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The characteristics of extreme cold events and cold air outbreaks in the eastern United States

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ABSTRACT: Periods of extreme cold impact the mid-latitudes every winter. Depending on the magnitude and duration of the occurrence, extremely cold periods may be deemed cold air outbreaks (CAOs). A systematic CAO index and ranking system was developed from 20 surface weather stations from 1948 through 2016, based on a set of criteria concerning magnitude, duration, and spatial extent. Standard deviations in temperature were used to identify extreme temperatures relative to the station. A total of 49 CAOs occurred during the 67-year period, with the majority occurring during mid-winter. The number of CAOs proved to be largely dependent on the stations latitude and maritime influence. The duration, magnitude, and spatial extent were dependent on the time of the winter season in which the CAO occurred. Furthermore, two prominent clusters of an increased number of CAOs occurred during the 67-year period, suggesting multi-decadal circulations may be a factor in CAOs.

KEY WORDS cold air outbreaks; synoptic; climate; United States; extreme cold; mid-latitudes

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1. Introduction

Cold air outbreaks (CAOs) are southwards displacements of polar air over the Northern Hemisphere (NH) during the winter months (Wheeler *et al.*, 2011). CAOs are often characterized by a large negative deviation in temperature across a wide spatial extent that lasts for multiple days. Extremely low temperatures can contribute to crop loss, water pipe damage, and ailments among the population (Cellitti *et al.*, 2006). The southwards extent of a CAO also plays a role in the overall impact of the event. During the winter of 1983–1984, a severe CAO led to the loss of hundreds of human lives, tens of thousands of cattle, and severe crop damage across the Midwestern and southeastern United States (Quiroz, 1984). Regions that climatologically see few CAOs tend to be inadequately prepared for the effects of extreme cold and are usually the most heavily impacted. Therefore, the identification of a CAO must account for the relative effects across climatologically diverse regions. The majority of research in the area of extreme cold events (ECEs) focuses on shifts in patterns associated with a changing climate (Donat and Alexander, 2012; Robeson *et al.*, 2014; Screen *et al.*, 2015; Kanno *et al.*, 2016). Of the studies that have examined CAOs (Walsh *et al.*, 2001; Cellitti *et al.*, 2006; Vavrus *et al.*, 2006; Wheeler *et al.*, 2011), few explicitly focus on the localized trends in a region and instead focus on climate model comparisons, the physical mechanisms that drive the CAOs, the trajectories of the Arctic air masses, or the changing probabilities of future CAOs across the globe. Although future projections and the physical mechanisms associated with CAOs are important, an intensive study of the trends in CAOs in a particular region will provide an avenue to better understand the physical mechanisms associated with localized changes and help provide verification of climate projections. This research, although similar to Cellitti *et al.* (2006), uses defined criteria to identify ECEs and CAOs in eastern United States since 1948, but focuses on the spatial and temporal trends of ECEs and CAOs across the region rather than the associated physical mechanisms. Furthermore, this study introduces a ranking system according to defined magnitude, duration, and spatial extent criteria to better depict the trends in CAOs over the past 67 years.

1.1. Cold weather regimes

The mid-latitudes, areas lying between 35° and 55°N, experience all four seasons and are commonly subjected to the intrusion of Arctic air masses during the winter. Because of the location of the mid-latitudes, they are prone to influences of both the subtropical (approximately 30°N) and polar (approximately 40°–60°N) jet streams, or narrow bands of fast, meandering winds at the top of the troposphere (Hudson, 2012). Of the two, the polar jet stream is the stronger one due to a larger temperature gradient within the jet stream. During the summer, the subtropical jet extends farther north and the mid-latitudes are predominantly inclined to warm weather. During the winter, when the equator-pole temperature gradient is the largest, the polar jet strengthens and extends farther south.

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The locations in which the polar jet extends southwards are subject to the southwards propagating Arctic air.

1.2. Study area

The majority of the contiguous United States resides in the mid-latitudes and most of the population lives in the eastern United States. According to Mackun *et al.* (2011), nearly 240 million people, or 75% of the population, live east of the Rocky Mountains. While the western United States experiences CAOs, the synoptic patterns that influence the displacement of Arctic air into the eastern United States and the decadal trends of these outbreaks often differ from those in the western United States (Vavrus *et al.*, 2006). A typical Rossby wave pattern that results in extreme cold temperatures for the United States rarely extends across the entirety of the contiguous United States. To maintain consistency in the synoptic patterns that result in CAOs and to limit the number of stations where data is acquired, the focus of this research is limited to 20 stations across the United States east of the Rocky Mountains. While similar in extent to Cellitti *et al.* (2006), the increase in the number of stations from 17 to 20 helps fill the gaps in the study area.

1.3. Identifying a CAO

Extreme cold impacts the mid-latitudes every winter. There is a wide range of possible causes for these events, thus the duration, magnitude, and spatial extent of extreme cold can be quite different from one event to another. Extreme cold weather may impact the United States via a broad southwards displacement of Arctic air, or following a heavy snowfall event. Heavy snowfall events often only affect a small spatial extent and southwards displacements of Arctic air may only last a day or two. Extreme cold may also occur locally from mesoscale processes, such as cold sinks in mountainous regions. The identification of a CAO is necessary to rule out isolated events and capture the extreme events with the most detrimental impacts on society according to a defined duration, magnitude, and spatial extent. Furthermore, a database of CAOs is a useful tool in a changing climate. They can be used for past-climate comparisons or for modelling future CAOs within a warmer climate.

Because of the differences in criteria applied based on specific purposes, there is no universal definition of a CAO. Both Wheeler *et al.* (2011) and Vavrus *et al.* (2006) noted the challenge in defining anomalous weather but recognized the need for a standardized CAO definition. Some identifications maintain more objectivity than others, but all address to a certain degree the magnitude, duration, and spatial extent. Many of the caveats that exist with the identification of CAOs are related to the subjectivity of thresholds applied to large regions. Therefore, the relative nature of cold air impacts should be considered when looking at a region as large as the eastern United States. Although several studies identifying CAOs across North America have been conducted over the last few decades (Walsh *et al.*, 2001; Cellitti *et al.*, 2006; Vavrus *et al.*, 2006; Wheeler *et al.*, 2011), a new identification of CAOs is conducted to incorporate the most objective criteria relative to the study area, while also expanding the CAO database through 2016.

1.3.1. Magnitude and duration

The magnitude and duration of an event can be determined in multiple ways. The most common approaches are the use of specific temperature thresholds and/or defined temperature anomalies, either in terms of degrees or standard deviations. Specific temperature thresholds allow an absolute comparison between different locations, whereas standard deviations in temperature allow relative comparisons with respect to the specific climate. The accumulated winter season severity index (AWSSI) utilizes absolute maximum and minimum temperature thresholds as part of a quantification of winter severity across the United States (Mayes Boustead *et al.*, 2015). This index is very useful for the intended latitudes; however, the absolute thresholds make it less applicable in climates where winter temperatures are consistently above or below these thresholds. In contrast, Wheeler *et al.* (2011) used a standardized anomaly approach to develop a climatology of CAOs over North America by looking at temperature anomalies, frequency, and geographical extent between the Whole Atmosphere Community Climate Model (WACCM) and European Reanalysis data (ERA-40). In this instance, a CAO was defined as having a surface temperature lower than 1.5σ below the 31-day centred climatological mean over a 45-year period, and a daily deviation in temperature greater than 2 °C (Wheeler *et al.*, 2011). Vavrus *et al.* (2006) used similar methods to those of Wheeler *et al.* (2011) in which they defined the magnitude and duration of CAOs by using general circulation models to look at surface temperatures at least 2σ below the December through February mean. Cellitti *et al.* (2006) constructed a criterion using observational surface temperatures for 17 stations across the eastern United States from November through March. They conducted sensitivity experiments with different case selection criteria (coldest 3-day and coldest 1-day periods) and found that regardless of the duration of the temperature averages, the clear majority of the selected cases remained the same. Cellitti *et al.* (2006) went on to address the CAO duration by defining the onset date of a CAO as the earliest date a 5-day CAO began at any station.

1.3.2. Spatial extent

Given that a CAO is inherently broad, delineating a minimum spatial extent is necessary to distinguish between CAOs and localized and/or brief ECEs. Additionally, it prevents the inclusion of stray locations that may be experiencing extreme cold resulting from circumstances other than the broader air mass. It is these mesoscale temperature influences along with varying spatial extents that create difficulties when identifying CAOs over broad areas. Because the eastern United States is a large area, it may take multiple days for a polar air mass to encompass several surface stations. This may lead to extreme cold lasting longer in the northern mid-latitudes than in the southern mid-latitudes. However, impacts from extreme cold differ depending on the climate of a specific region. Smaller temperature variations in the southern mid-latitudes may be just as impactful as larger variations in a region more accustomed to cold temperatures. Wheeler *et al.* (2011) applied a spatial criterion such that both the magnitude and duration conditions must be satisfied over a contiguous area of roughly 5° latitude by 5° longitude. The 5° by 5° spatial criteria removed stray grid points that satisfied the CAO criterion but were isolated from the contiguous CAO air mass. Vavrus *et al.* (2006) analysed projected trends of CAOs at the regional level with the eastern and western United States categorized as separate regions. They determined a CAO must meet the magnitude and duration criteria at a grid point for at least two consecutive days. Cellitti *et al.* (2006), who examined the 30 coldest 5-day average surface temperature anomalies, used a spatial extent of three or more contiguous stations where each station was within 600 km from the nearest station.

1.4. Impacts of climate change and variability on CAOs

Mid-latitude winter temperatures are subject to much variability as a result of both low- and high-frequency synoptic patterns. Understanding this variability is exacerbated by uncertainties regarding the changing climate and the degree of impact from natural and anthropogenic influences. CAOs, like winter temperatures, may experience changes in both strength and seasonality because of a changing climate. While heat-related weather extremes are expected to increase, changes in cold-related extremes are far less certain. Donat and Alexander (2012) found that global daily maximum and minimum temperatures had indeed become more extreme since the mid-20th century, with a shift towards warmer temperatures almost everywhere. Vavrus *et al.* (2006) ran projections of 21st century radiative conditions with seven global climate models (GCM) and found that CAOs are becoming most favoured over western North America and Europe. Based on these future projections, certain regions could experience a 50–100% decline in the frequency of CAOs while other regions maintain or increase in the frequency of CAOs (Vavrus *et al.*, 2006). Screen *et al.* (2015) used large ensembles of model simulations to examine the future risk of North American cold extremes and found that the likelihood of ECEs across the eastern United States was less than half as likely when compared to the period of 1980–1999. Similarly, Kanno *et al.* (2016) found that the total hemispheric cold air mass amount for the NH exhibited a significant decreasing trend from 1959 to 2012 and 1980 to 2012, although the geographical patterns differed for each period as a result of internal low-frequency dynamics. Robeson *et al.* (2014) examined the period of 1881–2013 (compared with 1984–2013 average) and found while the NH may be warming, not all regions are warming at the same rate, nor is warming consistent throughout the year. In fact, a decadal cooling trend was evident in regions of positive and negative anomalies during January and February (Robeson *et al.*, 2014). While most climate models are consistent in predicting warming in the NH during winter, recent trends in NH winter surface temperatures have shown large-scale cooling in eastern North America and Eurasia (Cohen *et al.*, 2012). The dynamically induced large-scale wintertime cooling may be a result of an increase in high-latitude moisture and an increase in snow cover across Eurasia (Cohen *et al.*, 2012). National Academies of Sciences, Engineering, and Medicine (2016) showed that the general consensus among scientific literature suggests extreme cold anomalies defined relative to a fixed temperature will continue to decrease in frequency (warm), although extreme cold anomalies could still increase for periods of time in certain regions. These findings suggest that CAOs in North America may not decrease linearly with a warming climate but may shift towards the latter half of winter or increase for periods of time as a result of internal low-frequency dynamics. However, numerous Arctic outbreaks in the eastern United States during the winters of 2013–2014 and 2014–2015 suggest wide spread, extreme cold is still very possible amid a changing climate. With such uncertainty regarding the changes in location and magnitude of cold extremes, studying CAOs relative to some defined criteria is important to contextualize the current trends.

2. Research design

2.1. Data

Surface temperatures can be obtained via surface weather stations and reanalysis data. Twenty surface weather stations were chosen (Table 1) because unlike gridded data, surface observations are recorded at airports and are generally better representations of the largest population centres. Of the 240 million people who live east of the Rockies, roughly one quarter (57 million people) reside in the metropolitan areas surrounding these 20 weather stations (U.S. Census Bureau, 2016). Observational surface temperature data are used from 20 airport weather stations or from Threaded Extreme (ThreadEX) stations across the eastern United States. This study uses the same 17 stations as Cellitti *et al.* (2006) with the addition of the Salina, Nashville, and Buffalo stations to help fill spatial gaps in weather station data and the ThreadEX stations to fill the large gaps of missing data noted by Cellitti *et al.* (2006). Daily maximum and minimum temperature data were downloaded for the years of 1948 through 2016 and edited to contain only the cold season months of November through March. Both maximum and minimum temperatures were used to obtain an accurate depiction of the air mass impacting the station and to limit potential mesoscale influences.

Threaded station extremes (ThreadEX stations), listed as area stations in Table 1, are a project designed by the National Oceanic and Atmospheric Association (NOAA), National Weather Service (NWS), National Climatic Data Center (NCDC), and Regional Climate Centers to address fragmentation in data that has occurred over time.

Table 1. Surface weather stations.

Weather station	WBAN number	FAA location ID	Missing days	Replacement station
Atlanta, Georgia	13 874	ATL	0	
Boston, Massachusetts	14 739	BOS	0	
Buffalo, New York	14 733	BUF	1	
Chicago, Illinois	Chicago area	Chicago area	0	
Cincinnati, Ohio	93 814	CVG	1	
Dallas, Texas	13 960	DAL	30	
Des Moines, Iowa	14 933	DSM	0	
Detroit, Michigan	Detroit area	Detroit area	0	
Little Rock, Arkansas	13 963	LIT	0	
Miami, Florida	12 839	MIA	0	
Minneapolis, Minnesota	14 922	MSP	0	
Nashville, Tennessee	13 897	BNA	0	
New Orleans, Louisiana	12 916	MSY	0	
Oklahoma City, Oklahoma	13 967	OKC	5	
Orlando, Florida	Orlando area	Orlando area	3	
Philadelphia, Pennsylvania	13 739	PHL	0	
Pierre, South Dakota	24 025	PIR	28	
Raleigh, North Carolina	13 722	RDU	0	
Salina, Kansas	Salina area	Salina area	347	
St. Louis, Missouri	13 994	STL	0	Abilene, Kansas and McPherson, Kansas

Replacement stations were used to fill the 347 missing days for the saline area station.

Missing data often occurs due to instrumentation errors or during the process of upgrading weather instruments. The number of missing days is identified in Table 1. A date is considered missing if either the maximum temperature or the minimum temperature is missing. Most stations had no data or only 1 day of missing data. Dallas and Pierre had nearly a month of missing data; however, most of the missing dates were not consecutive and only a few days occurred during the winter months. The Salina station had periods of consecutive missing data which extended a month or longer. To account for the missing days, the Abilene, KS and McPherson, KS stations were used to replace the missing days. The Abilene and McPherson, KS stations are located with 30 miles of the Salina station and have very little change in topography. The list of surface weather stations can be seen graphically in Figure 1.

2.2. Methods

2.2.1. *Identifying ECEs*

Before a CAO can be identified, there must be criteria set aside to determine whether a given location is experiencing anomalously cold weather. Thus, an ECE is defined according to a magnitude and duration criteria for a single station. A combination of approaches from both Wheeler *et al.* (2011) and Vavrus *et al.* (2006) were used. The criteria are as follows:

1 Daily maximum and minimum temperatures will be required to be at least 1.25σ below the 67 year daily climatological mean.
2 The duration must be at least 5 days in which the daily maximum and minimum temperatures are at least 1.25σ below the climatological mean.

The climatological mean used in the standard deviation calculation is computed for each day using a second-order polynomial regression of the mean maximum and minimum temperatures for each day, averaged over the 1948 through 2016 period. This smooths the data set over the course of a season, limiting the effects of one or two anomalous temperatures that may influence a daily average. Thresholds were adjusted from -1.20σ to -1.75σ in 0.05 intervals to look for natural breaks in the number of ECEs that occur as a result of different thresholds. No natural breaks were found and the -1.25σ threshold was chosen. A threshold of -1.25 results in a large enough sample size to adequately conduct a synoptic pattern analysis, while small enough to maintain the focus on the most extreme events.

As defined by Vavrus *et al.* (2006), using a period of consecutive days of anomalously cold temperatures rule out small impact events and limit the findings to large-scale Arctic intrusions. This study requires that a minimum of 5 days must meet the magnitude and spatial extent criteria to focus on the long duration Arctic air intrusions and the associated synoptic patterns. Similar to the magnitude criteria, 5 days was chosen to keep the sample size large enough for the synoptic pattern analysis, but filter out insignificant periods of cold air. To account for marginal days in the middle of a cold outbreak, in a given ECE, any 1 day may fall outside of the magnitude criteria ($>-1.25\sigma$) as long as the 5-day centred moving average does not fall below the -1.25σ threshold. The 5-day centred moving average was only used to ensure the duration criteria did not terminate prematurely and was not used to determine the onset or end of an ECE.

2.2.2. *Cold air outbreaks*

The identification of a CAO differs from an ECE in that it incorporates a spatial criterion which rules out micro-climatic effects on one specific station. Thus, it

Figure 1. Locations of surface weather stations.

reveals that the extreme cold exists at a regional level, affecting many more people than just an ECE. The spatial criterion requires that at least 3 of the 20 stations must simultaneously meet the ECE criteria and be contiguous to be considered a regional outbreak, as used in Cellitti *et al.* (2006). The spatial extent must also be justified by the typical evolution and extent of atmospheric regimes which spawn CAOs. A benefit of having a larger spatial extent is the ruling out of isolated topographic influences or influential weather at single stations. The onset of a regional CAO is determined once three stations meet the ECE criteria and is terminated when at least three stations no longer meet the ECE criteria. The distance between each of the surface stations (roughly 500–700 km) made a spatial extent of three contiguous stations the suitable choice to ensure a large enough sample size, while also limiting the results to large, regional CAOs. A ranking system was also included to contextualize the severity of each CAO (Table 2). The CAOs were ranked according to each criterion (1–49), then the ranks for each of the three criteria were added together for a cumulative score, with the lowest score being the most severe CAO.

To determine the degree of seasonality of CAOs, the winter season was divided into five 28-day periods, beginning on 1 November and ending after the latest occurring CAO on 23 March (Figure 4). Twenty-eight-day periods were used rather than months to create equal intervals to be used in the analysis. Each period is denoted with the letter P followed by the period number.

3. Results and discussion

3.1. Extreme cold events

ECEs occur most frequently in the northwestern stations and the far southeastern stations. The number of ECEs ranges from 27 in Raleigh to 77 in Pierre (Figure 2, bottom left). The number of days is classified as part of an ECE range from 176 in Raleigh to 572 in Pierre (Figure 2,

Table 2. CAO rank, year, onset date, duration of event, avg. *z*-score (max. and min. combined), spatial extent (number of cities included), and the score of the CAO (summation of CAOs ranked by duration, *z*-score, and spatial extent).

Rank	Year	Onset date	Duration	Avg. *z*-score	# of cities	Score
26	1950	21 Nov	9	−1.84	6	73
16	1951	25 Jan	10	−1.87	9	53
7	1951	1 Nov	8	−2.38	11	40
34	1951	12 Dec	10	−1.75	4	92
17	1955	21 Mar	10	−1.91	7	57
12	1958	12 Feb	10	−1.89	12	48
23	1958	5 Dec	11	−1.78	7	67
3	1960	20 Feb	26	−1.91	14	22
44	1961	8 Dec	7	−1.75	3	124
36	1962	7 Jan	6	−1.75	8	101
49	1962	16 Jan	5	−1.69	3	139
20	1962	24 Feb	12	−1.87	4	63
11	1962	6 Dec	10	−2.01	8	45
13	1963	18 Jan	11	−1.96	5	48
6	1963	9 Dec	15	−1.84	15	34
31	1965	16 Mar	6	−1.99	4	85
18	1966	20 Jan	12	−1.76	11	58
38	1967	15 Mar	5	−1.92	3	109
27	1970	4 Jan	8	−1.79	12	73
32	1970	15 Jan	8	−1.82	5	87
15	1972	2 Dec	13	−1.90	5	52
28	1973	4 Jan	9	−1.95	4	73
4	1977	5 Jan	19	−1.97	11	22
30	1978	29 Dec	11	−1.76	5	82
8	1979	5 Feb	14	−2.01	5	40
41	1980	26 Feb	7	−1.76	4	114
35	1981	7 Jan	7	−1.82	5	100
19	1982	6 Jan	13	−1.81	7	61
1	1983	14 Dec	17	−2.08	16	8
24	1984	13 Jan	9	−1.84	9	68
48	1985	29 Jan	7	−1.72	3	133
22	1985	23 Nov	11	−1.92	4	66
45	1985	13 Dec	8	−1.74	3	125
21	1986	7 Nov	8	−1.95	8	64
39	1988	4 Jan	7	−1.85	3	113
33	1989	31 Jan	8	−1.82	6	89
2	1989	11 Dec	15	−2.04	20	10
9	1991	1 Nov	9	−2.28	10	41
10	1994	12 Jan	10	−2.03	9	42
46	1995	7 Dec	6	−1.68	4	131
5	1996	25 Jan	11	−1.97	14	30
43	1998	7 Mar	6	−1.76	4	122
40	2000	17 Dec	9	−1.78	3	113
42	2000	29 Dec	6	−1.80	4	119
37	2005	1 Dec	9	−1.77	4	107
47	2007	1 Feb	8	−1.72	3	132
25	2010	2 Jan	11	−1.94	4	72
29	2014	9 Nov	10	−1.84	5	79
14	2015	12 Feb	12	−1.89	8	49

bottom right). The total days classified as an ECE correlates well with the number of ECEs, with the ratios of ECE days to the number of ECEs between 0.13 and 0.16 for all cities, suggesting that no one station experiences particularly long ECEs relative to another. While the overall spatial pattern is intuitive, with a greater number of ECEs farther north and inland, Orlando and Miami experience more ECEs than other southeastern stations, as their climatologically small deviation in temperatures throughout the course of the year can result in small temperature changes leading to large deviations.

3.2. Cold air outbreaks

From October 1948 through March 2016, 49 CAOs impacted the eastern United States (Table 2). The number of CAOs and CAO days per station is shown in Figures 2 and 3. Like ECEs, the majority of the CAOs occurred in the northwestern stations and a general trend of fewer CAOs the farther south and east the station is located. There is a noticeable maritime influence with the number of CAOs in near-coast stations such as Boston, Philadelphia, and Raleigh as the warm temperatures of

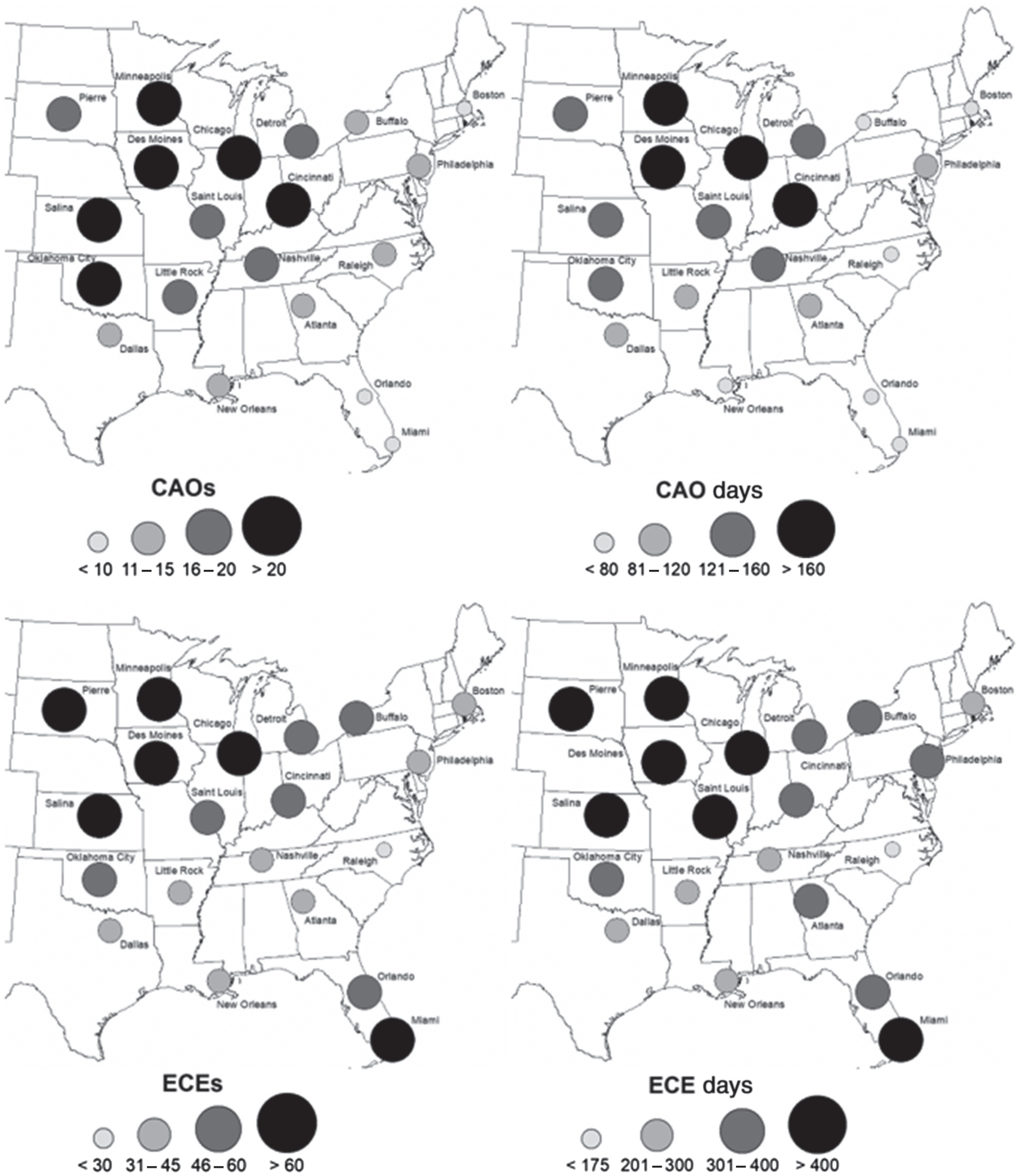


Figure 2. Top left: CAOs by station. Top right: total CAO days by station. Bottom left: ECEs by station. Bottom right: total ECE days by station.

the Gulf of Mexico and the Atlantic Ocean can moderate extreme temperatures. This is most clear in Figure 3 as Raleigh, Philadelphia, and Boston experience no CAO days during P1. While the standard deviation for each station takes into account the maritime influence, early season CAOs are much less likely to impact coastal cities with the same magnitude as inland cities since the maritime influence is much stronger. By late winter, the cooler waters are much more likely to allow persistent extreme cold to the degree of a CAO. This same effect is evident in Buffalo which also has much fewer CAOs than expected with respect to its northern latitude. This is a result of the moderation from Lake Erie, when not frozen, along with the other Great Lakes as Arctic air masses propagate southwards. This may also be the case for Detroit having fewer CAOs than stations of similar latitudes. The lower number of CAOs in Raleigh may also be a result of the Appalachian Mountains blocking the

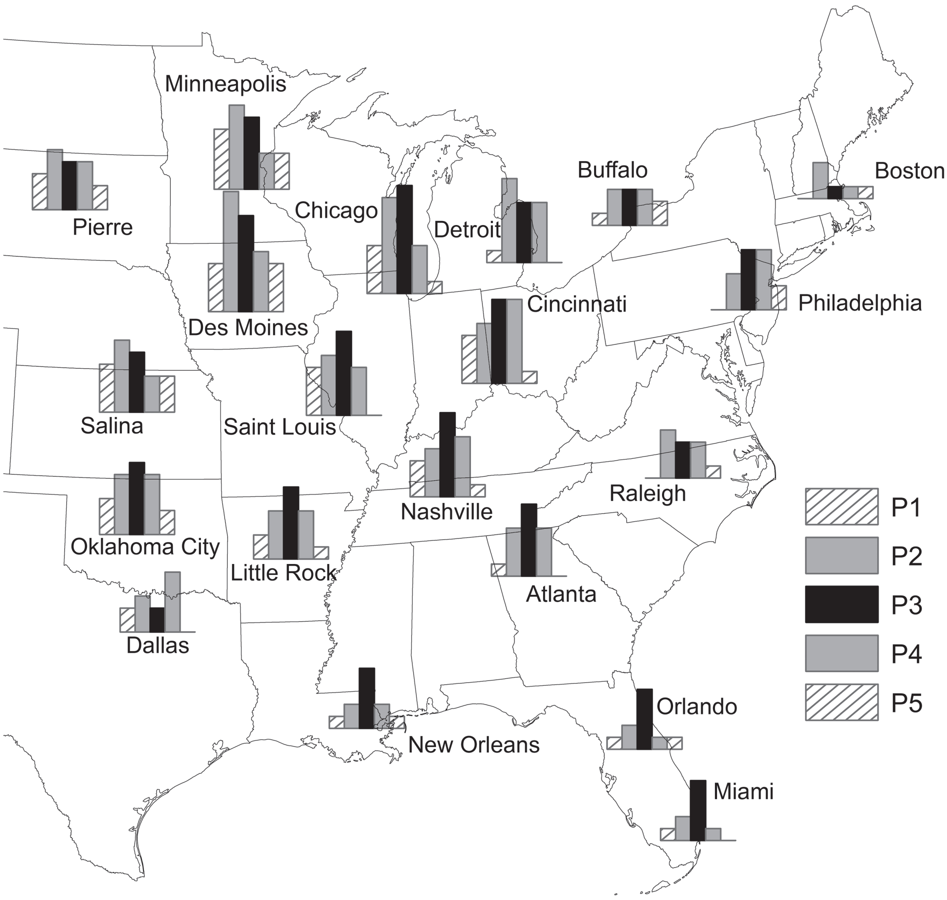


Figure 3. CAOs by period for each station.

Table 3. Top ten CAOs by magnitude (average z-score), duration (number of days), and the spatial extent (number of cities in the outbreak).

Onset	z-score	Onset	Duration	Onset	# cities
1 Nov 1951	−2.38	20 Feb 1960	26	11 Dec 1989	20
1 Nov 1991	−2.28	5 Jan 1977	19	14 Dec 1983	16
14 Dec 1983	−2.08	14 Dec 1983	17	9 Dec 1963	15
11 Dec 1989	−2.04	9 Dec 1963	15	20 Feb 1960	14
12 Jan 1994	−2.03	11 Dec 1989	15	25 Jan 1996	14
5 Feb 1979	−2.01	5 Feb 1979	14	12 Feb 1958	12
6 Dec 1962	−2.01	2 Dec 1972	13	4 Jan 1970	12
16 Mar 1965	−1.99	6 Jan 1982	13	1 Nov 1951	11
25 Jan 1996	−1.97	24 Feb 1962	12	20 Jan 1966	11
5 Jan 1977	−1.97	20 Jan 1966	12	5 Jan 1977	11

southwards displaced Arctic air masses to an extent. With the fewest number of ECEs and ECE days, when Raleigh experiences extreme cold, it is more often a part of a CAO. This may indicate that only the most extreme air masses, often during mid-winter, can overcome the blocking associated with Appalachian Mountains and reach Raleigh.

3.2.1. CAO extremes

The ten most extreme CAOs are shown in Table 3 and separated by magnitude, duration, and the number of cities included in the outbreak. The strongest CAO onset on 1 November 1951 with an average event magnitude of -2.38σ (Table 4) and ranked seventh overall (Table 2). The onset occurred on 1 November for all 11 cities, suggesting an October onset for several cities may have occurred. This event was documented by the U.S. Weather Bureau, who recorded an abrupt change from a mild October to a very cold November, with the lowest departures occurring from North Dakota to Wisconsin and only slightly below average temperatures across the far west and portions of New England (Klein, 1951). While a 6 °C average maximum temperature (−3 °C minimum) in Nashville on 1 November is not typically considered extreme cold, the magnitude relative to the

Table 4. CAO with the strongest magnitude, 1 November 1951.

Onset	Duration	*Z*-max.	Max. T.	*Z*-min.	Min. T.	City
1 Nov	6	−2.08	1	−2.60	−6	Buffalo
1 Nov	5	−2.36	−1	−2.92	−9	Chicago
1 Nov	5	−2.19	3	−2.12	−6	Cincinnati
1 Nov	7	−2.15	−1	−2.65	−11	Des Moines
1 Nov	6	−2.08	2	−2.67	−6	Detroit
1 Nov	5	−2.77	6	−1.82	−2	Little Rock
1 Nov	7	−2.38	−4	−3.15	−13	Minneapolis
1 Nov	5	−2.36	6	−1.74	−3	Nashville
1 Nov	6	−2.35	5	−2.17	−4	Oklahoma City
1 Nov	5	−1.96	−2	−3.31	−14	Pierre
1 Nov	8	−2.17	2	−2.25	−6	St. Louis

Z-max., *Z*-min., max. T. (°C), and min. T. (°C) are averages for the entire CAO.

Table 5. CAO with longest duration, 20 February 1960.

Onset	Duration	*Z*-max.	Max. T.	*Z*-min.	Min. T.	City
20 Feb	16	−2.06	−7	−2.26	−17	Salina
21 Feb	14	−2.12	−2	−1.96	−10	Oklahoma City
22 Feb	12	−2.03	4	−1.75	−4	Dallas
27 Feb	10	−1.77	−8	−1.98	−18	Des Moines
27 Feb	9	−1.78	−12	−1.98	−22	Pierre
29 Feb	6	−1.63	−10	−1.66	−20	Minneapolis
29 Feb	9	−1.71	−3	−1.63	−12	Cincinnati
29 Feb	17	−2.00	5	−2.29	−3	Atlanta
29 Feb	6	−2.11	1	−1.71	−6	Little Rock
29 Feb	7	−2.15	−1	−1.85	−9	Nashville
29 Feb	7	−2.05	−6	−2.15	−13	St. Louis
2 Mar	5	−1.58	13	−1.52	2	New Orleans
2 Mar	10	−2.22	1	−1.86	−8	Raleigh
3 Mar	11	−1.79	−1	−2.01	−9	Philadelphia

Z-max., *Z*-min., max. T. (°C), and min. T. (°C) are averages for the entire CAO.

time of season can result in human health impacts from a lack of acclimatization (Kaciuba-Uscilko and Greenleaf, 1989).

The CAO with the longest duration onset on 20 February 1960 and lasted 26 days (Table 5), ranking third overall. Fourteen cities were included in the CAO with the northeastern and southeastern United States not meeting the criteria. The U.S. Weather Bureau characterized the winter season as beginning mild but transitioning to intense cold in the southern United States, particularly in the month of February, with very mild temperatures across New England (Stark, 1960). Stark (1960) also noted the snowy conditions across the central and southern plains which align well with the longest CAO duration from Dallas to Des Moines.

Only one CAO, which began on 11 December 1989, encompassed all 20 cities in the study area (Table 6). This outbreak was a result of a strong, reinforced polar flow, characterized by an anomalously high pressure centred over the north central United States (NOAA, National Weather Service, 1989). The CAO started in the northwestern portion of the study area on 11 December and eventually propagated into the Florida Peninsula by 21 December. The NWS Office in Wilmington, North Carolina noted that record low temperatures were reached from Florida to North Carolina, with near-total destruction of the commercial citrus crop (NOAA, National Weather Service, 1989). The 11 December 1989 CAO ranked second behind the 14 December 1983 CAO. While the December 1983 CAO did not rank highest in any of the three criteria, it ranked second or third in all criterion, resulting in the most extreme CAO overall of the 67-year period, particularly for the south central and midwestern states.

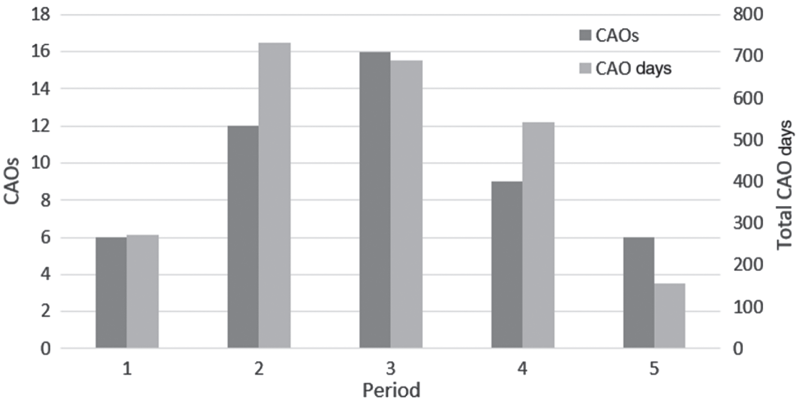
3.2.2. Seasonality of CAO characteristics

CAOs have a clear seasonal component with the majority of CAOs occurring during P2 and P3 and fewer in P1, P4, and P5 (Figure 4). The total CAO days is more telling than the number of CAO onsets in each period because the total count of CAO onsets does not account for their length. This is clearly seen in P2 (732 CAO days and 12 CAO onsets) and P3 (690 CAO days and 16 CAO onsets) where P2 experiences 4 fewer CAOs, but 42 more CAO days. This results from both longer duration CAOs or a greater number of stations affected by each CAO during P2. The opposite is evident during P5, where the total CAO days is proportionally smaller when compared with the number of CAO onsets. Figure 4 also shows the average CAO duration, magnitude (z-score), spatial extent (number of stations) per period. The mean duration of CAOs is

Table 6. CAO with most cities included, 11 December 1989.

Onset	Duration	*Z*-max.	Max. T.	*Z*-min.	Min. T.	City
11 Dec	14	−1.98	−11	−1.96	−19	Chicago
11 Dec	13	−1.96	−13	−2.06	−22	Des Moines
11 Dec	12	−2.03	−17	−1.99	−26	Pierre
11 Dec	13	−2.00	−8	−2.35	−18	St. Louis
12 Dec	13	−1.99	−8	−2.33	−19	Cincinnati
12 Dec	11	−1.86	−8	−1.95	−15	Detroit
13 Dec	12	−2.06	−3	−2.21	−14	Nashville
13 Dec	11	−1.98	−8	−2.49	−20	Salina
14 Dec	9	−2.14	−17	−1.69	−24	Minneapolis
14 Dec	11	−1.93	−1	−2.20	−12	Little Rock
14 Dec	10	−1.88	−3	−2.23	−13	Oklahoma City
16 Dec	9	−1.83	−4	−1.91	−12	Philadelphia
17 Dec	7	−1.89	−9	−1.78	−16	Buffalo
18 Dec	6	−2.23	−1	−2.22	−9	Dallas
19 Dec	6	−2.04	1	−1.89	−8	Atlanta
19 Dec	6	−1.81	−5	−1.75	−12	Boston
19 Dec	6	−2.38	4	−1.87	−3	New Orleans
20 Dec	6	−1.94	−1	−1.77	−11	Raleigh
21 Dec	6	−2.26	18	−2.03	7	Miami
21 Dec	5	−2.82	9	−1.90	1	Orlando

Z-max., *Z*-min., max. T. (°C), and min. T. (°C) are averages for the entire CAO.



Period	Dates	Avg. duration	Avg. Z-score	Avg. # cities
1	11/1 – 11/28	6.2	−2.10	7.3
2	11/29 – 12/26	8.0	−1.92	7.7
3	12/27 – 1/24	6.6	−1.85	6.6
4	1/25 – 2/22	7.3	−1.90	8.2
5	2/23 – 3/23	6.0	−1.87	4.3

Figure 4. Top: total number of CAO days (left *y*-axis) and CAO onsets (right *y*-axis) by month from November 1948 to March 2016. Bottom: average CAO duration, magnitude (*z*-score), spatial extent (number of cities) per period.

highest during P2 and P4 and shortest during P1 and P5. In terms of mean magnitude, the peak is in P1, although with only six CAOs, it is slightly skewed by CAO number 3 which had a magnitude of -2.38σ. Following P1, the mean magnitude is roughly similar, between −1.85 and −1.92. The spatial extent of CAOs on average is fairly similar throughout the year, except for P5, when the average is only slightly above 4.

Similar to the overall patterns noted above, at most stations CAO days increase rapidly during P2 and stay frequent through P3, before decreasing during P4 and P5. In many northern stations, the peak CAO activity can be found in P2, whereas, very few CAOs impact the southern and eastern stations during P1 and P5 with a sharp peak of CAOs in the south, particularly from New Orleans to Miami, during P3 (Figure 3). This is expected as the farther south displacements of cold air masses generally occur during mid-winter when the source region is coldest. Additionally, snowpack and cold temperatures to the north reduce the moderation of the air mass as it travels south. Chicago experiences a peak in CAO days during P3, most similar to the central stations of St. Louis, Little Rock,

Table 7. CAOs and ECEs by city.

City	CAOs	CAO days	ECEs	ECE days
Atlanta	15	112	43	303
Boston	6	40	44	283
Buffalo	12	76	47	318
Chicago	26	192	66	494
Cincinnati	24	161	52	367
Dallas	12	84	37	257
Des Moines	31	224	70	536
Detroit	18	123	54	384
Little Rock	17	112	37	254
Miami	9	68	73	469
Minneapolis	24	181	73	534
Nashville	20	126	40	265
New Orleans	11	59	32	201
Oklahoma City	21	143	47	310
Orlando	10	65	49	312
Philadelphia	15	112	45	310
Pierre	18	140	77	572
Raleigh	11	70	27	176
Salina	21	159	67	482
St. Louis	20	147	52	402

Nashville, and Atlanta. Although Dallas experiences its CAO-day peak during P4, the number of CAO days in P4 is similar to Oklahoma City and Little Rock. It is interesting to note that CAO days peak in Dallas during P4, but no CAO days occur during P5. Perhaps the southern latitude of Dallas may be just enough to limit late season CAOs during P5. However, this also occurs in Atlanta, Miami, St. Louis, and Detroit, suggesting that the lack of CAO days may be more attributed to the general retreat of the polar jet stream than localized geographical influences.

3.3. ECEs *versus* CAOs

The major difference between ECEs and CAOs is the number of events, with far more ECEs than CAOs, and the spatial distribution of events. ECEs occur most frequently in the northwestern stations and southeastern stations of Orlando and Miami. Orlando and Miami experience a high number of ECEs due to a low variability in temperatures throughout the course of the year. When including the spatial criterion, Miami and Orlando are often not contiguous to another station that also meets the ECE criteria; therefore, the events are not classified as CAOs. The spatial criterion also impacts the number of CAOs in Minneapolis and Pierre relative to the ECEs. The stations on the edge of the study will have fewer opportunities to be included in the spatial criterion of CAOs. Therefore, the northwestern stations that are also surrounded by other stations, such as Des Moines and Chicago, have more CAOs. The ECEs and CAOs by city are shown in Table 7.

3.4. CAO and ECE changes over time

Two clusters of CAO and ECE days are evident from 1948 to 2016 (Figure 5). From the 1950–1951 season to the 1969–1970 season (20 years), 42% of all ECE and CAO days occurred. From the 1976–1977 season to the 1995–1996 season (20 years), 37% of all ECE days occurred, while 45% of all CAO days occurred. These two 20-year periods account for 79% of all ECE days and 87% of all CAO days during the 67-year period. There is a noticeable decrease in CAOs over the past two decades. From 1948 to 2000, CAOs occurred on average every 1.18 years. From 2000 to 2016, CAOs occurred on average every 3.2 years. The Mann–Kendall test reveals that the decrease in ECE days is significant at the 0.05 level, while the decrease in CAO days is significant at the 0.10 level. Although fewer CAOs are evident since the last cluster of CAOs, the amount of years in the data set limits the ability to determine any long-term cyclic nature, thus an additional 10–15 years of data would be beneficial. The Mann–Kendall test was computed for the magnitude, duration, and spatial extent of CAOs during the 67-year period, excluding years with no CAOs (Figure 6). No significant trends in magnitude or duration of CAOs occurred during the 67-year period; however, the spatial extent of CAOs did suggest a significant decreasing trend. The historical record of seasonality of CAOs is shown in Figure 7, while there are some minor trends towards an earlier start and end date of CAOs, these are not significant.

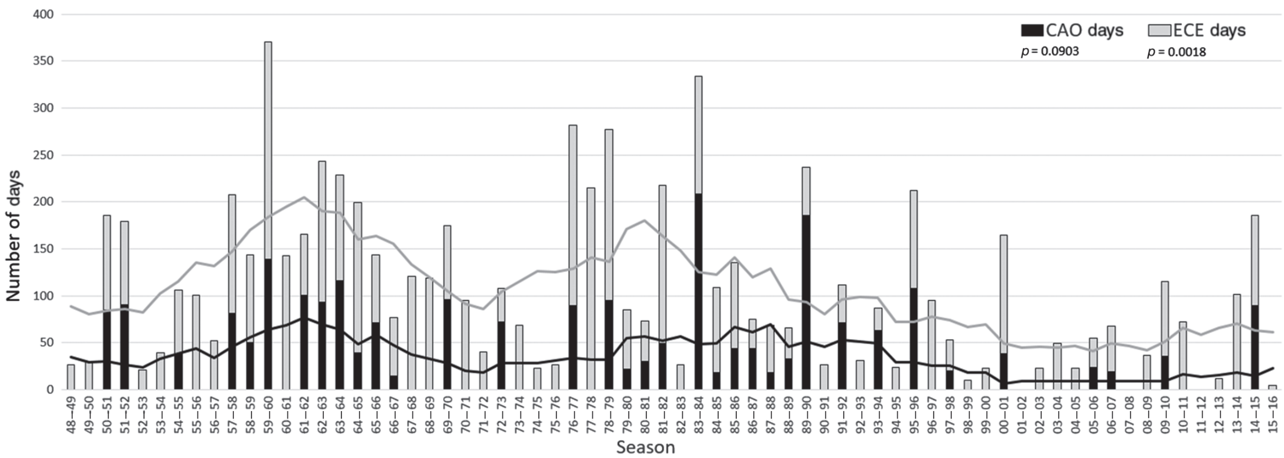


Figure 5. Number of CAO days (black) and ECE days (grey) by winter season from November 1948 to March 2016. The significance (Mann–Kendall test) of the linear trend in each series is denoted by the p-value in the upper right corner.

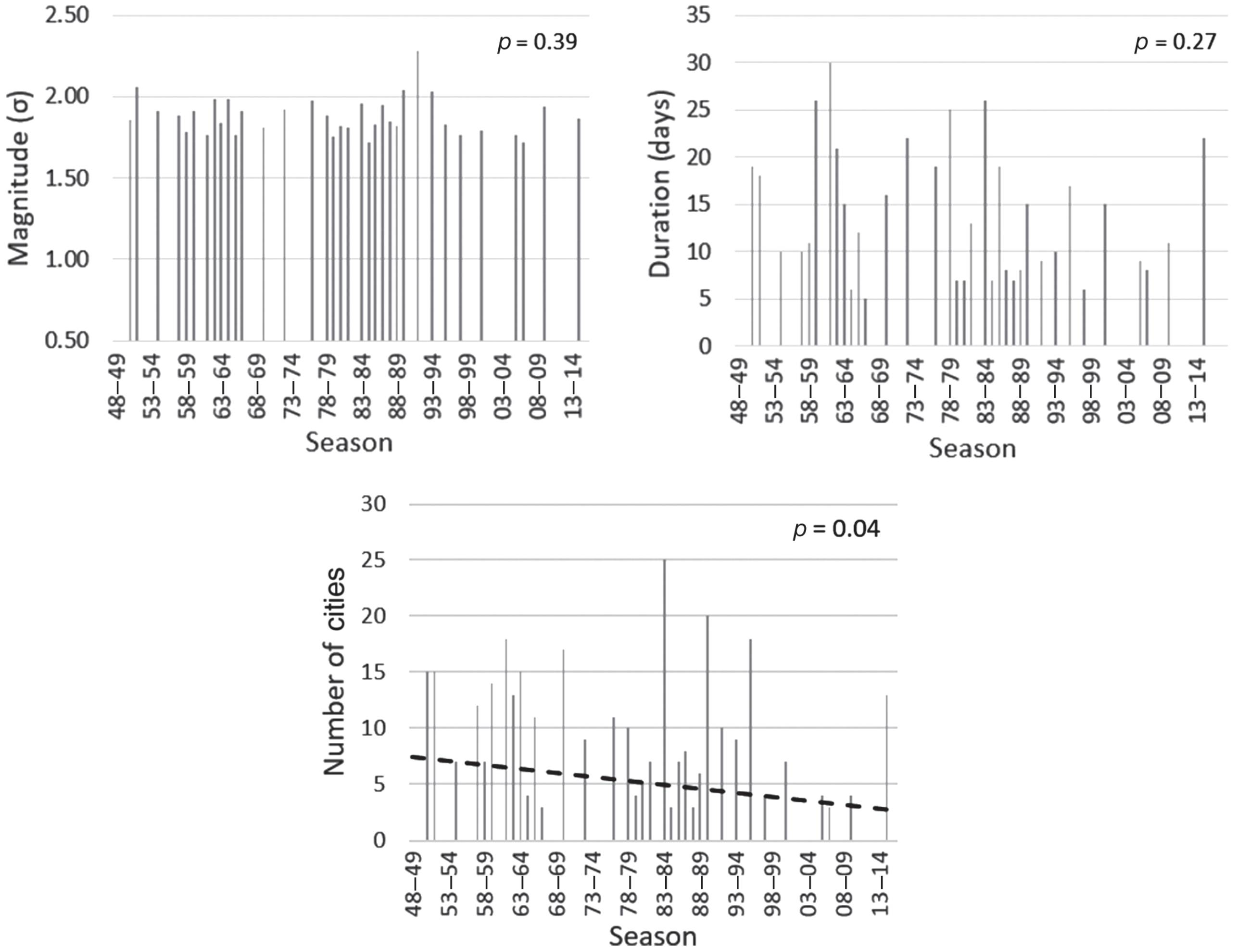


Figure 6. CAO magnitude (left), duration (middle), and spatial extent (right) per season. Seasons with multiple CAOs are average for the magnitude and totalled for the length and spatial extent. The significance (Mann–Kendall test) of the linear trend in each series is denoted by the p-value in the upper right corner. The linear trendline is included for the trends that are statistically significant.

3.5. Limitations

There were few potential caveats in this study. The weather station data had very few missing dates, none of which occurred during a possible CAO. However, with over 800 000 cells of temperature data, there exists the potential for human error when preparing the data and making calculations. The data set was extensively quality controlled to identify any errors. The identification of CAOs, while supported by the literature, maintain a level of subjectivity. The spatial extent chosen, while necessary with the use of surface station data, was the biggest limitation.

4. Conclusion

Extreme weather occurs relatively infrequently throughout the year, yet it is the extreme events that impact people and the economy the most. ECEs and CAOs are one form of extreme weather that affects regions in the mid-latitudes during the winter and may result in crop loss, excessive energy consumption, and even death. Although vast improvements in forecasting have been made over recent decades, necessary preparations for extreme events often require longer lead times than can be acquired from dynamical models, thus characterizing past events to improve our understanding of historical extreme weather is critical. From 1948 to 2016, a total of 49 CAOs were identified, 37 of which occurred during mid-winter periods P2–P4 (29 November to 22 February) and 12 occurred during early and late winter periods P1 and P5 (1 November to 28 November and 23 February to 23 March). P2 CAOs (29 November to 26 December) had the longest average duration of 8 days. P4 (25 January to 22 February) CAOs had the largest spatial extent on average, even with the largest spatial extent CAO (20 cities – 12 November 1989) occurring during P2. The largest magnitude CAOs favoured P1 (1 November to 28 November) with an average z-score of −2.10. The largest number of CAOs occurred in the upper Midwest, specifically Des Moines, with fewer CAOs occurring in the southern and eastern cities. The low number of CAOs in northern cities such as Boston and Buffalo can partly be attributed to Arctic air modification from the Great Lakes (Buffalo) and the maritime influence of the Atlantic Ocean (Boston).

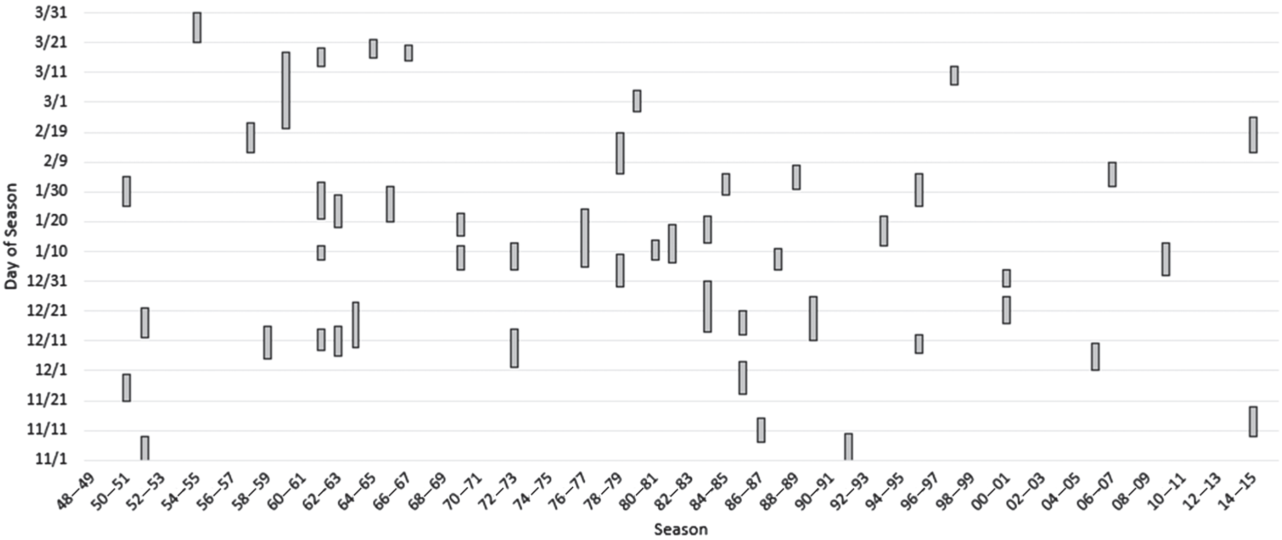


Figure 7. Date and duration of CAOs by winter season from November 1948 to March 2016.

Throughout the 67-year study period, the average magnitude and duration of CAOs remained nearly linear; however, the average spatial extent experienced a significant decrease over the period. Two 20-year clusters of CAOs and ECEs occurred from the 1950–1951 season to the 1969–1970 season and the 1976–1977 season to the 1995–1996 season, accounting for 79% of all ECE days and 87% of all CAO days. These clusters may be influenced by multi-decadal oscillations such as the Atlantic Multidecadal Oscillation which was primarily in the cool phase from the late 1950s – through the mid-1990s.

While similar to the Cellitti *et al.* (2006) study, the CAO data sets are noticeably different, primarily with respect to the way the methods used in this study not only increase but elevate the ranking of the early season (P1) CAOs in the data set. Early season CAOs may be impactful as they occur with a lack of intra-seasonal acclimatization, causing an increase in human mortality (Kalkstein and Davis, 1989). This study also identified 49 CAOs compared to 30 CAOs identified by Cellitti *et al.* (2006), which will benefit any future atmospheric analyses by providing a larger sample size. Furthermore, the trend in CAOs and ECEs found in this study agree with Vavrus *et al.* (2006) in that these events are still likely to occur, albeit less frequently, amid a warming climate.

This research has demonstrated a methodology for identifying and ranking CAOs and shown the characteristics of ECEs and CAOs across the eastern United States in terms of magnitude, duration, and spatial extent. It has shown that the latitude and maritime influence of a surface weather station can influence the time of season (P1–P5) in which the CAO most frequently occurs. Furthermore, the average duration, magnitude, and spatial extent of the CAO is largely influenced by the time of season in which it occurs. Future research will include a study on the relative-risk of increased mortality from ECEs and an atmospheric and teleconnection analysis to better understand the precursors to CAOs in the eastern United States.

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