A Climatology of Southern Appalachian Cold-Air Damming*

JARED A. RACKLEY AND JOHN A. KNOX

Department of Geography, The University of Georgia, Athens, Georgia

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ABSTRACT

A 30-yr climatology (1981–2010) of cold-air damming (CAD) events in the southern Appalachians was conducted using hourly surface observations and North American Regional Reanalysis (NARR) data. Analysis of the spatial distribution and frequency of these events reveals that some part of the Southeast is affected by CAD on 50 days out of each year, and even the northern Florida panhandle and much of Alabama experience CAD conditions on about 30 days annually. Spatially, different CAD types tend to exhibit one of two patterns in the southernmost extent of the cold-air dome: a more southerly dome with a ridge axis oriented from north-northeast to south-southwest or a more westerly dome with a ridge axis in a northeast to west-southwest orientation. These patterns may be the result of both splitting around the region of higher terrain in east-central Alabama and Coriolis forcing in stronger CAD types with higher wind speeds. Analysis of the frequency of CAD by type on a month-by-month and year-by-year basis confirms previous work that CAD is much more frequent during the cold season versus the warm season, with CAD occurring on 6.8 days month⁻¹ during December and only 1.3 days month⁻¹ during July. Analysis was also stratified by CAD type, revealing that weak/dry events were the most common. Classical type events with stronger and more favorably positioned parent highs exhibited the longest average duration, nearly 45 h, while other CAD types averaged approximately half as long.

1. Introduction

Topography is known to affect synoptic and mesoscale weather patterns throughout the world. One such effect, cold-air damming (CAD), occurs when a shallow, surface-based layer of relatively cold air becomes entrenched against the windward side of a mountain range (Richwien 1980). The shallow dome of cold and stable air that becomes established during a CAD event is often identified by the characteristic “U”- or “wedge”-shaped inverted ridge that appears in the sea level pressure field and is typically only present below the 850-hPa pressure level (Baker 1970; Bell and Bosart 1988; Lackmann 2011, 306–309). CAD can also be observed in the near-surface temperature field, where the difference in temperature

between the damming region and coast can exceed 20°C during strong CAD events (Bell and Bosart 1988).

Cold-air damming can best be described as the effects of “orographically modified geostrophic balance” (Bell and Bosart 1988) when statically stable flow encounters a mountain barrier. In the southeastern United States, CAD generally occurs when a strong surface anticyclonic system (typically 1030-hPa central pressure or higher), referred to as the “parent high” (Bailey et al. 2003), is situated to the north of the Appalachians (most favorably north of 40°N). As air parcels within the geostrophic flow about the parent high approach the Appalachians from the east, the parcels’ westward momentum is decreased and convergence occurs near the Appalachian barrier (Smith 1982). This weakens the northward-directed component of the Coriolis force and the flow turns to the south and accelerates in response to the now-unbalanced pressure gradient force. As the ageostrophic northerly flow accelerates, the Coriolis force strengthens once again and acts to deflect the flow in a toward-barrier direction, causing both an accumulation of mass and orographic ascent along the eastern Appalachian slopes. The mass accumulation and adiabatic cooling due to the orographic

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Corresponding author address: John A. Knox, Dept. of Geography, Rm. 204, The University of Georgia, 210 Field St., Athens, GA 30602.
E-mail: johnknox@uga.edu

ascent cause a hydrostatic pressure increase. Geostrophic adjustment occurs when the resulting pressure gradient force acting in the away-from-barrier direction is kept in near balance by the toward-barrier Coriolis force, creating and maintaining a strong northerly flow (Baker 1970; Richwien 1980; Bell and Bosart 1988; Xu 1990; Xu and Gao 1995). The cold advection favored in this flow results in increased static stability and enhanced hydrostatic pressure rises (Xu et al. 1996). Diabatic processes (i.e., clouds and precipitation) can also play an important, though usually secondary, role in cold-air dome maintenance through evaporational cooling and solar sheltering (Forbes et al. 1987; Bell and Bosart 1988; Lee et al. 1992; Fritsch et al. 1992; Langmaid and Riordan 1998; Bailey et al. 2003). As the cold airflow nears the southern extent of the damming region, the pressure gradient and Coriolis forcings are weakened and the flow begins to spread outward.

Though forecast accuracy and knowledge of CAD events have improved substantially over the past four decades, CAD remains a well-known challenge to operational forecasters in the southeastern United States (Baker 1970; Bell and Bosart 1988; Hartfield 1998). While not all CAD events are strong, many have a significant impact on the region's sensible weather, including temperature, sky cover, and precipitation. In particular, CAD is known to affect precipitation type during the cold season (e.g., Forbes et al. 1987; Keeter et al. 1995) and trigger convection along the cold-dome periphery, or "wedge front," during the warm season (Bosart et al. 1972; Ballentine 1980; Garreaud and Wallace 1998; Baker 2009). While modern mesoscale numerical models have significantly improved the forecasting capabilities of CAD events in the past two decades, the models still have a tendency to underestimate CAD impacts and duration, often eroding the cold-air domes prematurely (Forbes et al. 1987; Stauffer and Warner 1987; Bell and Bosart 1988; Keeter et al. 1995; Kramer 1997; Stanton 2003; Lackmann and Stanton 2004; Green 2006). Even today's rapidly updating, high-resolution mesoscale models (e.g., the High-Resolution Rapid Refresh) show a tendency to underestimate the effects of solar sheltering and erode the cold-air dome too quickly (Grumm 2015).

Bell and Bosart (1988) conducted a relatively long climatology of CAD events using a nonobjective classification scheme, and Bailey et al. (2003) conducted a shorter 12-yr climatology using objective and expanded classifications. However, a long-term climatology using the objective scheme has not been performed. Furthermore, while surface conditions (e.g., cloud cover, temperature, and sea level pressure) have been observed to

be relatively homogeneous within the cold dome, the previous literature largely ignores the varying degree of effects that CAD can have on conditions along its southernmost extent, namely central Georgia and even sometimes eastern Alabama. While cold domes have been observed to penetrate as far to the southwest as Birmingham, Alabama, weaker cold-air domes may only extend into northeastern Georgia. The extent to which CAD protrudes to the southwest can have significant impacts in this region. This study seeks to investigate these largely ignored varying impacts along the southernmost extent of CAD.

The primary objectives of this study are to 1) update the previous CAD literature with an extended objective climatology, 2) determine the previously unstudied frequency and spatial pattern of CAD impacts in the southern extent of the damming region, and 3) determine station-to-station CAD frequency variations from the CAD climatology as a whole.

2. Data and methodology

a. CAD detection algorithm

An updated and extended objective climatology of CAD was constructed using the Bailey et al. (2003, hereafter B03) objective CAD-identification algorithm. To identify a full spectrum of CAD events objectively, the CAD-detection algorithm was adapted and run for the 30-yr period from 1981 to 2010. This algorithm was designed to identify the characteristic inverted pressure ridge, cold-air dome, and ageostrophic northeasterly flow associated with CAD events using hourly surface observations and Laplacians $\nabla^2\chi$ of sea level pressure P_{SLP} and potential temperature θ in the mountain-normal direction. Following B03, Laplacians were evaluated using Python scripting for three mountain-normal lines of surface observations and a single mountain-parallel line that represents the northeasterly flow (Fig. 1). Each line contains surface observations from three stations within the damming region, with the center station representing the core of the damming region, and the stations on either side approximately perpendicular to the Appalachian Mountains. Line A consists of the following stations: Charleston, West Virginia (CRW); Lynchburg, Virginia (LYH); and Norfolk, Virginia (ORF). Line B includes: Bristol, Tennessee (TRI); Greensboro, North Carolina (GSO); and Wilmington, North Carolina (ILM). Knoxville, Tennessee (TYS); Greenville-Spartanburg, South Carolina (GSP); and Charleston, South Carolina (CHS), make up line C. Laplacians are calculated along these lines using

FIG. 1. The 10 surface stations and Laplacian lines constructed for the CAD detection algorithm (modified from Bailey et al. 2003).

$$\nabla^2 x = \frac{\frac{x_3 - x_2}{d_{2-3}} - \frac{x_2 - x_1}{d_{1-2}}}{\frac{1}{2}(d_{2-3} + d_{1-2})}, \quad (1)$$

where x is either the sea level pressure or the potential temperature and subscripts are stations from west to east along the mountain-normal line. In (1), d represents the distance between stations. Negative values of $\nabla^2 P_{\text{SLP}}$ are associated with a higher pressure at the center station, while positive values of $\nabla^2 \theta$ are associated with colder potential temperatures at the center station.

Temporal and numerical thresholds for CAD detection were applied to computed values. These CAD detection criteria are summarized as follows:

- 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 (1 mb = 1 hPa) 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).

As with previous CAD climatologies, vertical atmospheric soundings were not used, despite their usefulness in identifying CAD presence and strength, because of their limited spatial and temporal resolution. Utilization of the B03 algorithm allows for objective detection, classification, and comparison with respect to previous studies.

While this study does not stray from the original B03 algorithm implementation, the data sources used for hourly observations used in this work differ from those used in B03. Hourly surface station observations were retrieved from the National Centers for Environmental Information (NCEI) Climate Data Online (CDO) database, while the previous study utilized the older Solar and Meteorological Surface Observation Network (SAMSON) archives. This study also chooses to linearly interpolate missing data for gaps of up to 6 h versus the 3-h limit used in B03, as this helped to eliminate falsely detected CAD demise due to brief data gaps.

To maintain consistency with previous studies and to check the algorithm's accuracy, identified events were compared to a subjectively identified list of 30 CAD events

FIG. 2. Geographical domains applied to the location and intensity of the parent high at CAD onset for use in the CAD classification scheme (modified from Bailey et al. 2003).

from 1 January 2001 through 31 May 2002. This list was also used by B03, in which 26 of the 30 events were correctly identified. This study, using the criteria above, correctly identified all 30 events during the period. Surface analyses within the first several hours of initiation were viewed for each detected event, and no inconsistencies were observed. Still, it should be noted that the algorithm missed several events when compared to subjectively identified CAD databases (e.g., Baker 2009).

In an effort to avoid overcounting a single CAD event that exhibits periods of weakening below algorithm thresholds, consecutive CAD events that are synoptically driven by the same parent high and separated by fewer than 18 h were analyzed using reanalysis and surface data and combined into a single event as necessary. While this deviates from previous uses of the CAD detection algorithm, we believe that this serves as a more realistic representation of each CAD event.

b. Objective CAD classification scheme

Detected CAD events were stratified into cases using the classification scheme outlined in B03. We summarize this scheme below for the reader.

The B03 classification scheme is a modification of the method developed by operational NWS forecasters (Hartfield et al. 1996; Kramer 1997; Hartfield 1998). Classification of each event was based on the strength and location of the parent high and whether or not precipitation was falling within 6 h of onset at the center station of the first line activated (Fig. 2). These criteria were determined using a combination of surface observations and North American Regional Reanalysis (NARR) data (Mesinger et al. 2006), and defined six CAD cases as discussed in B03:

- 1) Classical diabatically enhanced onset (CDEN)—At 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 ensures that the anticyclone is strong and favorably positioned. Precipitation must be reported at the central stations in lines A, B, or C within 6 h of onset, and the total event duration must exceed 24 h.
- 2) Classical dry onset (CDRY)—The same criteria as for CDEN except that no precipitation is reported within 6 h of onset and diabatic processes play a negligible role.

- 3) Hybrid onset (HYBR)—Precipitation is reported at one or more of the center stations 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 or between 100° and 70°W, and the central pressure is not considered if the high is south of 40°N. This ensures that the parent high is either weak or is not optimally positioned for CAD, and that diabatic processes are capable of contributing to onset.
- 4) Weak/dry onset (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 40°N, or south of 40°N and between 100° and 70°W at onset. No precipitation is reported within 6 h of onset. This is consistent with weak synoptic forcing and a lack of a diabatic contribution.
- 5) In situ (INST)—Precipitation must be reported within 6 h of onset. If the parent high is south of 40°N, then the parent high must be centered east of 70°W. If the parent high is north of 40°N, then the parent high must be 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.

c. Cold-dome spatial extent

To quantify the previously unstudied variation in spatial extent and frequency of cold-dome intrusion into the southeastern United States (i.e., South Carolina, Georgia, Alabama, and Florida), a climatology of cold-dome spatial extent was also conducted for the 30-yr period. An objective CAD spatial extent algorithm was developed to identify the location of cold-air advection within the dome. While the previously discussed B03 algorithm generally determines whether CAD is present or not within the core damming region (i.e., Virginia, North Carolina, and South Carolina), this algorithm attempts to determine whether CAD is present at specified stations across the southernmost damming region. For simplicity, the algorithm relies on the assumption that northeasterly flow must be present and continuous from northeast to southwest within the cold-air dome of a damming event. Hourly wind observations of speed and direction for 21 stations across South Carolina, Georgia, Alabama, and Florida (see Table 1) were utilized to identify this. Selected stations were required to have a complete record for the period 1981–2010, and effort was made to maintain an adequate spatial distribution across the study area with stations located both within and without the assumed damming region.

Compiled times of CAD events identified by the detection algorithm were used to initialize the algorithm in order to reject cases of northeasterly cold-air advection unassociated with damming events. In short, no CAD events are diagnosed for the southernmost damming region without CAD also being present in the core damming region as per the B03 algorithm. Threshold values for acceptable wind directions at each station were selected based on an examination of wind observations during several CAD cases. The algorithm uses an upstream-to-downstream hierarchical network, requiring that upstream (i.e., to the northeast) stations have flow within the specified threshold before downstream stations are checked for CAD. Upstream stations with missing data or calm conditions are considered to be within the dome if stations immediately downstream have flow within their specified thresholds. Upstream stations were also required to have greater or equal sea level pressure than their downstream counterparts. To reduce the error in the algorithm caused by variable wind direction that occasionally occurs within the dome, times were analyzed in rolling 3-h segments, requiring that conditions for the station must fall within the specified threshold during at least 1 of the 3 h.

Calculated frequency of CAD by station was mapped both in total and stratified by CAD type and season using a GIS. The spline interpolation method (Burden and Faires 1993) was chosen to map the frequency of the CAD dome spatial extent using a smooth surface true to the sampled data points. For consistent comparison among CAD classes, map data were normalized by the total hours of CAD detected for each classification.

d. Data

Hourly surface observations for each station were obtained from the NCEI Global Surface Hourly database (DS3505) and were utilized in both CAD detection and CAD spatial mapping. Data for the 10 surface stations used in the CAD detection algorithm were downloaded for the full 30-yr period from 1981 to 2010. Meteorological fields included temperature, station pressure, sea level pressure, altimeter reading, and hourly precipitation. It was found that large portions of station pressure observations were missing for various stations within the archive even while sea level pressure observations and altimeter readings remained largely intact. Therefore, for times during which altimeter readings were recorded while station pressure was absent, the altimeter readings were used to compute the station pressure using

$$P_{\text{stn}} = P_a \times \left[\frac{(R_d - 0.0065h_m)}{R_d} \right]^{5.2561}, \quad (2)$$

TABLE 1. Surface stations used to analyze CAD spatial extent and the corresponding number of CAD hours, averaged CAD hours per year, and the average number of affected CAD days per year detected for each station during the 30-yr period.

CAD spatial extent stations			Total			Total No. of hours							
Station ID	City	State	Total No. of hours	No. of days yr ⁻¹	No. of affected days yr ⁻¹	% of total	Warm	Cold	CDEN	CDRY	HYBR	WKDR	INST
GSP	Greer	SC	19 003	26.4	48.7	94.7	5983	13 032	3170	5239	4373	4533	851
CAE	Columbia	SC	16 927	23.5	46.4	84.3	5480	11 457	2920	4698	3844	4090	723
FLO	Florence	SC	17 050	23.7	47.1	85.0	5583	11 477	2870	4679	3837	4178	777
AHN	Athens	GA	17 056	23.7	46.0	85.0	5403	11 661	2866	4785	3781	4196	715
AGS	Augusta	GA	16 341	22.7	45.5	81.4	5338	11 013	2849	4609	3568	3998	710
ATL	Atlanta	GA	13 374	18.6	41.2	66.6	4419	8959	2322	3977	2811	3273	536
MCN	Macon	GA	13 986	19.4	42.5	69.7	4665	9326	2382	4114	2857	3549	575
SAV	Savannah	GA	8249	11.5	34.1	41.1	3047	5203	1422	2453	1555	2145	361
RMG	Rome	GA	8172	11.4	34.3	40.7	3054	5119	1459	2274	1775	1992	382
CSG	Columbus	GA	13 039	18.1	40.5	65.0	4391	8651	2144	3934	2546	3463	507
ABY	Albany	GA	11 031	15.3	38.2	55.0	3873	7161	1980	3294	2076	2837	490
VAD	Valdosta	GA	6999	9.7	31.7	34.9	2777	4225	1244	2050	1367	1796	293
TLH	Tallahassee	FL	5522	7.7	28.4	27.5	2122	3400	1051	1551	1021	1488	244
ANB	Anniston	AL	12 313	17.1	38.9	61.4	4057	8257	2072	3749	2527	3088	478
HSV	Huntsville	AL	3961	5.5	24.2	19.7	1598	2362	701	1057	895	1000	196
BHM	Birmingham	AL	7548	10.5	31.4	37.6	2998	4552	1328	2195	1563	1971	300
MGM	Montgomery	AL	5072	7.0	27.9	25.3	1961	3111	893	1344	1028	1413	216
OZR	Ozark	AL	6060	8.4	28.8	30.2	2371	3691	1151	1517	1194	1640	373
MSL	Muscle Shoals	AL	2890	4.0	19.1	14.4	1205	1685	520	770	636	751	125
TCL	Tuscaloosa	AL	5598	7.8	27.3	27.9	2334	3265	1066	1532	1132	1487	234
MOB	Mobile	AL	5192	7.2	25.6	25.9	1921	3272	1088	1307	1007	1332	317

FIG. 3. (a) Monthly average frequency for all CAD days, all CAD events, and the strongest 350 CAD events. (b) Monthly frequency of CAD events and strongest 350 CAD events. (c) The average duration of events by month.

where P_{stn} is the station pressure, P_a is the altimeter reading, R_d is the gas constant for dry air, and h_m is the station height (Chu 1994). While this ensures the most complete dataset possible, it could account for

inconsistencies between this study and previous studies utilizing different datasets. In addition, observations were linearly interpolated for cases with missing reports of six or fewer consecutive hours to reduce the effects of missing

observations on CAD detection, temperature, sea level pressure, and station pressure.

The NCEI National Operational Model Archive and Distribution System (NOMADS) NARR-A online plotter was used to plot reanalyses of sea level pressure fields. NARR-A is available with 3-h temporal frequency and grid spacing of $32 \text{ km} \times 32 \text{ km}$. The central sea level pressure and location of parent highs were manually recorded using the NARR-A online plotter.

3. Results

a. Extended objective climatology

The CAD-detection algorithm was run using surface data for the 30-yr period from 1 January 1981 through 31 December 2010. Identified CAD frequency was analyzed by the number of hours, events, and affected days. All events included at least six CAD hours, while the CDEN and CDRY events included at least 25 CAD hours, as specified previously. CAD-affected days, hereafter referred to as CAD days, were those that included one or more CAD hours. Frequency was also stratified by CAD type and the month of occurrence to demonstrate seasonal variation.

The algorithm identified 703 events, affecting a total of 1504 days and encompassing 20069 h for the 30-yr period. CAD events were detected somewhere in the region by the algorithm on 13.7% of days during the period, or more than 7 weeks yr^{-1} on average. While different events have varying impacts, this result demonstrates the significant amount of time each year that CAD affects the Southeast.

Average monthly frequencies for the strongest CAD events and the total CAD events and days are shown in Figs. 3a and 3b. The results support previous studies in showing a more active cold season (defined as 15 October–15 April) versus a less active warm season. December had the highest event frequency, with 3.2 CAD events occurring per year. October and January followed closely with 2.9 and 2.6 events each year, respectively. June, July, and August (JJA) had the lowest frequency of CAD events with 0.6, 0.6, and 0.8 events annually. For the 30-yr period, the summer months (JJA) had a total of 128 days of detected CAD. While summer months certainly see fewer CAD events, two summer events (17–22 August 1981 and 5–6 September 1996) ranked in the top 4% of all events by strength, indicating that while summer events are few and generally weak, strong summer events are possible.

There is a significant departure from B03's 12-yr climatology for the month of August. B03 described August as having a frequency of just over 3 events per year,

FIG. 4. Variations in the number of CAD days per year. The data have a statistically insignificant downward trend of $0.39 \text{ days yr}^{-1}$.

while this study finds an average of 0.8 events per year over the 30-yr period. This difference is likely the result of the longer period and this study's decision to combine closely consecutive events dynamically forced by the same parent high.

Following previous studies (Bailey 2001; B03), CAD strength was computed for each event using a linear combination of normalized measurements for event duration, sea level pressure and potential temperature Laplacians, and magnitude of the along-barrier pressure gradient. B03 found that the frequency of the strongest cases more closely matched the Bell and Bosart (1988) 50-yr climatology. Indeed, the monthly frequency for the strongest 350 events in our study (shown in Fig. 3a) closely matches the results found by Bell and Bosart (1988), while the monthly frequency of all events shows a significant departure. Though the strongest 350 events showed a maximum during the winter months, the results demonstrate that strong events are still present during the spring and fall seasons when the wedge front can trigger convection.

Output from the CAD-detection algorithm was also analyzed by CAD hours per year, CAD events per year, and average CAD hours by month. Analysis of the average CAD hours by month was consistent with the event frequency by month. Very similar distributions for events per month, days per month, and hours per month indicate an approximately similar average length for individual CAD events across different months. Indeed, the average length of CAD events by month was clustered around 29 h, with the exception of July and August. On average, July events had an average duration of only 19 h, while August event durations averaged 24 h. March events had the longest average duration at 31 h. October had the highest average CAD hours at just over 87 CAD hours each year, while the lowest month, July, saw only an average of 12 CAD hours yr^{-1} . An analysis of CAD event frequency and hour

TABLE 2. CAD event classifications by percentage of total occurrence, percentage of the strongest 350 events, and the average duration.

Class	% of total events	% of the strongest 350 events	Avg No. of events per year	Avg duration (h)	Duration range (h)
CDEN	10.5	22.3	2.5	44.3	25–96
CDRY	17.2	34.3	4.0	45.2	25–126
HYBR	28.9	32.3	6.8	23.2	6–131
WKDR	30.7	18.7	7.2	22.0	6–134
INST	6.0	5.0	1.4	22.0	6–123
UNKN	6.7	4.0	1.6	19.9	6–71

frequency by year showed significant variability from year to year (Fig. 4). The most active year in the period was 1994, with 79 days and 1124 h recording CAD. The least active years were 2010 and 2006, with 28 CAD days (419 CAD hours) and 29 CAD days (365 CAD hours), respectively. The downward trend of $0.39 \text{ days yr}^{-1}$, while

intriguing and possibly related to slow ($0.0^{\circ}\text{--}0.11^{\circ}\text{C decade}^{-1}$) upward trends in September–May temperatures across the United States during 1981–2010 (NCEI 2015; not shown), is not statistically significant at $p = 0.05$.

Analysis was also stratified by CAD type (Table 2; Fig. 5). This revealed that weak/dry events were the most common, making up 31% of CAD events for the 30-yr period and an average of 7.2 yr^{-1} . HYBR events followed closely with 29%. CDRY, CDEN, UNKN, and INST events were 17%, 11%, 7%, and 6%, respectively. CDEN, CDRY, and WKDR events show a large peak in frequency during the cold season and minima during the summer months. HYBR monthly frequency is less clear, though the highest average HYBR events per month occurred in March. INST and UNKN events deviated from this pattern significantly. The INST monthly frequency shows a peak in April that continues through the summer months, while the UNKN monthly frequency appears to be bimodal with a secondary peak in June. It

FIG. 5. The average frequency by month for the different CAD classifications.

FIG. 6. Spatial extent and frequency within the southernmost extent of the damming region for all CAD events by percent of total CAD hours.

should be noted that these two categories were weaker in nature and therefore tend to have lower impact of sensible weather.

Classical-type events exhibited the longest per event average duration over the 30-yr period (Table 2), in part because of classification constraints (i.e., classical types must be longer than 24 h in duration). CDEN events ranged from 25 to 96 h with an average length of 44.3 h, and CDRY events ranged from 25 to 129 h with an average of 45.2 h. HYBR, WKDR, and INST events average approximately half as long, with 23.2, 22.0, and 22.0 h per event, respectively, though their ranges (131, 134, and 123 h respectively) include upper bounds similar to CDRY events. We speculate that the upper bound of the CDEN event range was possibly lower because of strong, but faster moving, parent highs. UNKN events recorded the shortest duration with an average of 19.9 h per event and a range of only 6–71 h. While WKDR events represented the highest percentage of total events by class for the period, analysis of the strongest 350 events (i.e., the strongest 50% of events) shows HYBR and CDRY with the highest percentages, followed by CDEN (Table 2). We also speculate that the CDEN, CDRY, and HYBR events tend to be stronger than other CAD types, because their parent highs are stronger.

b. Cold-dome spatial extent

The spatial distribution of CAD events for the same 30-yr period demonstrates that large variability in the spatial extent of the cold-air dome exists from event to event. Detected CAD hours are broken down site by site and stratified by type and season in Table 1. Unsurprisingly, Greer, South Carolina, the northernmost site considered in this analysis, experienced the highest number of detected CAD hours. However, because Greer is not the northernmost point of the damming region, the 19003 CAD hours detected specifically at Greer for the 30-yr period by the spatial extent algorithm fall short of the total number of CAD-algorithm-detected hours for the entire Southeast by 1066 h. The most surprising result is the frequency with which the cold dome pushes into Alabama and parts of Florida (Fig. 6). On average, CAD was detected at Birmingham 252 h (10.5 days) yr^{-1} and 184 h (7.7 days) yr^{-1} at Tallahassee, Florida. Even Mobile, Alabama, detected 173 h (7.2 days) yr^{-1} on average.

To verify the results from this algorithm, a case for which the algorithm analyzed the dome over southern Alabama and northern Florida was selected. The Weather Prediction Center surface analysis for 0900 UTC 15 October 2009 [Fig. 7; see the supplementary material

FIG. 7. WPC surface analysis for 0900 UTC 15 Oct 2009 showing a cold-air dome extending into southern AL and northern FL.

for an animation of the first author's simulation of this event using the Weather Research and Forecasting (WRF) Model] shows a case in which the cold-air dome, enhanced by a coastal low off the east coast of Florida, pushes well into this region. The algorithm performed well in correctly identifying and rejecting CAD presence at each station for the duration of the event. However, the algorithm did exhibit a tendency to sporadically falsely reject CAD for single hours when several stations within the cold dome reported calm winds. This may lead to a slight undercount in per

station reported CAD hours, though the effect appears to be small. Thus, a new result of our climatology—that CAD is a real phenomenon all the way to the Gulf of Mexico—is robust.

Analysis of the overall spatial pattern for site-by-site CAD frequency shows two apparent lobes of the cold-air dome: one extending to the west-northwest into Alabama and the second extending to the southwest toward Tallahassee (Fig. 6). Comparing these patterns to the regional elevation shows that the lobes tend to split around the region of higher terrain in east-central

FIG. 8. CAD spatial extent and frequency by differing CAD classifications. Percentages are out of the total occurrence for each classification as determined by the CAD detection algorithm.

Alabama [e.g., Mount Cheaha, elevation 734 m (2407 ft)]. Comparison of cold-season versus warm-season events (not shown) reveals that cold-season events slightly favored the west-northwesterly orientation into Alabama over the more southwesterly orientation into Florida. Warm-season events seem to favor both orientations equally, though the warm-season pattern over

north-central Alabama indicates that a higher percentage of warm-season events push into that region than cold-season events.

A comparison of spatial extent and frequency by CAD type is shown in Figs. 8a–f. CDEN, CDRY, and HYBR events all tend to slightly favor the west-northwesterly orientation into Alabama over the push

into Florida. As these three classifications represent stronger synoptic forcing, the rightward turn to the west-northwest is possibly due to the strengthened effect of the Coriolis force as stronger wind speeds develop in the area. At the same time, elevations decrease by more than a factor of 2 from the Smoky Mountains in Tennessee and North Carolina to the end of the Appalachians in Alabama, implying a doubling of the Froude number as the flow reaches Alabama and therefore a reduced blocking effect on these winds. Both INST and UNKN patterns show a displacement of the core of highest-frequency CAD to the northeast and seem to favor a southwesterly orientation. This is possibly due to the weak nature of these events as a result of little synoptic forcing.

4. Conclusions

This work objectively classifies cold-air damming along the southern Appalachians and maps its spatial extent within the southernmost damming region (i.e., South Carolina, Georgia, Alabama, and Florida) for a 30-yr period. While climatologies of cold-air damming have been constructed in the past, this study is the first to both objectively classify events and do so over a long period. In addition, mapping and analysis of the spatial extent of the cold dome across the southernmost damming region has not been performed previously. The purposes of this research are to assess the application of the B03 objective detection and classification schemes to longer time periods and to assess the frequency and extent to which the cold dome pushes into its southern reaches.

On average, CAD was detected by the algorithm on more than 50 days, or more than 7 weeks, each year. Fifty days per year is nontrivial for a phenomenon with the potential to significantly impact forecasts of sensible weather. As found in previous studies, detected CAD is much more frequent during the cold season than in the warm season. This can increase the potential for difficult winter weather forecasts with the threat of dangerous icy precipitation. However, the results also demonstrate that strong CAD events can occur during the spring and summer months when the cold-dome periphery may trigger or enhance convection.

Maps of cold-dome spatial extent reveal the surprisingly high frequency with which the cold dome pushes into portions of Florida and Alabama. Forecasters with CAD experience know that CAD can push as far west as Birmingham or as far south as Tallahassee; this study provides a quantitative measure of that assessment. The maps also indicate two potential trajectories once the dome pushes into central Georgia. A west-northwesterly path turns toward Anniston, Alabama, and north of the

Birmingham area. Its counterpart, the southwesterly trajectory, continues pushing into southwest Georgia and Florida. Cold-season events seemed to favor the west-northwesterly orientation, as did the stronger CAD categories. With further research, these findings may provide forecasters with a quick estimate of where and how far the cold dome will push given the synoptic conditions. Future work utilizing the WRF Model (Rackley 2015; see supplementary material) will attempt to shed further light on why and how these two different trajectories form.

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