# Where do Cold Air Outbreaks occur and how have they changed over time?

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Key points:

1. Cold air outbreaks have decreased in frequency, duration, magnitude, and spatial extent across much of the globe.
2. The Northern Hemisphere has experienced a larger decrease in cold air outbreaks than the Southern Hemisphere.
3. There are regional differences between the NNR and ERA5 datasets in the trends and spatial distribution of cold air outbreaks.

**Abstract**

On any given day, some region of the globe is likely to be affected by significant negative temperature anomalies. Depending on the severity, extreme cold periods may be deemed cold air outbreaks (CAOs). These CAOs can be detrimental to the agricultural industry and human health, especially in less prepared regions. A systematic CAO classification was developed using a set of criteria concerning magnitude, duration, and spatial extent from two gridded reanalysis datasets from 1979 – 2018. Trends in CAOs were calculated for different regions across the globe and the results from each reanalysis dataset compared with one another to identify discrepancies. CAOs were found to have decreased in spatial extent, frequency, duration, and magnitude across much of the globe, particularly across Alaska, Canada, and the North Atlantic, while an increase in CAOs was observed in Eastern Europe, Central Eurasia, and the Southern Ocean.

**Plain Language Summary**

On any given day, some region of the globe is likely to be affected by extreme cold. Depending on the severity, extreme cold periods may be deemed cold air outbreaks (CAOs). These CAOs can be detrimental to the agricultural industry and human health, especially in regions with a warmer climate. This study uses a set of criteria to examine CAOs across the globe from 1979 – 2018 and to determine how CAOs have changed over the last 40 years. CAOs were found to have decreased in size, intensity, frequency, and duration across much of the globe, particularly across Alaska, Canada, and the North Atlantic, while an increase in CAOs was observed in Eastern Europe, Central Eurasia, and the Southern Ocean. The large decrease in CAOs in the Northern Hemisphere is further proof that the Arctic is disproportionally affected by climate change.

**Key Words:** cold air outbreaks, extreme cold events, climate change, polar outbreak, cold wave, temperature trends, synoptic climatology, ERA5

## 1. Introduction

Climate change is expected to decrease the frequency of Cold Air Outbreaks (CAOs) in most regions (Vavrus et al., 2006). However, the climate system does not exhibit a simple linear response to global warming (Overland et al., 2016), rather changes in extreme cold are subject to regional and seasonal variability (J. Cohen et al., 2018; Robeson et al., 2014). Though much of the recent literature has focused on extreme heat events (R. M. Horton et al., 2016; Luber & McGeehin, 2008; Mora et al., 2017; Ragone et al., 2018; Sheridan & Allen, 2018), CAOs are extreme events that still occur frequently, causing severe damage to crops, livestock, and even increasing human mortality ( Quiroz, 1984). The largest impacts are often in regions that climatologically experience few CAOs and are inadequately prepared to mitigate the effects of extreme cold (Smith & Sheridan, 2019a). CAOs are not limited to certain regions as they can occur over land and water in polar and tropical regions (Fletcher et al., 2016; Garreaud, 1999; Huh et al., 1984; Kolstad et al., 2009). While CAOs over land have a more direct impact on human populations, CAOs over the oceans can indirectly impact humans by altering synoptic-scale circulations such as polar lows (Bracegirdle & Gray, 2008) via fluctuations in sea ice and ocean circulations (Kolstad et al., 2010; Pickart et al., 2003).

CAOs are commonly defined as large-scale, long duration periods of extreme cold (Cellitti et al., 2006; Kolstad et al., 2010; Smith & Sheridan, 2018). While the magnitude, duration, and spatial extent criteria are similar between studies, the criteria are tailored for the study region or research question. Studies that focus on CAOs over the ocean often use an upper atmospheric variable, such as 850-hPa temperature, for the magnitude criterion (Kolstad et al., 2010; Papritz et al., 2014), while studies that focus on CAOs over land favor a near-surface temperature variable (Cellitti et al., 2006; Smith & Sheridan, 2019b; Wheeler et al., 2011). The magnitude of a CAO is often assessed by calculating the standard deviation (Smith & Sheridan, 2018; Vavrus et al., 2006; Wheeler et al., 2011) or temperature (Cellitti et al., 2006; Walsh et al., 2001) anomaly of the atmospheric variable. Additional magnitude criterion, such as a maximum daily mean temperature threshold or a minimum departure from the daily mean temperature (Vavrus et al., 2006; Wheeler et al., 2011), are sometimes used to limit classifying CAOs from non-extreme circumstances. Many studies use a duration criterion which requires the magnitude criterion be met between one and five days (Smith & Sheridan, 2018; Vavrus et al., 2006; Wheeler et al., 2011), while other studies have used several different duration criterions for comparisons (Walsh et al., 2001). Though some studies define a spatial extent criterion, other studies omit the criterion entirely. Studies that used surface stations rather than gridded data have required at least three contiguous stations to simultaneously meet the magnitude and duration criteria (Cellitti et al., 2006; Smith & Sheridan, 2018) while studies that used gridded reanalysis data required the extent to be at least 5$^{o}$ latitude by 5$^{o}$ longitude (Wheeler et al., 2011).

Though few studies explicitly examine trends in CAOs, many studies have concluded that temperature have warmed systematically, particularly in the Arctic (Coumou et al., 2018; Diffenbaugh et al., 2017; Kanno et al., 2019; Medhaug et al., 2017; Rahmstorf et al., 2017; Screen & Francis, 2016). While these findings do not necessarily result in similar trends in extreme events like CAOs, periods of extreme cold have also been found to have decreased in frequency and severity in recent decades across many regions and this trend is projected to continue as the globe warms (Ayarzagüena & Screen, 2016; Park et al., 2011). However, regional responses to climate change are non-linear as other studies have shown periods of large-scale extreme cold are not only still possible, but may be increasing in certain regions during the winter (Cohen et al., 2012; Robeson et al., 2014). As with any study, results are dependent on the research question and sensitive to the dataset used, the time period of analysis, and the study domain. This makes it difficult to quantify changes in CAOs across the globe by just comparing the results from various studies. To address this gap in the literature, this study creates a global climatology of CAOs by using the NCEP/NCAR (NNR) and the newly released ECMWF ERA5 reanalysis datasets to quantify regional changes in CAO magnitude, duration, intensity, and spatial extent from 1979 – 2018.

## 2. Data and Methods

Two-meter temperature (T2m) data was acquired from the NCEP/NCAR (NNR) climate reanalysis dataset (National Center for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR)) and the recently released ERA5 reanalysis dataset from the European Center for Medium-Range Weather Forecasts (ECMWF). ERA5 T2m was acquired at a $1^{o}$ spatial resolution on an hourly timescale and converted to daily mean T2m while NNR daily mean T2m was acquired at a T62 gaussian grid (192 longitude and 94 latitude) spatial resolution from 1979 - 2018. Though the ERA5 is available at a 0.25$^o$ spatial resolution, this resolution is computationally expensive and not vital when calculating CAOs on a global scale.

### 2.1 Cold Air Outbreak Criteria

This study uses daily mean T2m because of the direct implications T2m has on humans and human systems. Three criteria for a CAO were designed to capture the most extreme CAOs while being flexible enough to capture the entire evolution of the event (Table 1A). The magnitude criterion requires the daily mean temperature to be at least -1.96σ (equivalent to the 2.5$^{th}$ percentile of the z-score distribution) below the 40 year (1979 – 2018) climatological mean for the time of year. The departure from the climatological mean must be at least -2$^o$C with a daily mean temperature below 20$^o$C. This threshold was chosen to better incorporate tropical regions as studies have shown daily mean temperatures near 20$^o$C may increase mortality in places such as India and Southeast Asia (Ingole et al., 2015). These additions to the magnitude criterion were made to limit CAOs during the summer or in locations where the temperature variation is small. This also reduces the CAO dataset to a smaller sample of events which have much larger societal impacts.

The daily spatial extent, which is a summation of all contiguous grid points that meet the magnitude criteria, must be at least 1,000,000 km$^2$. Contiguous grid points are defined by being connected in the horizontal, vertical, or diagonal direction. Non-contiguous grid points that meet the magnitude criterion and are within one grid point of the larger contiguous group of grid points are included to account for mesoscale influences, such as topography, that may isolate one or more grid points that should otherwise be included in the CAO. A spatial extent of 1,000,000 $km^2$ is used because it is small enough to capture CAOs across southern hemispheric landmasses, such as Southern Africa and South America, while also being large enough to exclude small-scale extreme cold events that may result from snowfall or topographical influences.

The duration criterion requires the magnitude criterion (σ <= -1.96) be met for at least five consecutive days. As with the magnitude criterion, five consecutive days is used to limit the CAOs to the most extreme events. If the daily mean temperature does not exceed the magnitude criterion (Ex: -1.90σ) but the five-day running mean standard deviation is below -1.96σ, then it will be counted as meeting the magnitude criterion. This is added to give the duration criterion some flexibility and to make sure no grid point is excluded from a CAO prematurely because of a narrowly missed threshold. The duration will begin on the first day in which the spatial extent criterion is met and end on the last day the spatial extent criterion is met.

### 2.2 Regionalization of Cold Air Outbreaks

While most studies predefine regions according to the area of study (Kolstad et al., 2009; Vavrus et al., 2006; Walsh et al., 2001), a flexible regionalization allows regions to be created for particular climate zones or areas of interest. Furthermore, defining regions according to

CAO characteristics allows a more holistic analysis of the atmospheric patterns that precede CAOs in each region. Regions are created by correlating the CAO duration of a central grid point with surrounding grid points where only contiguous grid points with correlations equal to or greater than 0.75 are included in the region. The central grid point is determined by first selecting relative regions, such as the eastern U.S. or Europe, then calculating a local maximum in the total number of CAO days from 1979 – 2018 in each relative region. Relative regions were chosen according to similarity in climatological characteristics, CAO characteristics, and CAO trends during the period of study. This combination of relative and statistically defined regions merges the user's climatological expertise with data derived inputs to produce a more objectively defined region. Because the regions are statistically similar, atmospheric analysis can be better generalized to the region rather than having to account for climatological differences or unknown differences in CAO characteristics across regions.

Historical trends in CAOs were analyzed for each region to determine the magnitude of change. Trends for the Southern Hemisphere (SH) were calculated over 40 winter seasons (January 1 – December 31) and trends in the Northern Hemisphere (NH) were calculated over 39 winter seasons (July 1 – June 30). Theil-Sen slope estimation was used to estimate the change in the number of CAOs and CAO days, as well as other CAO characteristics, by region and by individual grid point. Because of the limited sample size (39 in NH and 40 in SH), the Theil-Sen slope estimation was calculated from 1000 bootstrapped samples and statistical significance determined from the confidence intervals produced from the bootstrapped samples. Because the spatiotemporal relationships of gridded data can result in false significance (LaJoie &

DelSole, 2016; Wilks, 2016), a false discovery rate was used to better determine the field significance of the data.

## 3. Results and Discussion

### 3.1 Cold air outbreak climatology

The spatial distribution and frequency of mean annual cold air outbreak (CAO) days is very similar between the ERA5 (Figure 1a) and NNR (Figure 1b). CAOs occur across landmasses and the oceans and stretch from the tropics to the polar regions in both the Northern Hemisphere (NH) and Southern Hemisphere (SH). On land, CAO occur most frequently across North America, Western Eurasia, and central South America. Though CAOs occur most frequently across the polar regions and mid-latitudes, CAOs still occur in subtropical regions. This is evident with the large number of annual CAO days across central South America, and also along the southern edge of the Sahel region in Africa, Southeast Asia, and South Africa where up to 11 CAO days occur per year. While CAOs tend to occur downstream of regions of preferred atmospheric blocking (Vavrus et al., 2006), they also tend to follow the spine of mountain ranges (Garreaud, 1999). This is evident in the large number of CAO days east of the Rocky Mountains in North America, east of the Andes Mountains in South America, and in Southeast Asia east of the Tibetan Plateau. Furthermore, if the temperature distribution was the same for all locations the number of CAOs would be the same, however, locations that are negatively skewed are more likely to experience extreme cold than regions with a more normal temperature distribution (Figure A1) (Vavrus et al., 2006). This is the primary reason for the large number of annual CAO days across South America and the Southern Ocean.

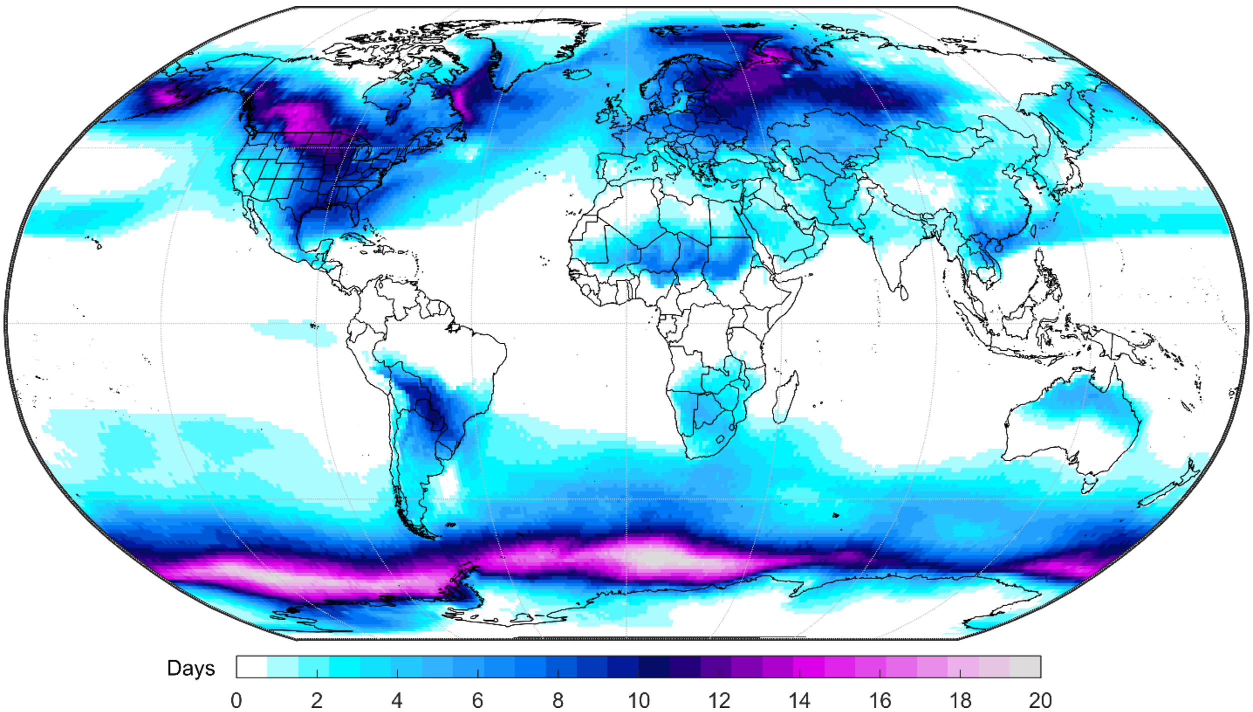


*Figure 1a: ERA5 mean annual CAO days.*

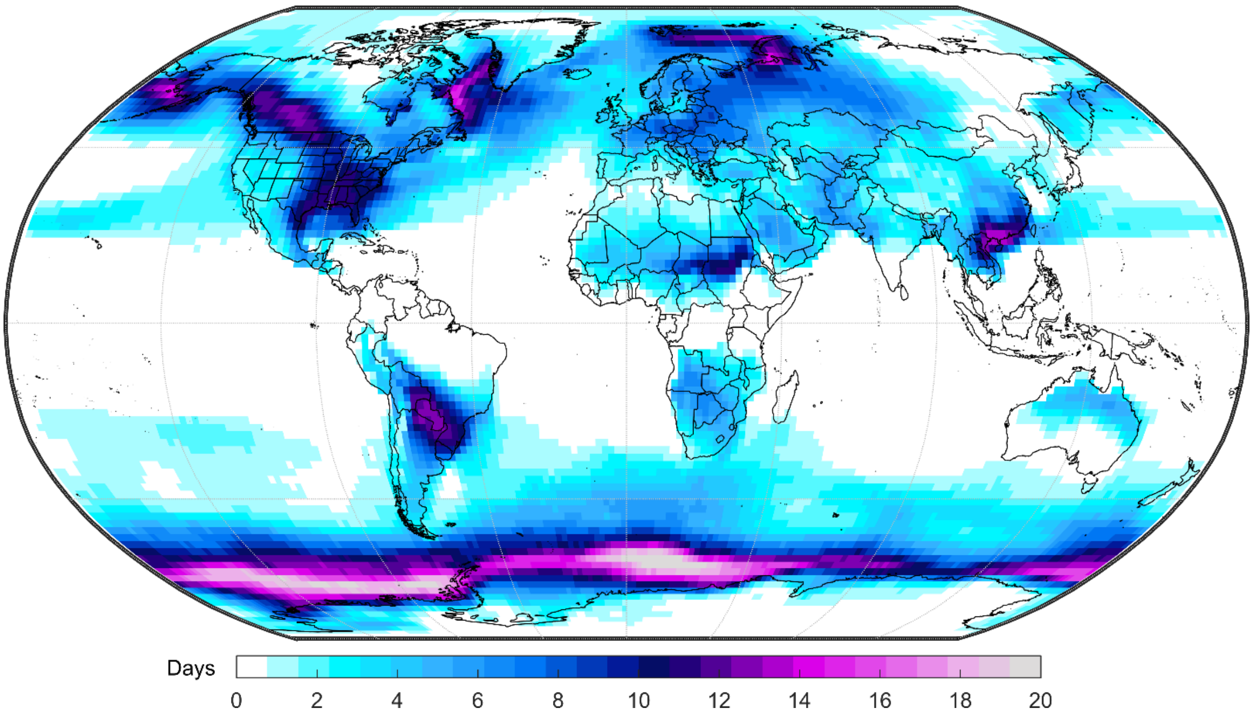


*Figure 1b: NNR mean annual CAO days.*

### 3.2 Differences between ERA5 and NNR

The differences between the ERA5 and NNR CAO days are largest in climatologically complex regions, near large topographical features or maritime influences. There is also a large difference in CAO days across Eurasia, where the ERA5 shows approximately five more CAO days per year than the NNR in many locations. These discrepancies across Eurasia may be attributed to the different resolution and physical parameterizations between the two reanalysis datasets. The ERA5 dataset produced 1,684 total CAOs from 1979 – 2018, which is 64 CAOs fewer than the NNR. Many of the discrepancies between the two datasets are related to the coarser resolution of the NNR which tends to satisfy the spatial extent criterion (1,000,000 $km^2$) more often than the ERA5, leading to more CAOs and at times longer duration CAOs. This is most evident across South America and southeast Asia, where the NNR has a higher frequency of annual CAO days.

### 3.3 Cold air outbreak trends

Because of the similarities in the results between the two datasets and the higher spatial resolution of the ERA5, the remainder of the analysis focuses on the results from the ERA5.

The largest changes in CAO days tend to occur in locations with the highest annual number of CAO days (Figure 2a) with the Northern Hemisphere undergoing a more systematic decrease in CAOs than the Southern Hemisphere. While the change in annual CAO days across Europe and Southeast Asia has been minimal, North America has experienced a 25% to 75% decline in annual CAO days, with the largest declines across Alaska and Canada (Figure 2b). Similar decreases in CAOs have also been observed across South America and South Africa. CAOs over the oceans have decreased between 50% and nearly 100% in the North and South Atlantic. This is most evident in the region stretching from the Labrador Sea toward the Barents-Kara Seas, where the number of CAO days per year has declined from upwards of 15 days to near zero. The large decrease in annual CAO days across the Arctic is likely attributed to variations in sea-ice extent and the North Atlantic Oscillation, exacerbated by Arctic amplification (J. Cohen et al., 2014; Delworth et al., 2016; Francis & Vavrus, 2012; Francis et al., 2017). With the reduced Arctic sea ice extent, regions that were ice-covered early in the study period are now ice-free, shifting the temperature distribution and reducing the frequency of CAOs over ice-free water.

The opposite is evident across the Antarctic, where sea ice had increased over recent decades through 2016 (Comiso et al., 2016). The change in Antarctic sea ice along with fluctuations in sea-surface temperature and the southern annular mode may contribute to the increased frequency of CAOs across much of the Southern Ocean (Bracegirdle & Kolstad, 2010). While the number of annual CAO days has declined for most regions since 1979, they have more than doubled across Central Eurasia with large increases also evident across the South Pacific Ocean and South Atlantic. The increase in CAO days across Central Eurasia may be attributed to decreases in sea-ice across the Barents-Kara Seas which favor increased autumn snowfall across Eurasian (J. Cohen et al., 2014; Kretschmer et al., 2017). A larger snow cover extent strengthens the Siberian High promoting cold-air advection in Central Eurasia from an anticyclonic flow (J. Cohen & Jones, 2011). Changes across the Southern Ocean are less systematic and are more likely related to internal climate variability such as the Atlantic Multidecadal Oscillation and the Southern Annular Mode (Bracegirdle & Kolstad, 2010).

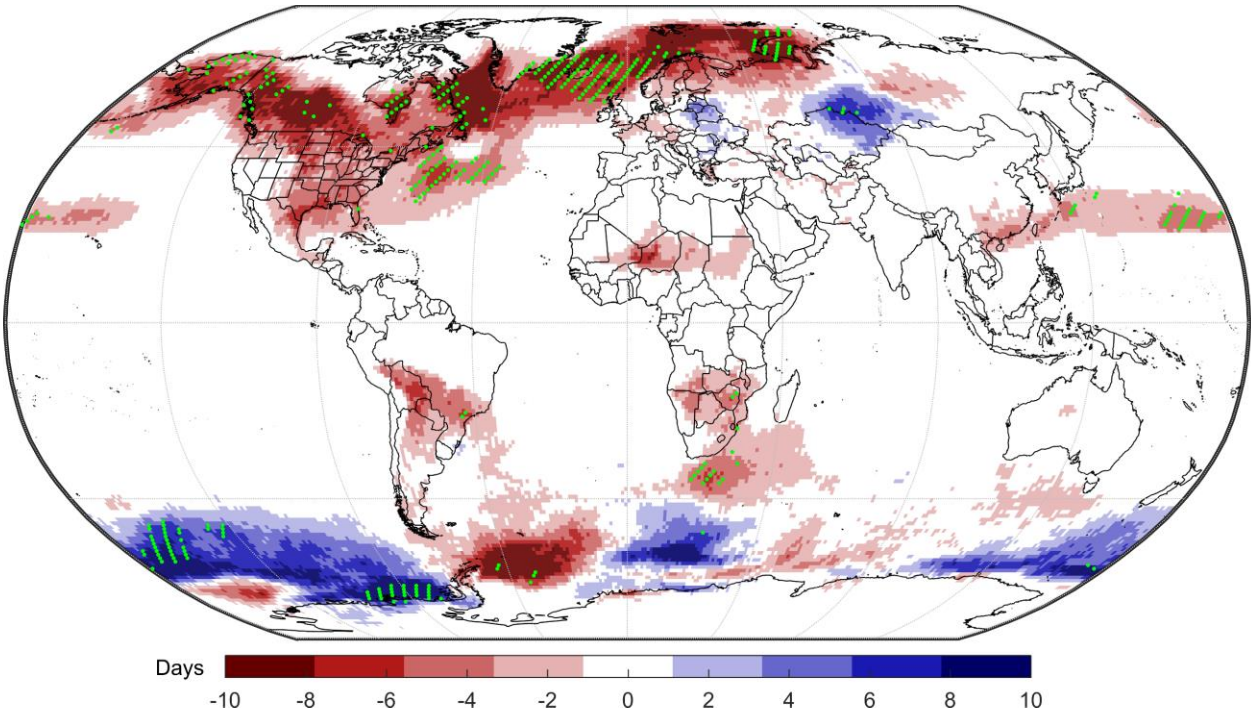


*Figure 2a: ERA5, change in mean annual CAO days (1979 – 2018). Every $5^{th}$ significant grid point at the $\alpha = 0.10$ level is denoted with green dots.*

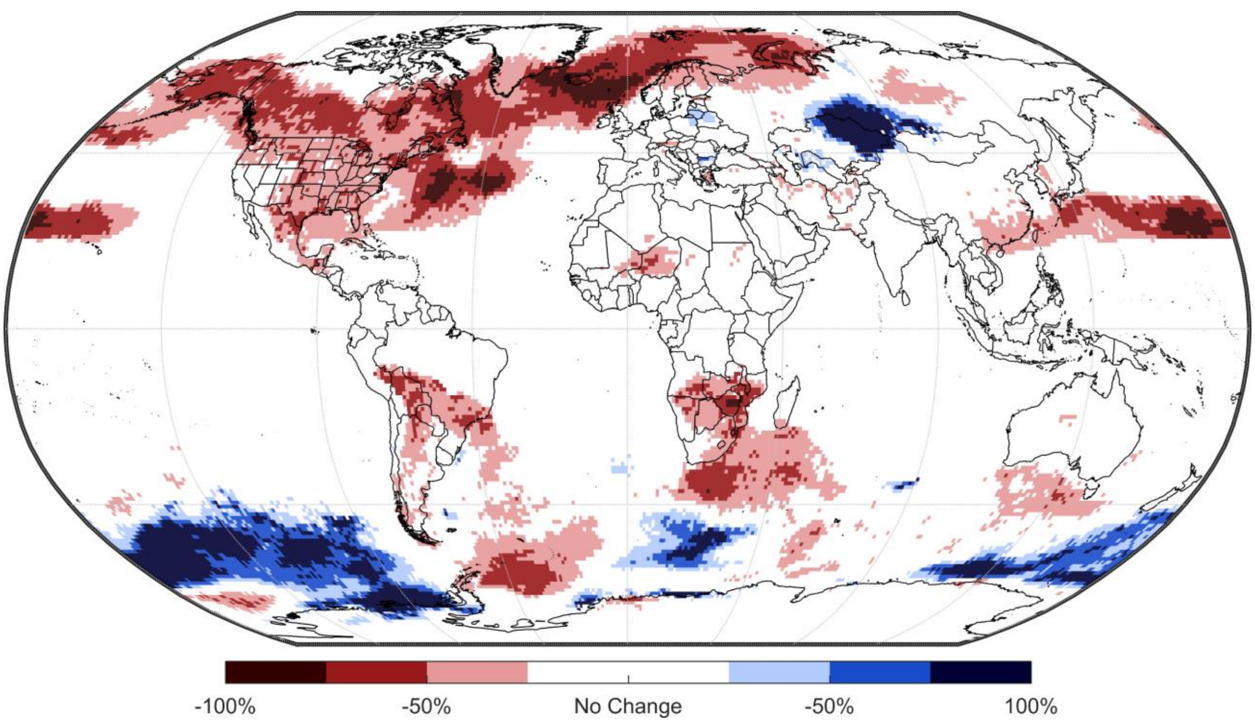


*Figure 2b: ERA5, 1979 – 2018 percent change in mean annual CAO days.*

CAOs are extreme events that occur relatively infrequently, thus detecting significant changes in these events is difficult. However, large changes in annual CAO days, which incorporates the occurrence and duration of each CAO, suggest that CAOs have changed significantly in many regions. This is corroborated by the change in the mean CAO duration (Figure 3a) and the maximum CAO duration (Figure 3b), where locations that are seeing fewer/more annual CAO days have generally experienced an annual decrease/increase in both the annual mean and annual maximum CAO duration. The maximum duration CAO duration has decreased by more than 5 days across Alaska and the Labrador and Barents-Kara Seas, with an increase in duration similar in magnitude but smaller in spatial extent across Eastern Europe and Central Eurasia. Furthermore, locations that have experienced declines in CAO duration also tend to have less intense CAOs (Figure 3c). This is most evident across Alaska, along the Gulf Stream, the Barents-Kara Seas, and near the Antarctic Peninsula. Outside of Alaska, North America has seen little change in CAO magnitude, suggesting CAOs that occur across much of Canada and the United States are as extreme as early in the study period. With a general increase in temperature across this region (Vose et al., 2017) and decrease in CAO days, this region may be becoming less acclimatized to extreme cold and more susceptible to cold-related mortality when CAOs do occur (Smith & Sheridan, 2019a). CAOs across the Southern Ocean, Central Eurasia, and Eastern Europe have not only increased in frequency and duration, but also in magnitude since 1979. This may be a result of variations in the circumpolar vortex and/or changes in regions of preferred atmospheric blocking (D. E. Horton et al., 2015; Luo et al., 2018; Martineau et al., 2017), where a more meridional circulation across Western Eurasia would displace Arctic air equatorward, resulting in a decrease in CAO days in the Barents-Kara Sea and an increase from Eastern Europe to Central Eurasia.

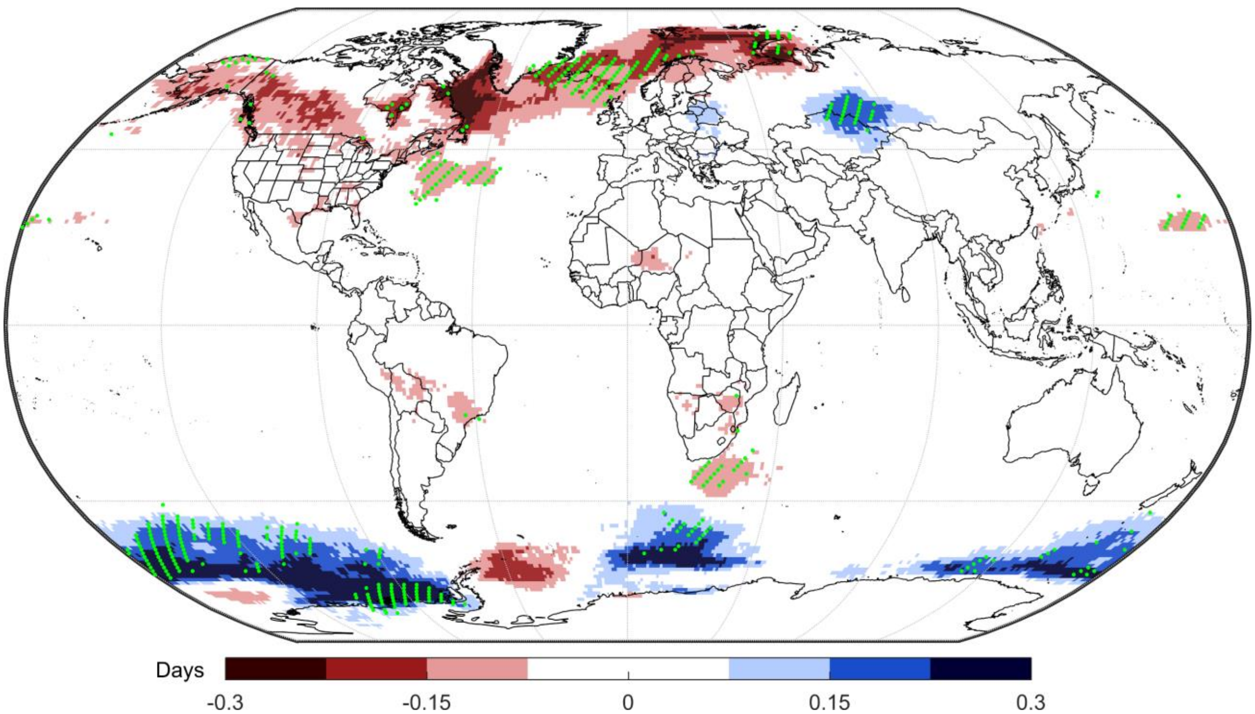


*Figure 3a: ERA5, Change in mean CAO duration. Every 5th significant grid point at the α = 0.10 level is denoted with green dots.*

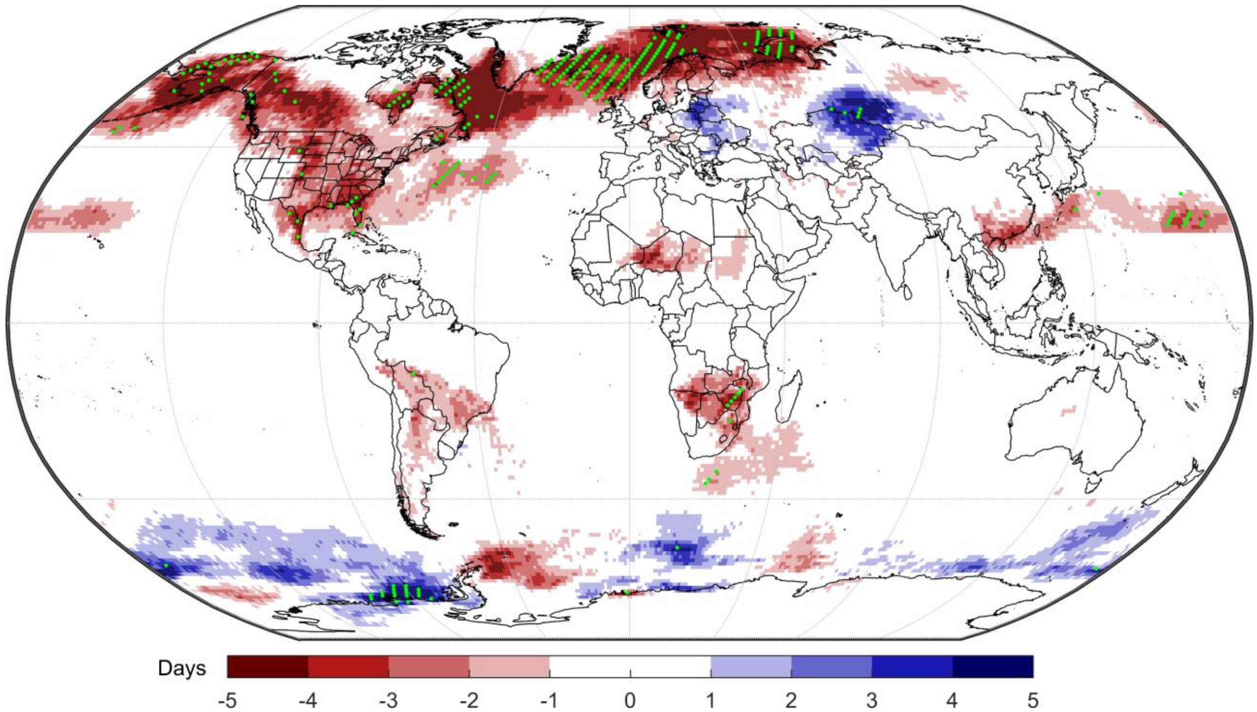


*Figure 3b: ERA5, change in maximum CAO duration. Every 5th significant grid point at the α = 0.10 level is denoted with green dots.*

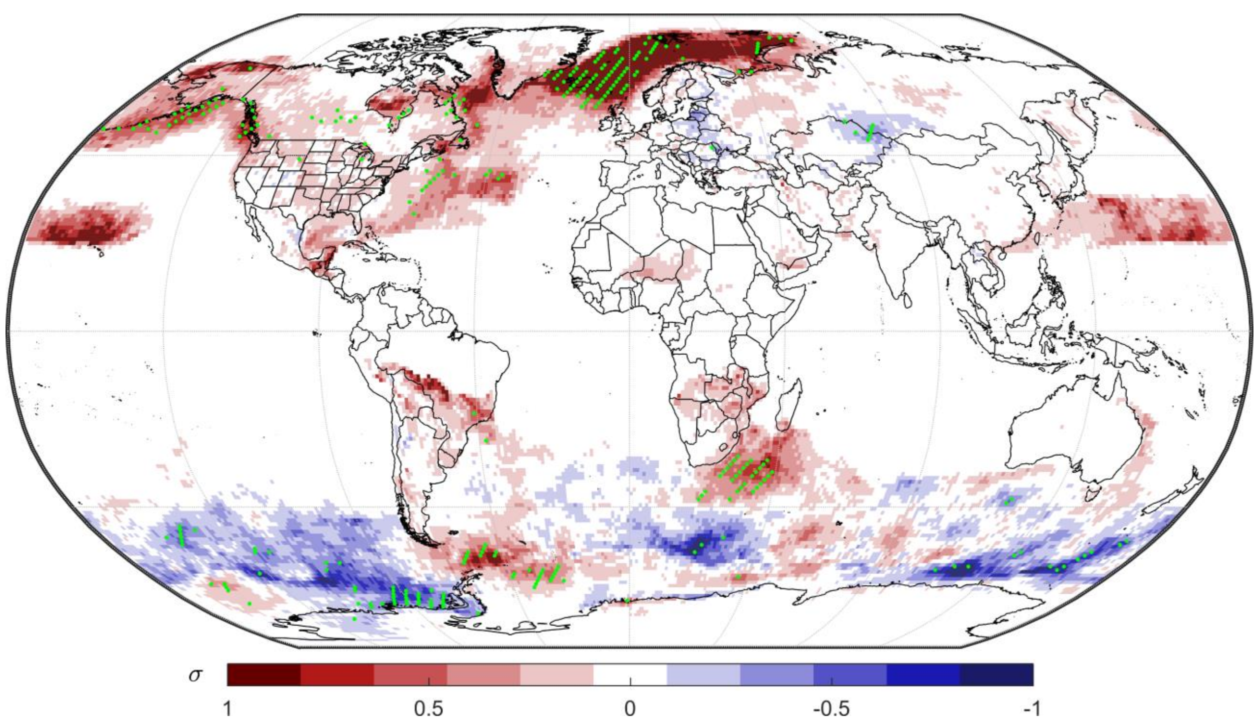


*Figure 3c: ERA5, change in minimum z-score. Every 5th significant grid point at the α = 0.10 level is denoted with green dots.*

The total spatial extent, which is a summation of the spatial extent of all CAO days each winter, has decreased significantly for both the NH and SH (Figure A1). In the NH, the seasonal CAO spatial extent has declined steadily since the early 1980s while the largest decrease in the SH has occurred in the last three years. This rapid decrease in the SH coincides with the large reduction in Antarctic sea ice since 2016 (Meehl et al., 2019). The mean spatial extent of each individual CAO has decreased by approximately 337,980 $km^2$ for the NH and 55,261 $km^2$ for the SH since 1979, though only the decrease in the NH is significant. This suggest not only has the duration of CAOs decreased, but the spatial extent of each CAO has decreased, particularly in the NH. Moreover, the spatial extent for each hemisphere is significantly correlated ($\rho = 0.64$), suggesting there may be a relationship between CAOs in the SH and NH. The strong relationship may partly be attributed to systematic warming across the globe, thus decreasing the number of CAOs in both hemispheres in recent decades.

CAOs occur across a large portion of the Earth, but more frequently in certain regions (Figure 4 & Table 1). These thirteen regions encompass regional CAO hotspots over large human populations and over the ocean. Nearly every region, except Central Eurasia (region 6) and South Pacific (region 13), have experienced a decrease in CAO days. The largest decrease in CAO days has occurred in the Labrador Sea (region 3) and Barents-Kara Seas (region 7) with a slope indicating a decrease of 10 CAO days since 1979, followed by Canada (region 2) which has seen a decrease of 7 CAO days since 1979. The maximum duration CAO has decreased by 8 days in the Labrador Sea and Barents-Kara Seas and 7 days in Alaska (region 4) since 1979. Furthermore, the CAO season length, which begins with the first CAO day of the season and ends with the last CAO day, has decreased for many regions, with CAOs occurring less frequently during the early and late portions of the winter season. While the Eastern U.S. (region 1) and Canada (region 2) have seen little change in the season length, Alaska has seen the length between the first CAO day to the last CAO day decrease by over 80 days since 1979, a trend that has been observed in previous studies (Walsh & Brettschneider, 2019; Gan et al., 2017).

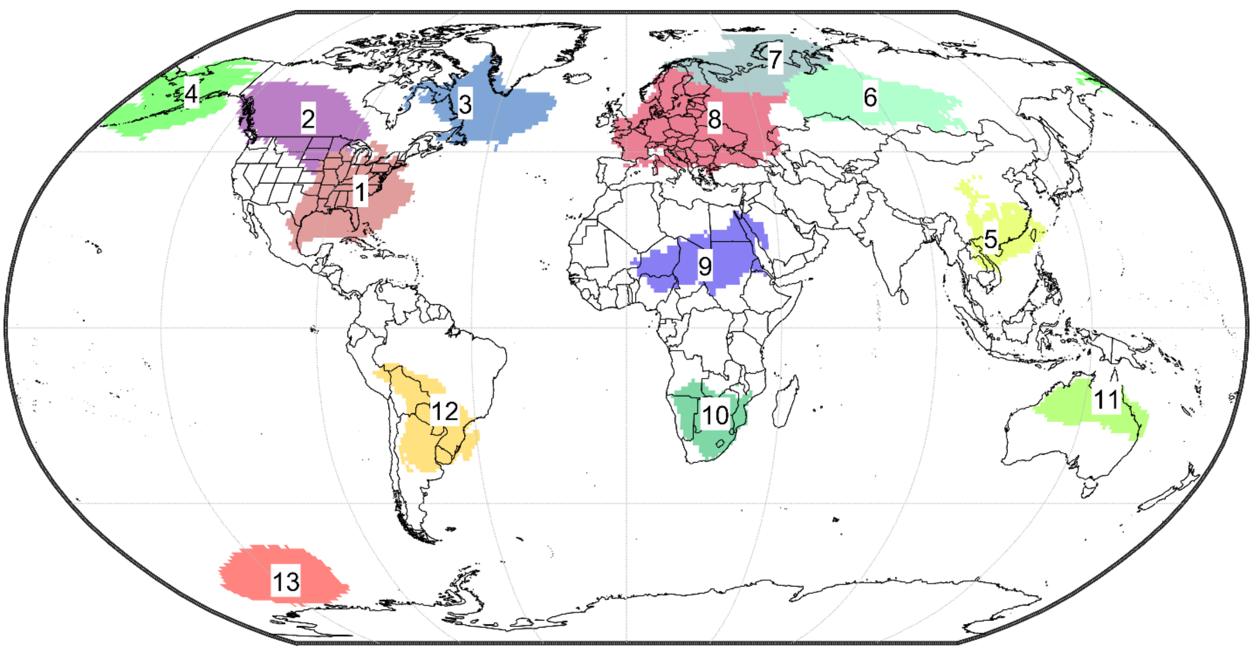


*Figure 4: Regions based on the CAOs produced from the ERA5 dataset.*

*Table 1: Regional CAO statistics. Regions 1-9 are in the Northern Hemisphere and regions 10-13 are in the Southern Hemisphere. Significance at the α = 0.05 level is denoted with underlined, bold, italic values. Δ denotes the change in each category.*

| | | | | Δ | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Region** | **Location** | **1979 CAO Days** | **2018 CAO Days** | **CAO Days** | **Max. Duration** | **Mean Duration** | **Min. σ** | **First CAO Date** | **Last CAO Date** | **Season Length** |
| 1 | Eastern U.S. | 10 | 6 | -4 | ***-5*** | -0.4 | 0.2 | -3 | -5 | -2 |
| 2 | Canada | 14 | 7 | ***-7*** | -3 | -0.5 | ***0.8*** | 5 | 0 | -6 |
| 3 | Labrador Sea | 15 | 5 | ***-10*** | ***-8*** | ***-1.5*** | ***0.8*** | 12 | ***20*** | 7 |
| 4 | Alaska | 10 | 5 | ***-5*** | ***-7*** | -0.6 | ***0.4*** | ***40*** | ***-42*** | -82 |
| 5 | Southeast Asia | 7 | 4 | -3 | -4 | -0.5 | -0.1 | 4 | ***-27*** | -31 |
| 6 | Central Russia | 8 | 9 | 1 | 2 | 0.7 | -0.1 | 12 | ***-18*** | -30 |
| 7 | Barents-Kara Seas | 15 | 5 | ***-10*** | ***-8*** | -1.1 | ***0.5*** | 16 | -11 | -27 |
| 8 | Europe | 9 | 8 | -1 | -3 | 0.1 | 0.0 | 8 | ***-21*** | -29 |
| 9 | N. Africa | 9 | 6 | -3 | -3 | -0.2 | 0.1 | -7 | -6 | 1 |
| 10 | South Africa | 6 | 2 | ***-4*** | ***-6*** | -0.7 | 0.1 | -3 | -10 | -7 |
| 11 | N. Australia | 5 | 4 | -1 | -2 | 1.9 | ***-0.7*** | 10 | -14 | -23 |
| 12 | South America | 9 | 4 | ***-5*** | -1 | -0.1 | 0.2 | -14 | 12 | 26 |
| 13 | South Pacific | 13 | 18 | 5 | 2 | 0.1 | -0.5 | 4 | ***-18*** | -22 |

### Limitations

Because the goal of this study is to create a global climatology of CAOs, the same CAO criteria was used for the entire globe potentially limiting the classification of CAOs in complex regions. The length of the study also impacts the results; thus, the results may change once the ERA5 dataset is made available back to 1950 and this study is extended to include the additional data.

## 4. Conclusion

Cold Air Outbreaks (CAOs) are extreme events with potentially large impacts on human health, animals, agriculture, energy industry, and more. With most of the research on CAOs having a regional focus and varying definitions, it is difficult to determine how CAOs have systematically changed in recent decades and how these changes may be related to internal and external climate variability. While the individual CAOs and 1979 - 2018 climatology of CAOs from the ERA5 and NNR were very similar, the differences highlight the variability that can arise between studies that use different datasets.

This study concludes that while the frequency, magnitude, and duration of CAO days has increased in Eastern Europe, Central Eurasia, and much of the Southern Ocean, the majority of the globe has experienced a 25% to 75% decrease in CAO days. The largest changes have occurred in Alaska and Canada, with 50% to 75% declines in CAO day frequency with declines over the North Atlantic between 50% to nearly 100%. The extent of the decreases in annual CAO days is not counteracted by the increases in CAO days across Eurasia and is likely attributed to Arctic amplification. Though CAOs have decreased in frequency over the SH land masses, particularly in central South America, the overall change has been less than that in the NH due to increases in CAO days across the Southern Ocean. The discrepancies in CAO trends may be attributed to fluctuations in atmospheric circulations in both the NH and SH and the differences between the total land mass in each hemisphere. Though non-linear, the decrease in CAOs across the NH is largely systematic, with many locations trending toward a complete reduction in CAOs as defined by the 1979 – 2018 climate normal.

This work will be expanded to better understand atmospheric and oceanic drivers of CAOs to better determine how internal and external climate variability in the Arctic, tropics, and mid-latitudes interact through multiple, often poorly understood, processes to cause these extreme events. Global forecast model skill will also be evaluated to identify model biases in the forecasted location, duration, and intensity of CAOs. Finally, climate models will be used to project changes in CAOs across the globe using this newly updated climatology and compared with previous projections of CAOs to evaluate sources of error in in the previous model projections.

**Acknowledgements and Data**

The final NNR and ERA5 cold air outbreak (CAO) datasets are currently being reformatted to be more user friendly but will be deposited in the DataONE prior to acceptance.

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## Appendix

*Table A1: Criteria for a Cold Air Outbreak.*

| Cold Air Outbreak Criteria | |
|---|---|
| 1. Magnitude | a. σ = -1.96 (2.5$^{th}$ percentile)<br>b. Daily mean < 20$^{o}$ C<br>c. Daily departure from mean > 2$^{o}$ C |
| 2. Duration | a. 5 days minimum |
| 3. Spatial Extent | a. 1,000,000 km$^2$ |

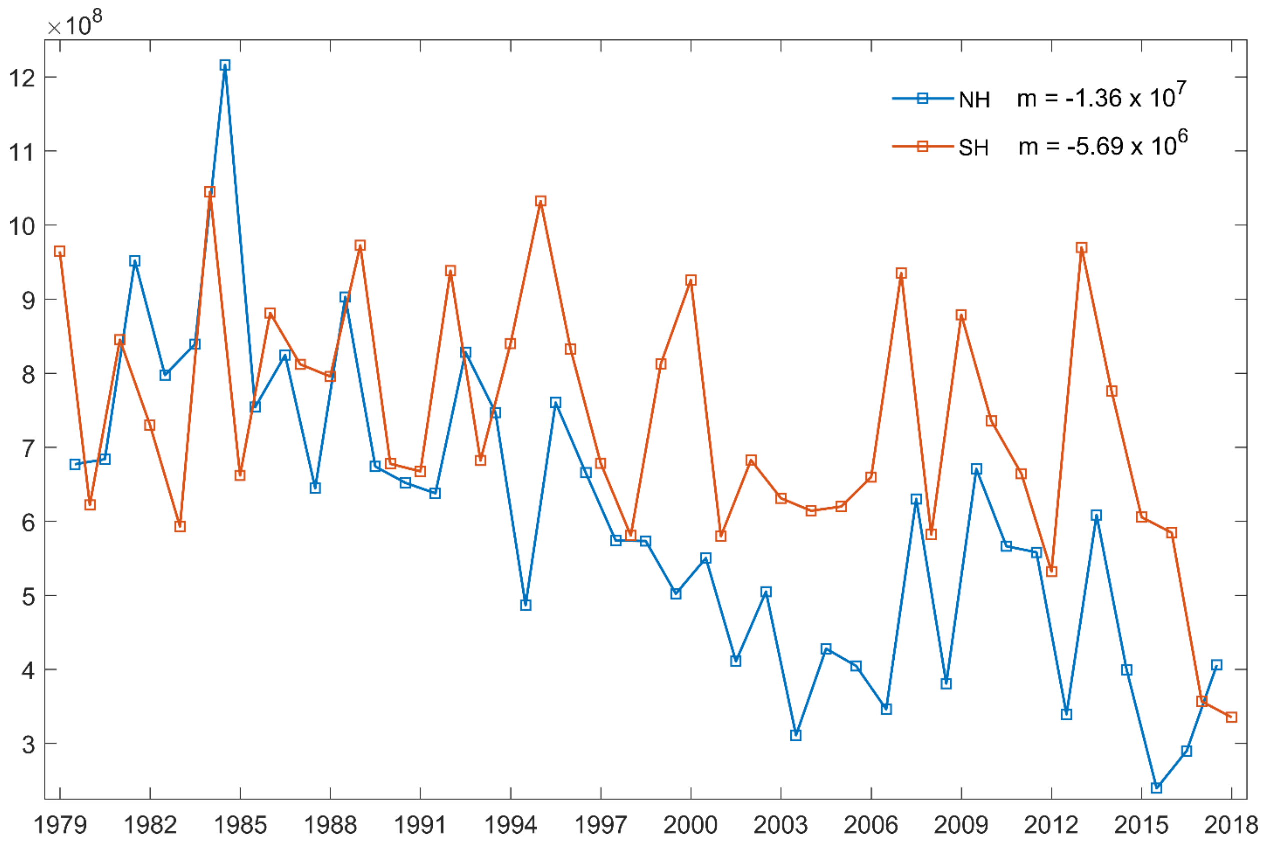


*Figure A1: ERA5, total spatial extent of CAO days per season for the Northern Hemisphere (NH; blue line) and Southern Hemisphere (SH; orange line). The correlation between the NH and SH is 0.64. The correlation between the NH and SH and slopes for both the NH and SH are significant at the α = 0.05 level.*

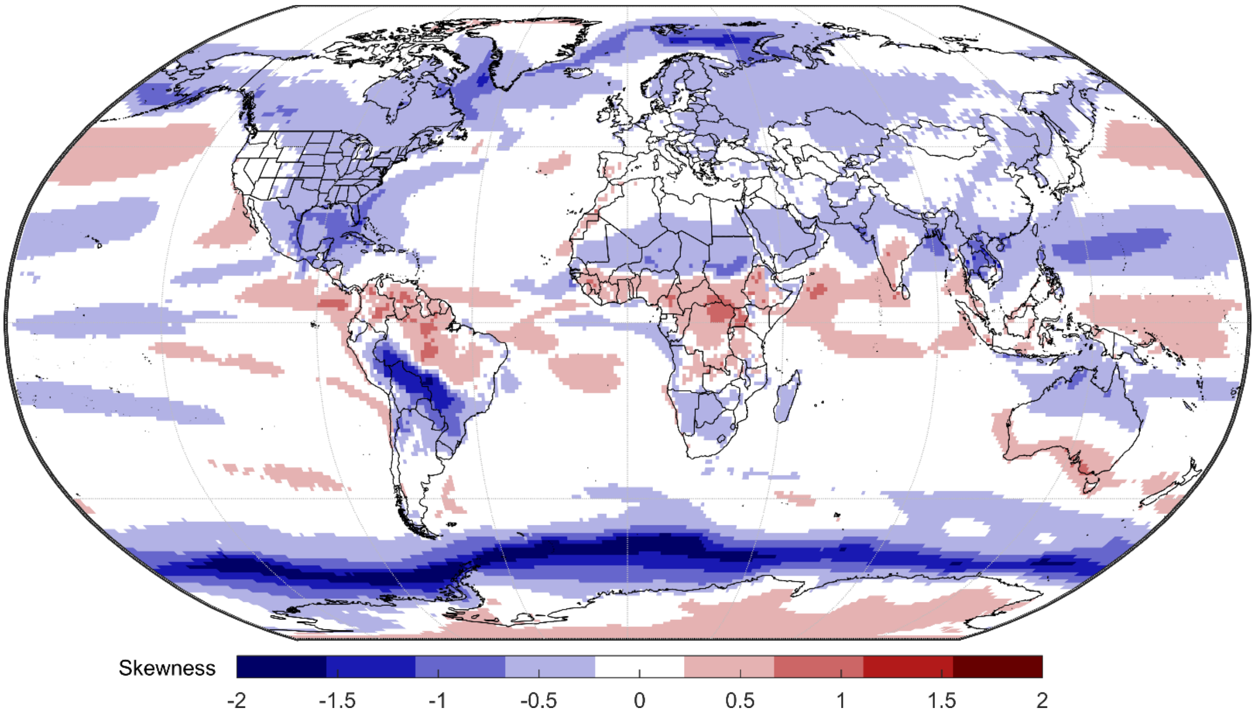


*Figure A2: Skewness in two-meter temperature data from the ERA5 dataset.*

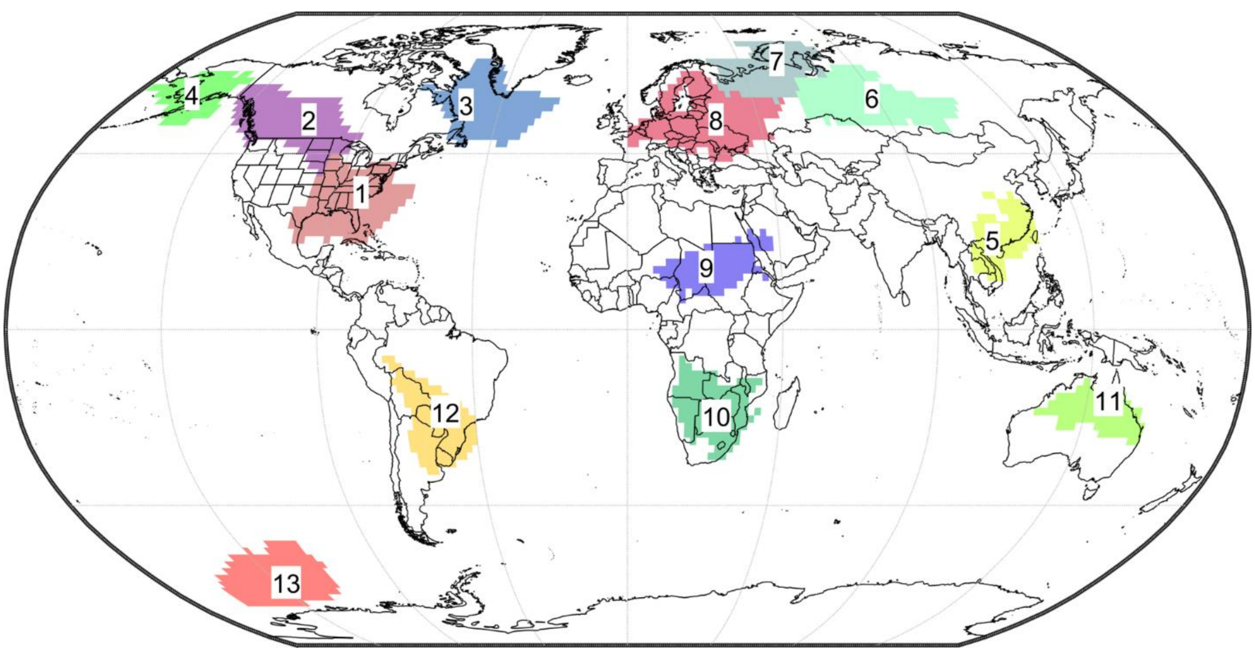


*Figure A3: Regions based on the CAOs produced from the NNR dataset.*