the fact that the algorithm was designed to identify weak events in addition to strong, we anticipated that it would identify some marginal CAD events, and it has been shown that some detected events did not possess all of the commonly recognized CAD attributes. Some discrepancies were noted in the timing of CAD onset and demise, and a few events were missed by either the algorithm or in the subjective identification. However, in general there was good agreement. For example, the algorithm correctly detected 26 out of 30 subjectively identified events during the period from 1 January 2001 through 31 May 2002.

b. Data

Hourly surface data from the National Climatic Data Center (NCDC) Solar and Meteorological Observation...
Network (SAMSON) and Hourly United States Weather Observations datasets were utilized in this study. Data for the 12-yr period from 1984 to 1995 were imported into the General Meteorological Package (GEMPAK). Meteorological fields included station pressure, temperature and dewpoint, wind speed and direction, hourly precipitation, present weather, ceiling height, visibility, relative humidity, and cloud cover. Station pressure was reduced to sea level using
\[
\ln p_s = \ln p_{stn} + \frac{g}{R_d T_v} z_{stn}, \tag{3}
\]
where \(p_s\) is the sea level pressure, \(p_{stn}\) is the station pressure, \(z_{stn}\) is the station elevation, \(T_v\) is the average virtual temperature computed using the hourly surface report in conjunction with a standard atmosphere lapse rate (without the additional vapor correction factor), and \(R_d\) is the gas constant for dry air (Bluestein 1992, section 2.1.5). To minimize the diurnal effects on temperature, \(T_v\) was calculated by averaging the current surface value with the value 12 h earlier. When pressure or temperature data were missing for up to three consecutive hours, linear interpolation was performed to fill the gaps. For additional details regarding this procedure the reader is referred to Bailey (2001).

Gridded National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data were used to generate synoptic-scale composites for different CAD types. This dataset was obtained from the National Oceanic and Atmospheric Administration–Cooperative Institute for Research in Environmental Sciences (NOAA–CIIRES) Climate Diagnostics Center. The NCEP–NCAR reanalysis data possess 2.5° × 2.5° horizontal grid spacing, 6-h temporal frequency, 17 isobaric levels for upper-air parameters, and several additional sea level and near-surface fields (Kalnay et al. 1996). The grids were ingested into GEMPAK in order to facilitate storage, manipulation, and display.

c. Objective CAD classification scheme

In order to stratify the CAD cases, the classification scheme of Kramer (1997) and Hartfield (1998) was applied. The classification of each event was based on the strength and location of the parent high and whether precipitation was falling at any of the line D stations at the onset of the event. The gridded reanalysis data (for the closest analysis time to CAD onset) were used to determine the strength and location of the parent high. To determine if precipitation was falling at the onset of an event, the detection algorithm examined hourly precipitation values at the center station of the first line activated within 6 h of onset.

Modification of the NWS classification scheme described in section 1c was necessary in order to account for some events that did not fit the original classification scheme. For example, a CAD event featuring a parent high that is clearly weaker than what would accompany a “classical” event, but which is devoid of evidence for evaporational cooling to help initiate CAD, would not fit in the original scheme. In other nonprecipitating cases, the parent high was strong but progressive in nature, or centered south of 40°N. In order to include these weaker events, an additional classification of “weak dry” was created. In order to differentiate those classical events where diabatic processes were involved at onset from those driven primarily by synoptic-scale forcing, the classical category was subdivided into precipitating and nonprecipitating events at the onset of damming.

The strength and location of the parent anticyclone is an important factor in modulating the degree to which a given CAD event is driven by synoptic-scale processes. The character of the parent high is in part a reflection of the upper dynamics; confluence and differential negative vorticity advection typically accompany the movement of strong anticyclones into New England (Kocin and Uccellini 1990, section 5.2). The CAD scheme developed by operational forecasters in the Appalachian damming region utilizes the characteristics of the parent high as a surrogate for the strength of synoptic forcing, and notes the presence or absence of precipitation as a measure of the diabatic contribution. Careful examination of many CAD cases led to the following classification criteria:

1) Classical diabatically enhanced (CDEN)—At the 6-h analysis time closest to CAD onset, the parent high in the NCEP sea level pressure analysis must be centered north of 40°N between 100° and 65°W with a central pressure greater than or equal to 1030 mb. This criterion ensures that the anticyclone is strong and favorably positioned. The duration of the event must exceed 24 h so as to eliminate progressive highs. Precipitation is reported at the central stations in lines A, B, or C within 6 h of onset.

2) Classical dry onset (CDRY)—The same criteria as for CDEN except that no precipitation is reported at any of the center stations within 6 h of onset. Again, the parent high is strong and located in a favorable position for CAD, but diabatic processes play a negligible role in CAD initiation.

3) Hybrid (HYBR)—Precipitation is reported at one or more of the center stations in lines A–C within 6 h of onset. The parent high must exhibit a central pressure of less than 1030 mb and be centered between 100° and 65°W if north of 40°N at onset. If the parent high center is located south of 40°N, the high must be centered between 100° and 70°W and the central pressure is not considered. These criteria ensure that the parent high is either weak or is not optimally positioned for CAD, and that diabatic processes are capable of contributing to CAD onset.

4) Weak dry (WKDR)—The central sea level pressure in the parent high is less than 1030 mb, with the high centered between 100° and 65°W and north of
5) In situ (INST)—Precipitation must be reported within 6 h of onset. These criteria are consistent with weak synoptic forcing and a lack of diabatic contribution. If the parent high is north of 40°N, then the parent high must be centered east of 65°W. These criteria represent cases where the high is unable to provide significant synoptic support to damming but had passed the region previously, leaving in place dry air at low levels.

6) Unclassifiable (UNKN)—All cases that do not fit one of the above categories. Some of these cases include those that fit the description of INST except that no precipitation fell at the onset of the event. Others include events where a strong arctic high (>1050 mb) was centered west of 100°W but was large enough to affect most of Canada and provide support for Appalachian CAD. Other cases featured a cyclone to the southwest of the damming region.6

Figure 4 summarizes the parent high location requirements for the CAD classification scheme.

d. Compositing

Implementing a technique similar to that employed by Ferber et al. (1993), Colle and Mass (1995), and Lackmann et al. (1996), composites based on the classification scheme outlined in the previous subsection were generated by averaging the NCEP–NCAR reanalysis grids relative to a center time. The composites were created for three different “center times” corresponding to the CAD onset time (defined as the first hour of detection), peak time (defined as the time of maximum mountain-normal $V^2p$), and the demise time (defined as the last hour of detection). To establish continuity between the hourly data employed in the detection algorithm and the 6-hourly NCEP–NCAR reanalysis grids, the closest (0000, 0600, 1200 and 1800 UTC) analysis time to the center time of the event was denoted as $t = 0$. The generated composites span a period of $t - 96$ to $t + 96$ h about the center time. The cases were stratified into warm or cold season (cold season was defined as the period from 15 October through 15 April). Only the cold season composites are presented in this study.

Composites allow for an objective means of isolating similarities among the cases within the sample. However, the composites do not necessarily resemble all of the individual cases within the sample. The variability in the track of the parent high or a shift in the location of common features among cases in the sample results in the “smearing” of features. The degree of smearing increases with increasing departure from the center time (onset, peak, or demise time). Anomalies are defined as the difference between the composite and the weighted monthly climatological fields. The climatological fields were constructed from the monthly means calculated over the 12-yr period weighted by the number of cases in a particular month. The statistical significance of the composited features from climatology was tested using a two-tailed Student’s $t$ test (Panofsky and Brier 1968) with the null hypothesis stating that the composite means are not significantly different from the climatological means. The null hypothesis was tested at the 95% and 99% confidence levels. The significance of the composited features generally decreases as the time away from the center time increases due to increased variance in the composite sample.

3. Results

a. Climatology

Following testing of the CAD-detection algorithm, it was used to interrogate historical surface data from 1 January 1984 through 31 December 1995. In all, the algorithm identified 353 events during this period. The monthly frequency of CAD events identified by the algorithm is presented in Fig. 5. Perhaps the most surprising result was that the algorithm identified a large number of warm-season events. July exhibited the lowest CAD frequency, as noted in previous studies (Bell and Bosart 1988). However, September experienced the highest overall frequency of 3.5 events per month, followed closely by August with slightly more than 3 events. The latter result departs significantly from the climatology of Bell and Bosart (1988). However, when

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*Any synoptic pattern that produces an along-barrier pressure gradient in the presence of stable air can lead to CAD. In some cases, a cyclone to the south led to such a gradient even without a clearly identifiable parent high. There were too few of these cases to construct a statistically meaningful composite.\(^6\)*
consideration is restricted to the strongest CAD events, the results produced by the algorithm are actually consistent with those of Bell and Bosart.

An objective measure of CAD strength was computed as a linear combination of normalized measurements of event duration, the magnitude of the maximum sea level pressure and potential temperature Laplacians, and the magnitude of the along-barrier pressure gradient (Bailey 2001). Using this methodology, the 200 strongest CAD events were identified. When the monthly frequency of these 200 events was considered in isolation, the lowest frequency again occurred in July, but the highest frequency occurred in February (Fig. 5). Only 14 of the strongest 200 events occurred in the 3-month period including June, July, and August. A more detailed investigation of warm-season CAD events will be included in a subsequent study.

The breakdown of CAD events by type for the cold season is as follows: CDEN, 19; CDRY, 73; HYBR, 20; WKDR, 48; INST, 6; and UNKN, 14. In the warm season (16 April–15 October), the combined frequency of the two classical types decreased to 19 (versus 92 in the cold season), while the occurrence of HYBR events increased considerably (there were 41 warm-season HYBR events).

b. Composite analysis

Composites for several parameters (Figs. 6–16) were constructed for each of the CAD types described in section 2c. For reference, cold-season CDEN and CDRY events averaged 50 and 48 h in duration, WKDR events averaged 32 h, and HYBR events averaged 23 h. The average duration of the small sample of INST events was only 11 h. Included in the CDEN, CDRY, and HYBR descriptions are composites corresponding to 24 h prior to CAD onset, the time of CAD onset, and peak strength (as objectively defined using the maximum sea level pressure Laplacian). The presentations for WKDR and INST contain only onset-centered fields.

1) **Diabatically Enhanced Classical CAD (CDEN)**

By convention, classical CAD events must exhibit a parent high that is strong (central pressure > 1030 mb) and favorably located to the north of the Appalachian damming region. Precipitation must be observed at one or more of the stations in the central damming region within 6 h of CAD onset. The sequence of composites for the 19-case cold-season CDEN sample is presented in Figs. 6–8.

At 24 h prior to the onset of CAD, a prominent 250-mb jet extends from southwest to northeast across eastern North America. Peak winds in excess of 55 m s$^{-1}$ are observed over the eastern Great Lakes region (Fig. 6a). A positive 500-mb geopotential height anomaly is present over the eastern United States, with 99% statistical significance over the southeast (Fig. 6b). A general area of troughing is present at the 500- and 250-mb levels west of the jet. Strong confluence is evident to the east of this lifting trough along the western flank of the aforementioned jet. The region corresponding to the right entrance of the upper jet (e.g., over Arkansas) is characterized by increased relative humidity at the 850-mb level (Figs. 6a,c). The region of larger relative humidity is consistent with the expected location of the rising branch of a thermally direct transverse ageostrophic circulation (e.g., Uccellini and Kocin 1987). A band of 850-mb relative humidity in excess of 70% extends from the Gulf coast states northeastward into New England (Fig. 6c). Examination of the corresponding sea level pressure field reveals a region of troughing (and the implied presence of a cold front) extending from near the Gulf coast into New England, generally corresponding to the band of enhanced relative humidity (Figs. 6c,d). This front marks the leading edge of a cold air mass associated with the parent anticyclone. This strong high pressure system is centered over the upper Midwest beneath the confluent 250-mb jet entrance region, with the suggestion of CAD east of the Rocky Mountains extending from Nebraska into Texas (Fig. 6d).

At the time of CDEN CAD onset, the core of the jet at the 250-mb level has shifted eastward to New England, with a well-defined right jet entrance evident in the gradient of the isotach field over the mid-Atlantic region (Fig. 7a). The relative orientation of the isotherms and geopotential height contours at the 850-mb level imply warm advection over the Southeast, consistent with quasigeostrophic (QG) ascent and relative humidity in excess of 90% (Fig. 7c). It is interesting that warm advection at the 850-mb level is taking place in a region that has recently experienced a cold frontal passage (Fig. 7d). Based on the requirement for CDEN classification, precipitation is falling within the dam-
A prominent anticyclone, with a central pressure in excess of 1030 mb, extends from Minnesota into New York State. At this time, the isobars along the southern flank of the high are nearly zonal in orientation, providing a southward-directed along-barrier pressure gradient force in the damming region. The implied ageostrophic near-surface northerly flow in the damming region east of the Appalachians acts in the same sense, and may be reinforced by the lower branch of the expected ageostrophic circulation in the upper jet entrance (e.g., Kocin and Uccellini 1990, section 5.3.3). The major axis of the parent anticyclone over the Great Lakes is oriented in an east-west direction, consistent with the orientation of the confluent jet entrance aloft.

The composite for the time of peak CDEN CAD strength reveals a slight weakening of the 250-mb jet relative to the earlier composites (Fig. 8a), although the damming region remains in the right entrance of this feature. A shortwave ridge, statistically significant at the 99% level, is evident in the 500-mb height field (Fig. 8b). Moist air remains in place across the southeastern United States, accompanied by continued warm advection at the 850-mb level (Fig. 8c). The upper trough located to the west of the damming region, though weakening, has progressed into the Mississippi River valley. The presence of the upper trough, the upper jet configuration, and lower-tropospheric warm advection are all consistent with QG ascent and the location of high relative humidity over the southern portion of the Appalachian damming region (Figs. 8a–c). In the sea level pressure field, a striking CAD signature is apparent, even in the coarse NCEP–NCAR reanalysis data (Fig. 8d). Ridging east of the Appalachians is more pronounced.
than troughing to the west, although the latter feature is evident across Kentucky and Ohio, with an inverted trough extending northward from the Gulf coast.

2) **Dry Onset Classical CAD (CDRY)**

Figures 9–11 display the CDRY composites for 73 cold-season events. Recall that this subtype is characterized by a strong and favorably located parent high north of the damming region, but that precipitation is not observed in the damming region prior to or during CAD onset. Twenty-four hours prior to CAD onset, the 250-mb jet is weaker and centered farther east relative to the CDEN composite (Figs. 9a and 6a). There is little evidence for the southwestern extension of this jet into the southern United States as was seen in the CDEN composite. The less pronounced jet entrance, in conjunction with weak ridging aloft west of the Mississippi River valley, is consistent with a much lower 850-mb relative humidity in the CDRY composite (Figs. 9a–c and 6a–c). The sea level pressure field again features a strong anticyclone as in the CDEN composite, but the center is farther east, with ridging extending southward into the south-central states (Fig. 9d). The implied location of the cold front is also east of its location in the CDEN composite (Figs. 6d and 9d). This suggests that the CAD onset occurs more quickly upon the heels of cold frontal passage in the CDEN events relative to CDRY. In other words, CAD onset for CDRY is often delayed more than 24 h following cold-frontal passage. We speculate that this time is required for the impact of differential thermal advection to increase the lower-tropospheric static stability sufficiently for significant blocking to take place. In contrast, precipitation may serve to enhance static stability in the CDEN case.

At onset, the CDRY composite indicates some strengthening of the 250-mb jet east of New England, with a prominent shortwave ridge evident at the 250- and 500-mb levels extending from the Great Lakes into the Southeast (Figs. 6a,b and 10a,b). This ridge is also reflected in the 850-mb geopotential height field (Fig. 10c). Unlike the CDEN composite, the 850-mb ridge axis in the CDRY composite is centered over the damming region, and as a result there is an absence of warm
advection over the damming region (although warm advection is evident well to the west over the Mississippi River valley). In contrast to the zonally elongated anticyclone at onset in the CDEN composite, here the anticyclone is meridionally elongated, with ridging extending strongly southward from the center of the parent high (Fig. 10d). The meridional elongation of this anticyclone is consistent with the presence of a shortwave ridge aloft, suggesting that a significant contribution to the convergence aloft above the surface anticyclone is related to differential negative vorticity advection, in addition to the confluent jet. In contrast, the zonal elongation of the surface anticyclone in the CDEN composite suggests that jet dynamics are the dominant factor in the QG forcing for that case.

The composite for the peak of the CDRY events is broadly similar to the CDEN composite, suggesting that although these two types begin differently, they end up looking more similar (Figs. 8 and 11). Ridging aloft is evident over the eastern United States at both the 250- and 500-mb levels in the CDRY composite, with a weaker trough to the west (Figs. 11a,b). Warm advection and 850-mb relative humidity in excess of 70% extend from the Southeast coast northwestward into North Dakota and Minnesota (Fig. 11c). The characteristic CAD ridge signature is evident in the damming region in the sea level pressure field (Fig. 11d).

3) HYBRID CAD (HYBR)

Hybrid CAD events are defined by a weaker (central pressure <1030 mb) or less favorably located parent high, and by precipitation in the damming region within 6 h of CAD onset. Composites based on 20 cold-season HYBR CAD events are displayed in Figs. 12–14.

Overall, the HYBR composite is similar to the CDEN composite but with weaker features. The 250-mb jet is weaker and slightly farther south relative to the CDEN composite 24 h prior to CAD onset, although the orientation is similar (Fig. 12a). A region of warm advection is evident at the 850-mb level over the lower Mississippi River valley, coincident with an inverted trough in the sea level pressure field (Figs.
12c,d). The orientation of sea level isobars along the Gulf coast suggests the northward advection of lower-tropospheric moisture (Fig. 12d). Relative to the classical types, the parent high at the surface at this time is weaker, less organized, and farther west. The surface anticyclone is building eastward into the northern Great Plains and western Great Lakes region, again located beneath a region of confluent flow at the 250-mb level.

The 250-mb composite for the time of HYBR CAD onset is again similar in some respects to the corresponding CDEN composite, although there is a more pronounced suggestion of a distinct secondary jet maximum over southeastern Texas (Fig. 13a). This feature, in conjunction with a primary jet maximum near New England, is suggestive of the coupled jet entrance–exit scenario described by Uccellini and Kocin (1987) for some East Coast winter storms. The most prominent feature at the 500-mb level is the trough over the southern Great Plains (Fig. 13b). At the 850-mb level, warm advection and a region of relative humidity in excess of 80% are present over the southeastern United States (Fig. 13c). Several synoptic-scale features indicate QG forcing for ascent in the region of higher 850-mb relative humidity, including warm advection, a prominent upper trough to the west, and a right jet entrance structure at the 250-mb level (Figs. 13a–c). Examination of the sea level pressure field reveals a cyclone over the Gulf coast region, with a relatively weak anticyclone centered over New York State (Fig. 13d). The deviation of sea level pressure from climatology (shaded in Fig. 13d) indicates that the cyclone represents nearly as strong an anomaly as the anticyclone (4–8 mb for each).

The combination of an upper trough to the west, warm advection at the 850-mb level, and the suggestion of a coupled left exit–right entrance jet signature at the 250-mb level remains evident at the peak time for HYBR CAD (Fig. 14a). The inverted trough noted previously for the HYBR onset time now and exhibits a closed isobar in the sea level pressure field (Fig. 14d). Note that because HYBR events are on average of shorter duration than CDEN and CDRY, the time difference between the onset and peak is less than 12 h,
which accounts for the overall similarity of Figs. 13 and 14.

4) **Weak Dry CAD Events (WKDR)**

Observations indicate that CAD may occur even when the parent high is weak, or centered in a less than optimal location. With relatively weak forcing on the synoptic scale, the presence of clouds and/or precipitation can help to initiate or maintain the CAD. However, provided that the antecedent air mass is sufficiently stable, damming may occur even with a weak or poorly positioned parent high and in the absence of precipitation. These events are sometimes weak and short lived, yet in some cases exert strong influences on sensible weather parameters in the damming region. Figure 15 depicts the composite for 48 such WKDR cases at the time of CAD onset. The WKDR composite bears strong similarity to the CDRY composite (Fig. 10), but with much weaker features. The jet entrance at the 250-mb level exhibits a weaker along-flow wind speed gradient (Fig. 15a), consistent with a weaker transverse circulation there. As with the CDRY composite, ridging is centered over the damming region at the 850-mb level (Fig. 15c). A meridionally elongated parent high extends from southern Quebec into the mid-Atlantic region (Fig. 15d).

5) **In Situ CAD Events (INST)**

In situ CAD events are generally characterized by weak and poorly positioned parent anticyclones. In some in situ cases, we found that the along-barrier pressure gradient was largely due to a cyclone to the southwest rather than to an anticyclone to the northeast. Although the CAD detection algorithm was designed to identify even weak CAD events, only a relatively small number of events of this type were identified (six cold-season events), probably owing to the small spatial extent of many INST CAD events. The limited number of stations utilized in the detection algorithm (Fig. 3) may preclude identification of many in situ events. For completeness, Fig. 16 presents a composite based on a sample of six cold-season INST cases. Based on the small
sample size, one must use caution in interpreting this composite.

The structure of the 250-mb jet for the INST composite (Fig. 16a) bears a strong resemblance to that in the HYBR composite (Fig. 14a), with a strong jet maximum over the eastern United States and the suggestion of a coupled jet structure. The lack of statistical significance in the 500-mb geopotential height field is a reflection of large case-to-case variability and a small sample size (Fig. 16b). Relative humidity in excess of 80% at the 850-mb level covers the southeastern United States, with a pronounced trough over the Mississippi River valley (Fig. 16c). A weak cyclone is evident in the sea level pressure field, with the suggestion of a coastal/warm front extending from Georgia to offshore of North Carolina (Fig. 16d). The parent anticyclone is centered well offshore, although a ridge extends westward into the northeastern United States north of the damming region. The coarse resolution of the NCEP–NCAR reanalysis is insufficient to fully capture the damming itself at this time.

c. Discussion of composites

Perhaps the most important result derived from the composite analysis is confirmation that CAD is not a monolithic phenomenon. The composites conclusively demonstrate fundamental differences in the synoptic-scale settings (both at the surface and aloft) of various CAD types, consistent with the experience and observation of operational forecasters. However, the fundamental distinction appears to be between precipitating and nonprecipitating CAD onset, motivating our subdivision of cases that were previously combined as classical in the original scheme. The HYBR composite appears as a weaker version of the CDEN composite, while the WKDR composite is a weaker version of the CDRY composite. The composites illustrate marked differences in the QG dynamics driving the parent high between precipitating and nonprecipitating CAD events. The precipitating CAD types (CDEN and HYBR) appear to be dominated by jet dynamics and exhibit a relative absence of ridging aloft, while the dry types (CDRY and WKDR) feature a larger contribution from a shortwave
ridge aloft. The wet-onset composites (CDEN, HYBR, and INST) all exhibit a prominent jet maximum over the southern United States, while this feature is absent in the dry-onset composites (CDRY, WKDR). The dynamics driving the anticyclone in all cases are generally consistent with the findings summarized by Kocin and Uccellini (1990, chapter 5) and references therein.

**d. Sensible weather comparison**

The utility of subdividing and classifying CAD events stems from differences in the synoptic patterns and sensible weather parameters associated with individual CAD types. Generally, CAD is associated with relatively cool temperatures at locations within the cold dome. In order to quantify this observation, the departure from the climatological maximum temperature at GSO was determined for the first 2 days following the onset of CAD (as defined by the first hour of activation by the detection algorithm). The colder of the 2 days was then used in computing the average climatological departure for each CAD subtype, as presented in Fig. 17. The maximum temperature at GSO for CDEN events averages 10.7°F below the climatological value for 19 cold-season events. The average for CDRY is 8.8°F below climatology, and for HYBR it is 6.9°F. The weak CAD types (WKDR and INST) have an average departure of 5.1 and 3.6°F below climatology, respectively.

Inspection of the 92 cold-season classical CAD events revealed that some events exert a much stronger impact on the maximum temperature than others. In order to elucidate the differences between CAD events that exert a dominant influence on sensible weather and those that have little impact, we further stratified the sample of classical CAD events based on the departure of the maximum temperature at GSO from climatology. The left-hand panels in Fig. 18 represent a composite based on 19 classical CAD events during which the GSO maximum temperature was less than or equal to 2°F below average, or above average (low-impact events). The right-hand panels are based on a composite of 21 events during which the maximum temperature at GSO was 15°F or more below the climatological value (high-im-
Despite superficially similar sea level pressure patterns, the high- and low-impact composites are characterized by marked differences aloft. At the 250-mb level, a coupled jet signature is clearly evident in the high-impact composite (Fig. 18b) relative to the low-impact composite (Fig. 18a). In the high-impact composite, wind speeds in the northern jet exceed 60 m s\(^{-1}\), while in the low-impact composite the maximum wind speed is less than 50 m s\(^{-1}\). The southwestern jet maximum is absent in the low-impact composite (Fig. 18a). The low-impact composite is characterized by strong ridging at the 500-mb level over eastern North America, with geopotential height anomalies greater than 12 dam over the Great Lakes region (Fig. 18c). In contrast, the 500-mb height field in the high-impact composite shows little ridging over eastern North America and highly confluent flow to the west of a prominent trough over the Canadian Maritimes (Fig. 18d). The ridging at the 500-mb level is consistent with a meridionally elongated anticyclone in the sea level pressure field for the low-impact composite, while the high-impact composite indicates more of an east–west elongation of the high (Figs. 18g,h). Comparisons of the composite 850-mb fields (Figs. 18e,f) reveal a closed cyclone centered over Oklahoma in the high-impact composite, while this feature is weaker and located farther north in the low-impact composite. Aside from a more zonal elongation of the parent high in the high-impact composite, the strength and location of the parent high between these two composites is quite similar. The consequences of strong jet dynamics and warm advection in the lower troposphere are consistent with a tendency toward ascent in the high-impact composite, rendering clouds and precipitation more likely for these events. The presence of high relative humidity at the 850-mb level in the high-impact composite supports this conclusion. In the low-impact composite, upstream ridging at the 500-mb level, relatively weak jet dynamics, and an absence of lower-tropospheric warm advection are consistent with a decreased likelihood of clouds and precipitation. Even CAD events that are accompanied by a prominent parent high and strong CAD signatures are not necessarily as...

**Fig. 13.** As in Fig. 6 except for HYBR CAD events at onset.
Fig. 14. As in Fig. 6 except for HYBR CAD events at peak strength.

associated with strong surface temperature impacts. In these cases, even if damming is taking place, sunny skies and strong solar heating evidently nullify the impact of CAD on surface temperature. A more comprehensive examination of the sensible weather impacts of CAD, including parameters other than temperature, will be the subject of subsequent investigations.

e. CAD demise

One of the greatest forecasting challenges associated with CAD is the prediction of the cold dome demise (Keeter et al. 1995). In order to examine this issue, composites centered on the last active detection time were generated. However, inspection of individual cases indicated that several distinctive CAD-erosion scenarios occurred even within a given CAD type. In other words, the CAD demise scenario was found to be independent of CAD type. In our ongoing research efforts, we have developed composites specifically designed to differentiate between different CAD erosion processes and scenarios; these results are beyond the scope of the current paper.

4. Conclusions

The purposes of this research are to (i) develop and test an objective algorithm that is capable of identifying the complete spectrum of CAD events, (ii) develop objective criteria for the classification of CAD according to the physical processes driving the event, (iii) describe the synoptic patterns accompanying different CAD types, and (iv) distinguish the synoptic setting of CAD events that exert high versus low impacts on maximum surface temperature in the damming region. For strong CAD events, the results from the detection algorithm are consistent with earlier studies, indicating a winter or early spring peak in CAD occurrence. However, the algorithm revealed a large number of warm-season CAD events, some of which were associated with strong impacts on sensible weather. As an initial measure of CAD impact, the departure of maximum temperature from climatology at GSO was computed for the 2 days following CAD onset.

The results of the CAD-classification scheme devised by operational forecasters in the Appalachian damming region are generally consistent with those obtained from...
the more objective classification of CAD events presented in this study. Clearly, CAD is not a monolithic phenomenon, with distinct synoptic patterns evident for each damming subtype (in addition to some similar attributes). Perhaps one of the most important findings of this study is that 19 out of 90 (~20%) of the CAD events of the “classical” variety exert very little impact on sensible weather (quantified using the maximum temperature at GSO), despite similar sea level isobar configurations to high-impact CAD events. When the classical CAD sample was stratified by high- and low-impact on GSO maximum temperature, several distinct features emerge: (i) the presence of a coupled jet structure and an active southern jet stream in the high-impact cases, (ii) pronounced ridging at the 500-mb level in the low-impact cases, (iii) moist southerly flow and warm advection at the 850-mb level in the high-impact composite, and (iv) a more zonally elongated parent high in the high-impact composite. These synoptic-scale signatures may be useful to operational forecasters in the Appalachian CAD region. The composites presented in this study suggest that operational forecasters may use differences in the upper-air flow pattern to aid in distinguishing high-impact CAD from low-impact cases.

The important influence that clouds and precipitation exert on the magnitude of CAD impact, in conjunction with the increasingly prominent role of numerical models in the forecast process, illustrate the potential for problems during CAD events in which model precipitation forecasts are inadequate. Typically, model forecasts will exhibit a warm bias during CAD due to the tendency to scour the cold dome prematurely. However, during CAD events in which cloud cover is limited, maximum surface temperatures may reach or exceed climatological averages even for strong events. When NWP models overpredict precipitation intensity and coverage during CAD onset, forecasters should be prepared for the possibility of a model cold bias. Similarly, forecasters may wish to adjust forecasts so as to increase CAD influences during situations in which the operational models exhibit negative biases in precipitation amount and coverage. Careful examination of observational data (e.g., satellite, radar, and surface obser-
vations) can prove valuable in early recognition of model quantitative precipitation forecast (QPF) failure; detailed knowledge of how to adjust forecasts during these situations will require forecaster experience and a sound knowledge of CAD processes.

Upcoming case studies will focus on the ability of operational NWP models to represent CAD processes in the presence and absence of precipitation, and examine the ability of models to represent CAD erosion. Additional future research will focus specifically on the warm-season CAD events mentioned in section 3a, and on the CAD erosion problem discussed in section 3d.

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Fig. 16. As in Fig. 6 except for INST CAD events at onset.

Fig. 17. Average departure from climatology of daily maximum temperature at GSO for different cold-season (Oct–Apr) CAD types (°F). The average consists of the coldest of either of the first 2 days for each CAD event.
FIG. 18. Comparison of high- and low-impact CAD, based on maximum temperature at GSO: (a), (c), (e), (g) as in Figs. 6a–d, respectively, except for a composite based upon 19 events during which the maximum departure from climatology of the high temperature at GSO was less than or equal to 2°F (low-impact events). (b), (d), (f), (h) As in (a), (c), (e), (g) except for a composite based on a sample of 21 cases in which the departure from climatology of the high temperature at GSO was −15°F or colder (high-impact events). Composite is for time of CAD onset.
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