Characteristics and observed seasonal changes in Cold Air Outbreaks in Hungary using station data (1901–2020)

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Abstract

In this paper, we investigated Cold Air Outbreaks (CAOs) in Hungary using temperature data from ten weather stations located near populous Hungarian cities. Our main motivation for performing this research was the fact that in this rapidly changing climate, these events continue to represent a threat to infrastructure and human life, such as the outbreaks experienced in early 2021 (e.g., Texas, USA) and late 2022 (Winter Storm Elliott). In addition, no comprehensive study of CAOs in Hungary has been conducted using station data. The definition of CAO used in this paper is that the daily mean temperature had to be in the lower 10th percentile of the daily climatology for five consecutive days, and we allowed a maximum two-day gap between periods matching the criteria above, after which we merged events together. We found that the number of CAOs in Hungary decreased considerably in recent decades (due to increasing mean temperatures), and the climates of the investigated stations became increasingly homogenous. Developing our understanding of CAOs around the world is important because, due to climate change, their seasonal distribution may change in a way that negatively impacts our life and economy.

Keywords: cold air outbreaks, weather extremes, climate change, Hungary

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Introduction

Cold Air Outbreaks (CAOs) are massive weather events in which a cold air mass usually moves equatorward and persists in lower latitudes for periods of a few days up to weeks. These events have significant variability in duration, spatial extent, and frequency, which makes their research challenging. Most CAOs occur in the northern hemisphere, mainly because of the greater amount of land mass above mid-latitudes (Smith, E.T. and Sheridan, S.C. 2020). Additionally, cold outbreaks can also reach lower latitudes in the southern hemisphere, from June to August (Vera, C.S and Vigliarolo, P.K 2000), as we saw in 2021, where two CAOs hit South America (one in June and one in July), causing damage to crops and cocoa fields. The influence of CAOs has been researched the most in North America; here they may be even more severe than in Europe, as the mountain ranges of the continent cannot stop the movement of cold air deep into the southern parts of the USA. In Europe, winter precipitation could be associated with the number of winter CAOs, generally the decades with more CAOs also had higher snowfall totals in that season (Kis, A. and Pongrácz, R. 2021). CAOs also occur over oceans (maritime CAOs), causing heat loss to the oceans below (Papritz, L. and Spengler, T. 2017), and inducing polar-mesoscale cyclogenesis. Terpstra, A. *et al.* (2021) found that two-thirds of maritime CAOs in the North Atlantic Ocean generated these polar cyclones, which may cause strong winds and heavy snow over land (Brümmer, B. *et al.* 2009). Maritime cold air outbreaks (MCAOs) are slightly weaker and have less spatial extent in the southern hemisphere compared to the northern hemisphere. Still, the

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frequency of these MCAOs is similar in both hemispheres (Fletcher, J. *et al.* 2016). These southern hemisphere MCAOs are often induced by deep extratropical cyclones (Papritz, L. *et al.* 2015). There are many precursors to a CAO, such as massive blocking patterns (Kossakowska, M. and Zdunek, M. 2013), increased meridional jet stream (Rossby wave breaking) and sudden stratospheric warmings (Kolstad, E.W. *et al.* 2010; Zhang, M. *et al.* 2022). These intense events in the stratosphere can heavily influence the weather patterns in the northern hemisphere in winter, causing severe CAOs in North America and Europe (King, A.D. *et al.* 2019). Such an event occurred on 4 January 2021, which then caused a CAO in February when the cold air mass reached as south as Texas, leaving thousands without electricity and heating for days (Doss-Gollin, J. *et al.* 2021).

Intensive research is being performed on CAOs, despite their number decreasing in almost every part of the world in this changing climate (Smith, E.T. and Sheridan, S.C. 2020). There are many different approaches to the investigation of these extreme events, and there are even different CAO definitions because, ultimately, there is a lack of consensus among papers and researchers in other parts of the world. For example, Walsh, J.E. *et al.* (2001) used 1-3-5 day anomalies to detect CAOs and calculated backward trajectories to determine where the cold air mass originated. Tomassini, L. *et al.* (2012) used the lower 10th percentile in their climatology but worked with a more robust 15-day minimum duration. The spatial extent of CAOs may be investigated using reanalysis data (Walsh, J.E. *et al.* 2001; Smith, E.T. and Sheridan, S.C. 2020; Huang, J. *et al.* 2021) or station data (Smith, E.T. and Sheridan, S.C. 2018) or a combination of these two (Matthes, H. *et al.* 2015). Over land it is better to use near-surface variables (e.g., surface temperature or temperature at 2 metres) for the CAO criteria (Walsh, J.E. *et al.* 2001; Matthes, H. *et al.* 2015; Smith, E.T. and Sheridan, S.C. 2018), while over the oceans, it is advisable to use an upper atmospheric variable (e.g., 850 hPa temperature) (Kolstad, E.W. *et al.* 2009, 2010). In the warming climate, the frequency of these extreme cold events appears to be decreasing especially in the Arctic, where the rate of warming is the highest, therefore, we find the most negative trends at latitudes above 60°N (Matthes, H. *et al.* 2015). Although CAOs still occur even in unexpected places, sea ice loss in response to climate change may make these events less severe (Ayarzagüena, B. and Screen, J.A. 2016). However, there is a high level of uncertainty in the follow-up effects of sea ice loss: it may cause more persistent weather patterns (due to smaller temperature differences), leading to warmer but longer-lasting CAOs. It is also projected that most of Europe may get less snowfall, thus, less snow cover in the future (Kis, A. and Pongrácz, R. 2021), which lowers CAO intensity through the difference in radiative surfaces. Less intense CAOs may also mean lower heating demands in future heating seasons in the Carpathian Basin (Skarbit, N. *et al.* 2022). A new study (Smith, E.T. and Sheridan, S.C. 2021) using the CMIP6's socioeconomic pathways found that the number of CAO days may decrease in the future to near-zero across the globe (using the 1981–2010 climatology as reference), but they found significant variability in the North Atlantic region where CAO frequency may also increase as a result of climate change.

Focusing on Hungary, these CAOs generally occur during the advection of cold airmass from the northwest after cold fronts accompanied by strong winds or from the northeast – in this case, on the edge of a Scandinavian or Siberian high-pressure system. The biggest threats associated with these events are cold temperatures, which increase heating demands; wintry precipitation – especially freezing rain, which causes infrastructural damage and dangerous driving conditions; and frost damage to crops and blooming fruit trees in the spring. The strongest CAOs in the past ten years occurred in March 2018 and February 2021 (Horváth, Á. 2018; Kurcsics, M. *et al.* 2021).

Data and methods

We used daily mean temperatures obtained from the repository of the Hungarian Meteorological Service (odp.met.hu). This is a high-quality dataset created from weather station observations in Hungary. Data from 10 stations were available (Sopron, Szombathely, Keszthely, Pécs, Budapest, Túrkeve, Szeged, Debrecen, Miskolc, Nyíregyháza) between 1901 and 2020 *(Figure 1)*. The dataset has only a few missing days, which did not affect our results. Most of the stations are situated in lowland areas, but some of them are proximity to small mountainous areas.

We used the R programming language to calculate the results from the data. After importing into data frames, we used the "heatwaveR" package (Schlegel, R.W. and Smit, A.J. 2018), which was originally developed in Python for marine heatwaves, as in Hobday, A.J. *et al.* (2016), but can be used to detect CAOs over land. (The details of the setup of this package for this study can be found in the Appendix.) We used this package to produce a 30-year climatology from our daily data, which consists of the daily distribution of mean temperatures for every day of the calendar year (later referred only as climatology). We chose the period between 1991 and 2020 as our reference, mainly because this way we can detect more events, even in the climate change affected warmer last thirty years. The criteria of a CAO were the following:

– The daily mean temperature is in the lower 10th percentile of the climatology for five consecutive days.
– There is a maximum of a 2-day gap between periods matching the above criteria, in which case the two were considered as a single event.

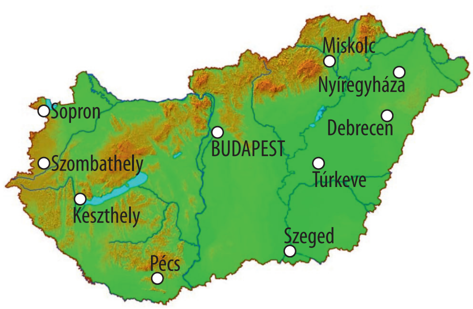


Fig. 1. Location of stations on the topographical map of Hungary

Because we used station data, the spatial extent of these CAOs was not investigated (this is possible, but given the relatively small size of the country, we decided to focus only on duration and intensity). We used the following statistics in our research *(Table 1)*:

These statistics are the most reliable and representative for investigating different CAO events. We also used the start, peak and end date of each event, and for further categorization, we split the calendar year into four seasons (winter, spring, summer, and autumn) and later into months, using the start date of events in this process.

Results

In this section we first investigated the characteristics of CAOs in Hungary over the span of 120 years. After that we discuss how these events changed over time, looking at seasonal and regional aspects.

Characteristics of CAOs in Hungary

Using our CAO definition, we detected 3,237 events at 10 stations over the span of 120 years. From these CAOs, 983 started in the winter months, 803 in spring, 673 in summer and 778 in autumn. On a monthly

Table 1. List of statistics used in the analysis of CAOs

Statistic	Definition
Mean intensity	Average daily temperature anomaly during the event, °C
Peak intensity	Maximum daily temperature anomaly during the event, °C
Cumulative intensity	Sum of daily temperature anomalies during the event, °C
Absolute intensity	Daily mean temperature on the peak day of the event, °C
Duration	Duration of the event in days

scale, 445 events hit the country in January, which is nearly double the amount of the other month's average. On the other end, the stations recorded the least amount of CAOs in July (176). From the 120 years, only two (2015 and 2020) did not have any CAO, while in 1978, there were 68 events (all stations combined). The station near Sopron had the most events (394) during our research period of 1901–2020, while Szeged and Keszthely had the least (255 and 257 events, respectively). Sopron also had the strongest CAO event from 4 January 1942 to 22 February 1942, lasting 46 days and accumulating over 400 °C of cumulative CAO intensity. Going back to the seasonal scale *(Figure 2)*, we show the number of events at each station in four seasons (*Figure 2*, a), and the number of

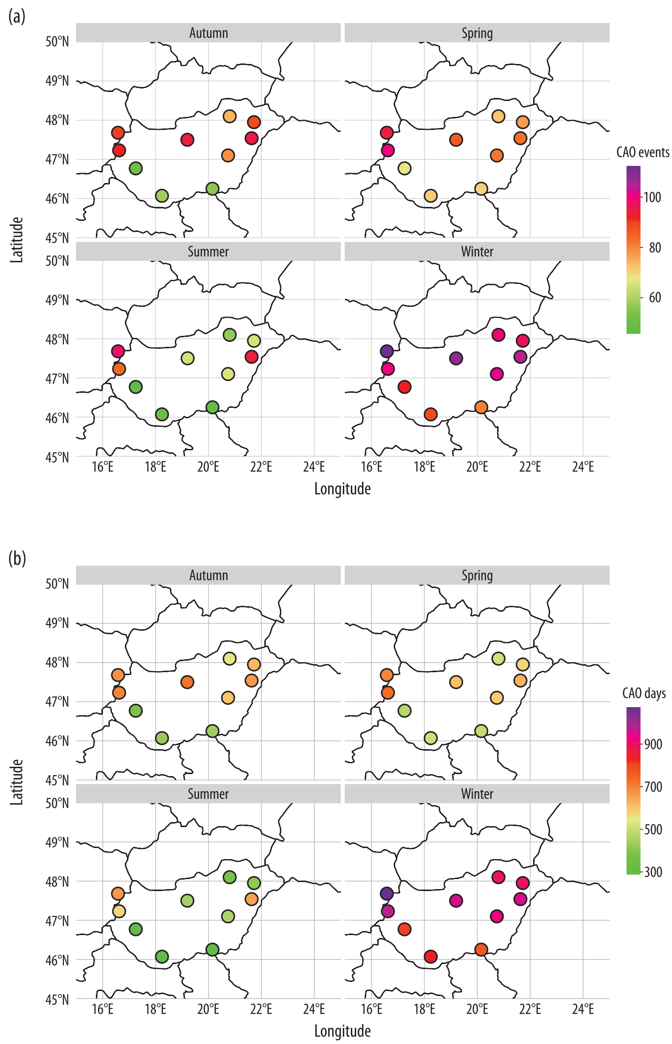


Fig. 2. The number of CAO events (a) and CAO days (b) between 1901 and 2020 at 10 Hungarian stations across four seasons. *Source*: Authors' own elaboration.

CAO days (duration of events summarised) in the same way (*Figure 2*, b). We can see that, on average, the winter season had the most events and CAO days, and the summer season had the least. The variation between the stations seems to be bigger in summer and autumn and smaller in winter and spring. We uncovered more regional differences on this scale, but these are discussed with the observed changes of CAOs occurred between 1901 and 2020.

After that, we looked at how the statistics in *Table 1* correlate during the whole period in each month. We visualised all CAO events on a scatterplot (*Figure 3*, a and b) to better understand the relation between the different statistics.

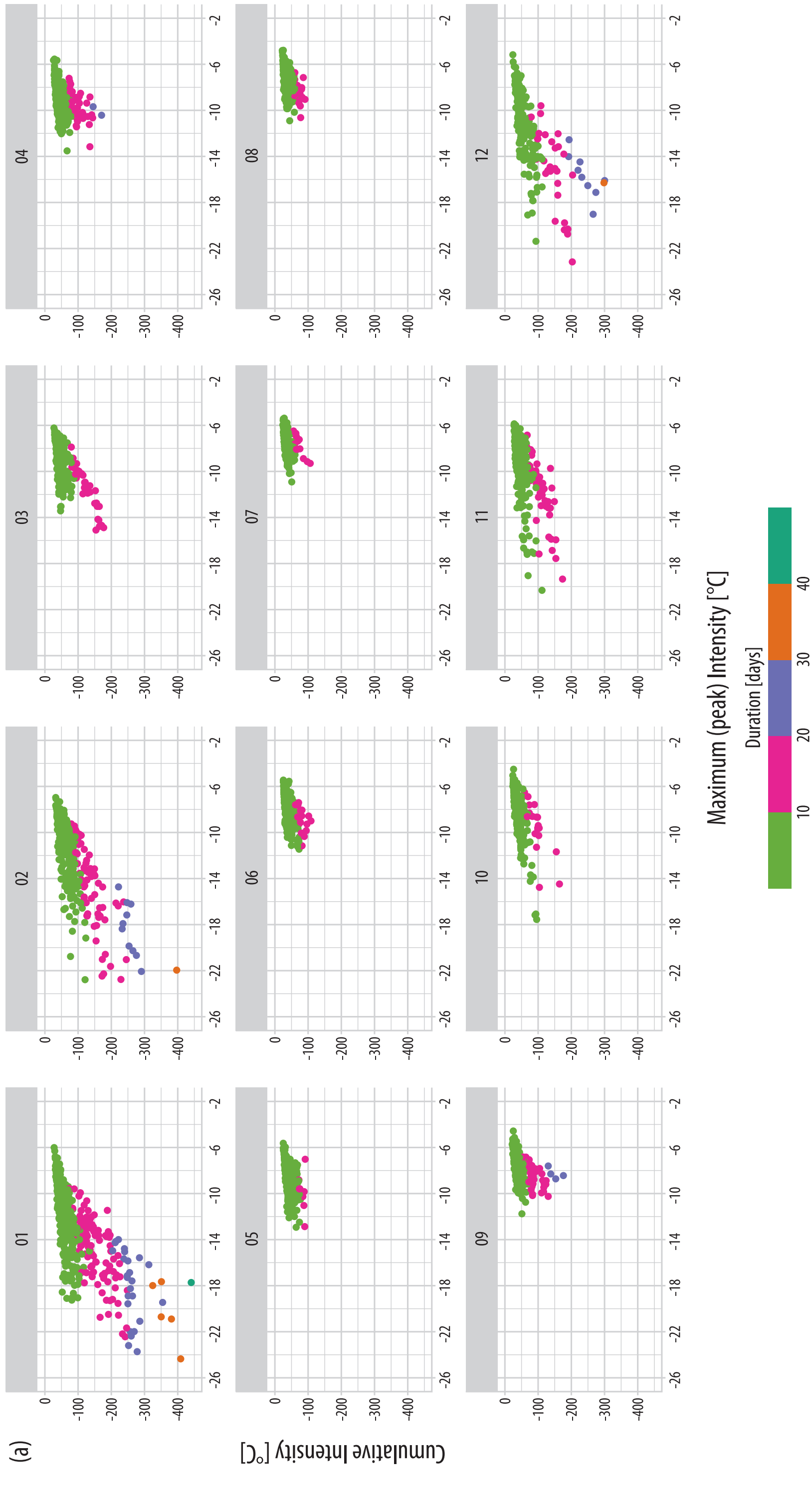
The duration of most CAOs was lower than 20 days with the majority of cases lasting between 5 and 10 days (green and pink colours on *Figure 3*, a). Longer-lasting CAOs only occurred in the three winter months and in April and September, but rarely in these last two months. As expected, longer events had the lowest cumulative intensities (in this case, meaning they were stronger), but the relation between peak intensities of CAOs and their respective duration is highly nonlinear. The cumulative intensity varied more between the months of the year, with the winter months having the strongest and the summer months having the weakest events in Hungary. The scatterplots also showed us the underlying relation between the peak and cumulative intensities of CAO events. This relation appears to be linear in some months (e.g., March, May, June, July, August, October, and November), while in the other months, it is more nonlinear (there are higher cumulative intensities to the same peak intensity). We can also observe that the winter months all have more variation between events, given that there were peaks with lower than -20 °C in these months. On *Figure 3*, b the colours represent the absolute intensity, which is defined as the daily mean temperature of the peak day during each event. In the summer months, daily mean temperatures dropped between 8 and 18 °C during CAO peaks, in spring and autumn it had a great variability between -10 and 15 °C, but in November, there were some events with even colder mean temperatures. The three winter months had the lowest daily temperatures at peaks, in many cases falling below -20 °C, which can cause infrastructural problems.

Observed changes of CAOs between 1901 and 2020

In the previous chapter, we introduced the characteristics of cold air outbreaks in Hungary and in this chapter, we analyse how the CAO statistics changed over time. We also investigate seasonal and regional differences, so our approach reflects that motivation *(Figure 4).*

Firstly, we looked at the seasonal changes to the five statistics mentioned earlier (mean, peak, cumulative, absolute intensity, and the duration of events). We used boxplots to visualise each year and added local regression smoothing (LOESS – locally estimated scatterplot smoothing) to our graphs. This is a nonparametric method for smoothing data, especially in the presence of outliers. It uses local weights to detect trends in shorter timeframes, which benefits us. Because the intensities are measured in negative values, we depict increasing (decreasing) intensity when the values get lower (higher).

In autumn, the duration of events ranged between 5 and 15 days; longer CAOs only occurred before 1920. There was a slightly increasing trend from 1970 to the mid-1990s, but overall, there is no significant change in duration (*Figure 4*, d). The mean and peak intensity in this season had a decreasing trend until 1950, then an increasing trend until 1990. In the last 30 years, both intensities decreased by nearly 1 °C, meaning that the CAOs became weaker (*Figure 4*, c and e). The cumulative intensity had the same trend as the mean and peak, but we could see some stronger events that occurred between 1980 and 2000 (*Figure 4*, b). Here, we can also see less difference between stations than in the case of the previous strong CAOs before 1940. The absolute intensity had its


(a)
Cumulative Intensity [°C]
Maximum (peak) Intensity [°C]
Duration [days]
10
20
30
40
01
02
03
04
05
06
07
08
09
10
11
12

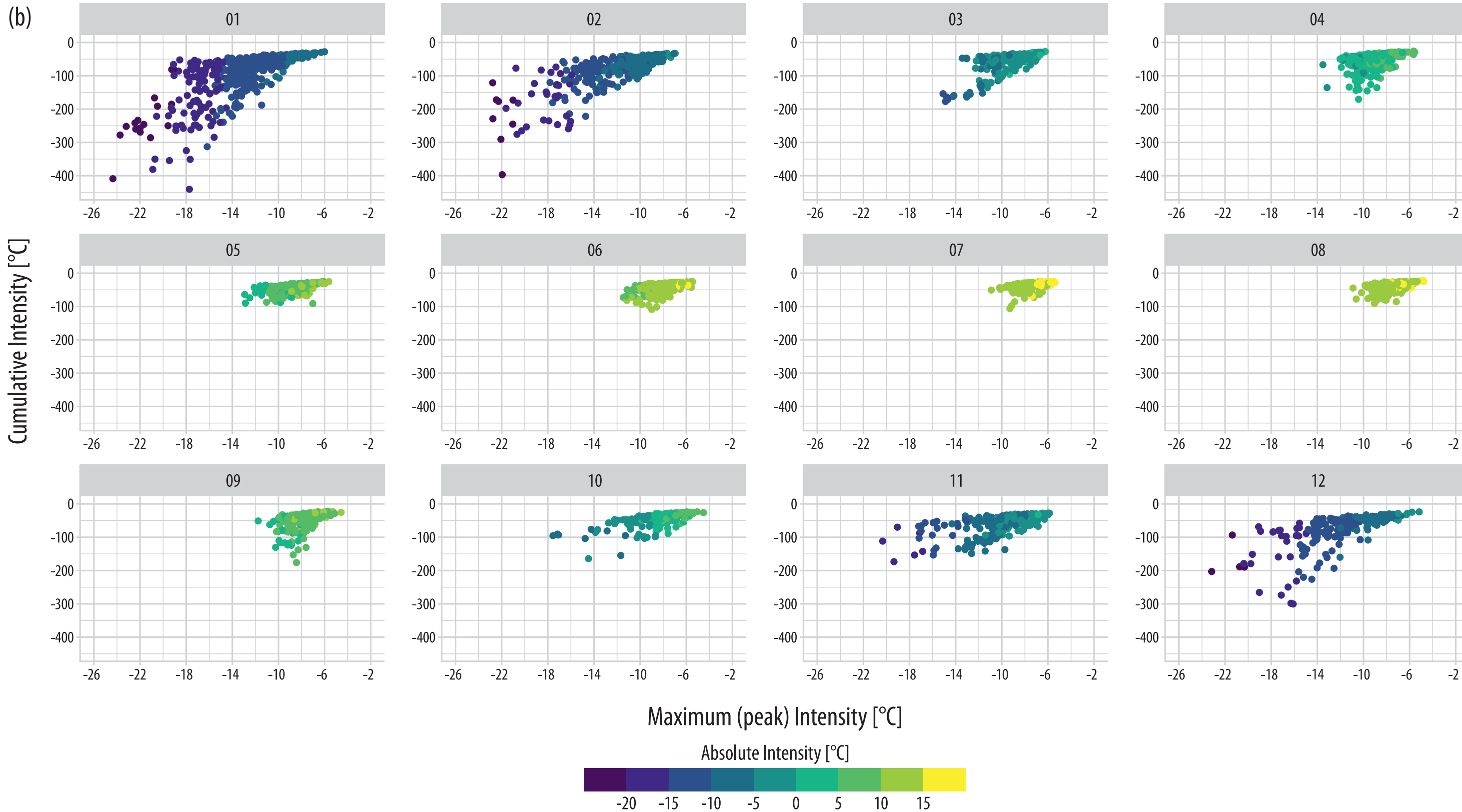
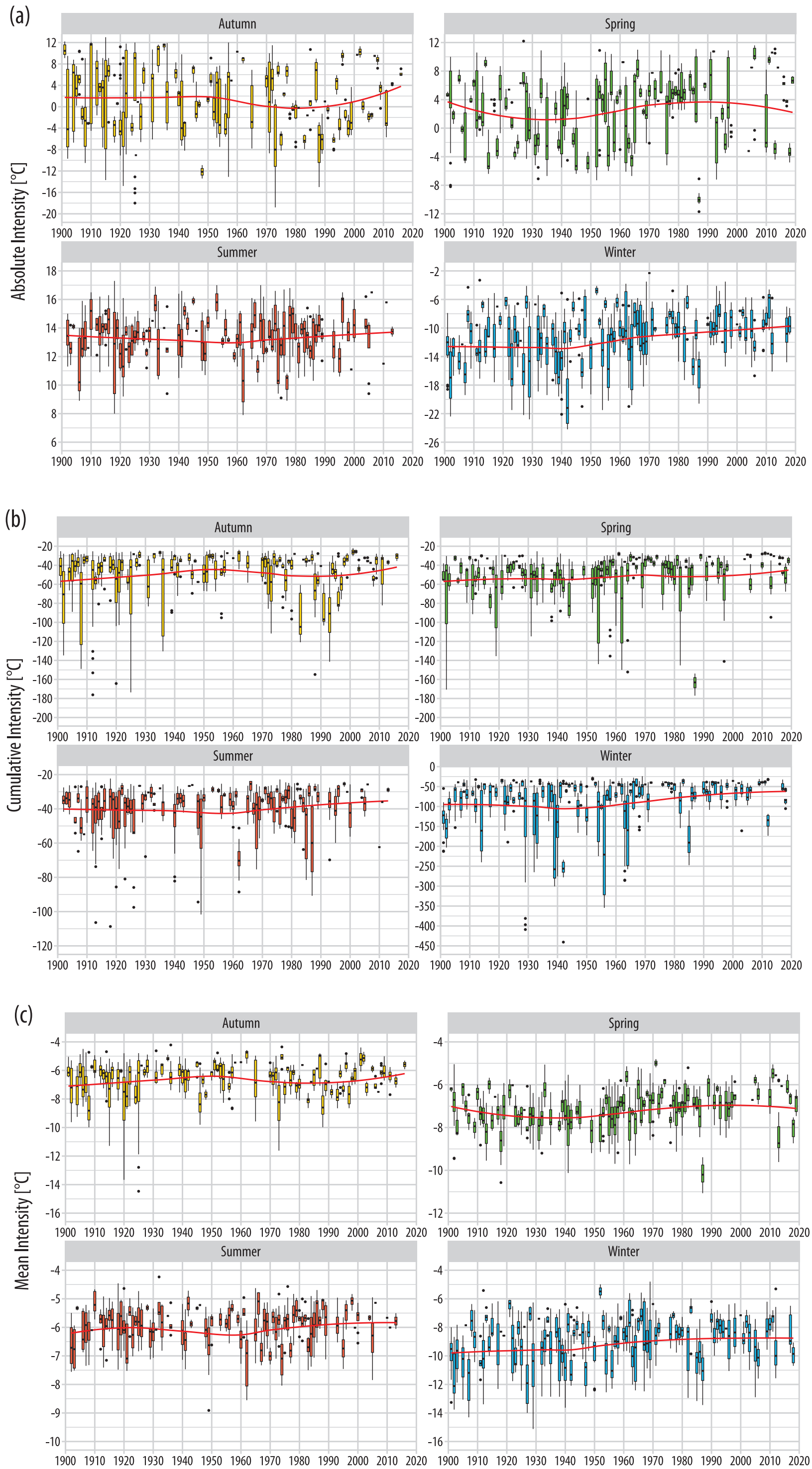


Fig. 3. Cumulative intensity of CAO events (y-axis) plotted against the maximum (peak) intensity of events (x-axis) during the whole 120-year period in each month of the calendar year. The colours show the duration of events in days (a), absolute intensity of events (b). All values except duration are in °C.
Source: Authors' own elaboration.


(a)
Absolute Intensity [°C]
Autumn
Spring
Summer
Winter
(b)
Cumulative Intensity [°C]
Autumn
Spring
Summer
Winter
(c)
Mean Intensity [°C]
Autumn
Spring
Summer
Winter

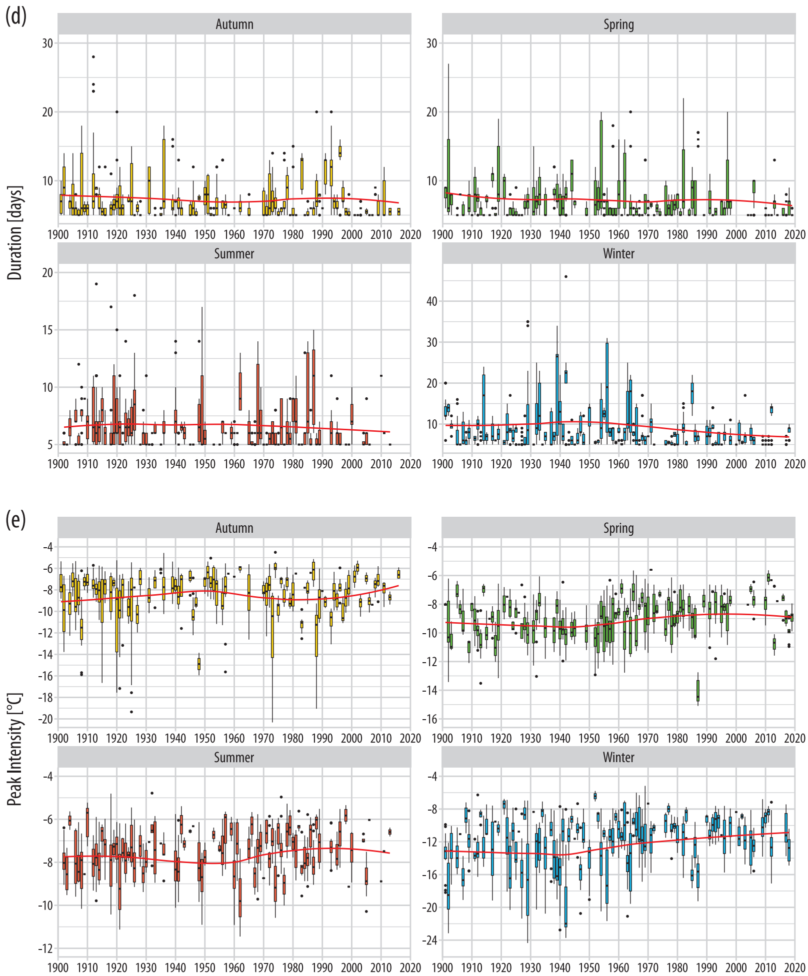


Fig. 4. Observed changes in the five CAO statistics used in our study between 1901 and 2020 across four seasons. Red line is local regression smoothing (LOESS) in every graph. We show the boxplots of Absolute intensity (a), Cumulative intensity (b), Mean intensity (c), Duration (d) and Peak intensity (e). *Source:* Authors' own elaboration.

most significant variation in the three autumn months compared to the other seasons. With the great internal variability and fewer and fewer events in the last 30 years, we have found no significant conclusions regarding this statistic (*Figure 4*, a).

Looking at the other transition season, spring, we can see similar characteristics to autumn in event duration, the last 20 years having shorter CAOs than the 100 years prior (see *Figure 4*, d). The mean and peak intensities reveal an interesting difference: in the last 20 years, there has been an increasing trend in both statistics in this season (see *Figure 4*, c and e), but due to a small number of cases, it is not significant. There was an increase in intensity until 1950, while a decreasing trend was found after that until the mid-1990s. On the other hand, the cumulative intensity of spring CAOs shows a decreasing trend in the whole period, but there was a strong event in almost every decade, the strongest being in March of 1987 (see *Figure 4*, b). The absolute intensity ranged between -6 and 10 °C in this season, but with the same great variability as in autumn (see *Figure 4*, a).

The summer season had the weakest events of all seasons and mainly in two periods during the 120 years. The first period was between 1905 and 1925, and the second from the mid-1960s to 1990. Both periods had nearly identical characteristics, the first slightly colder than the latter. There were longer events at some stations in the 1980s (see *Figure 4*, d), but most events were shorter than 10 days in the summer months. Between these two periods, there were a small number of events, but in the last 30 years summer season CAOs started to disappear because of the effects of increased warming of summers in Hungary.

Lastly, we analysed the changes in winter season, which had the most and strongest events. There were many cases where longer than 20-day CAOs occurred between 1930 and 1970 (see *Figure 4*, d). After that, there was only one occurrence of this duration, the length of events decreased to an average of 5 to 10 days. We also discovered a decreasing trend in mean intensity (see *Figure 4*, c) in the whole period (1 °C per 120 years) and a slightly greater decrease in peak intensity (see *Figure 4*, e) (1.5 °C per 80 years from 1940). There were more strong events looking at the cumulative intensity until 1970 with greater variability, but after that, we observed the same decreasing trend, only two years had strong events (see *Figure 4*, b). The absolute intensity had greater variation until 1990, ranging between -22 and -2 °C, with the last 30 years having smaller variation (see *Figure 4*, a).

We also compared the four seasons during our research period on a simple line chart *(Figure 5)* to illustrate the shift in seasonal CAO occurrence. For our comparison, we chose the 10-year moving average of CAO days on an annual basis and the station average (for simplicity). We can see that the number of CAO days decreased in the winter season and increased in the other three seasons in the first 20-30 years, the autumn and summer seasons had 10 and 9 CAO days yearly, while winter and spring seasons had around 6 days. The moving average of winter season CAO days increased rapidly after 1925 until 1950, reaching 10 to 15 days annually. After a short decline, it had the most days of the seasons until the early-1970s. The spring season had a peak in the early-1960s, with 10 CAO days yearly, while autumn and summer seasons had just a few days annually. Around 1975, all seasons had the same moving average number of CAO days, and the summer season had the greatest number of them for a short period. The autumn season had two smaller peaks, one in 1980 and another in 1997, while the winter season had a third peak between 1985 and 1995. In the last 20 years, all seasons have had a decreasing trend, with the moving average falling below 5 CAO days.

To assess regional and seasonal differences together throughout the years, we constructed *Figure 6*, a and b, where we visualised the number of CAO days summarised in each decade at each station. We used decades here for simplification, knowing that it can mask inter-decadal characteristics, but we could already analyse those on previous figures. On *Figure 6*, b we split the winter season further into months and added November from the autumn season to our regional analysis, because these were the months with the greatest number of events and had the greatest internal variability.

We can see that in autumn, the most CAO days occurred in the 1910s, 1920s, 1970s and 1990s. Budapest had more than 120 CAO days in the 1910s, but no regional trends appear in the data (see *Figure 6*, a). The other two decades had a more homogenous distribution of CAO days, most stations having 60-90 days in these 10-year periods. In the 2010s, Budapest had no CAO events during the autumn season. In spring, the most CAO days occurred in the 1950s and 1960s, in this timeframe, Sopron, Szombathely and Túrkeve stations had over 90 CAO days. We found two opposite regional patterns, one in the 1970s and one in the 1990s. In the first decade, the western stations (Sopron, Szombathely,

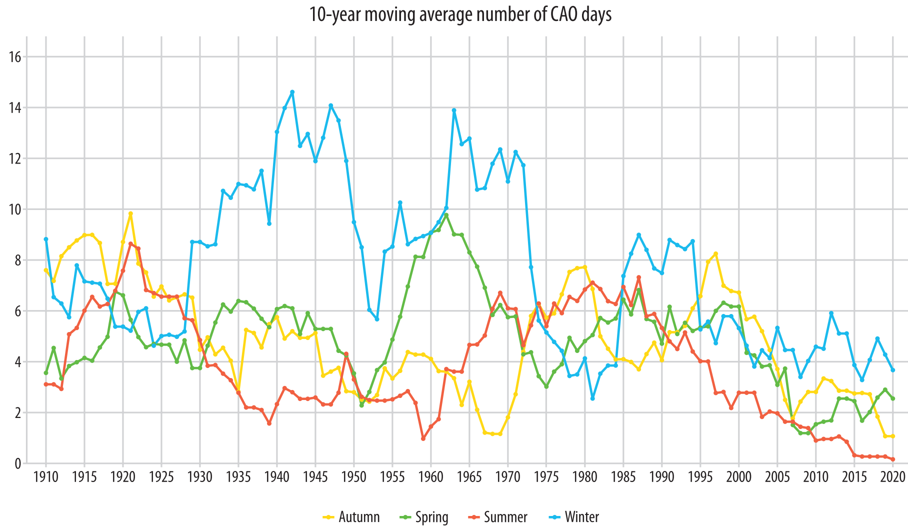


Fig. 5. 10-year moving average (right-aligned) number of CAO days (station average shown) during our research period (1901–2020). *Source:* Authors' own elaboration.

Pécs, Keszthely) had more than 45 CAO days, while the rest of the stations in the east had less. In the second decade, the stations in the eastern part of Hungary had between 60 and 90 CAO days, while the western stations had slightly fewer CAO days than that figure. In the summer season, Sopron had 146 CAO days in the 1910s, which is an outlier among all stations. Debrecen also had more summer CAO days than any other station: 95 in the 1920s, 101 in the 1980s and 107 in the 1970s. In the last 30 years, the number of CAOs decreased rapidly this season. Only 3 out of 10 stations registered CAO days in the last decade. The winter season had the greatest number of days, mainly in the first seven decades of the whole period. In 10 cases, the decadal number of CAO days was over 120 days, in the 1940s, Sopron even had 193 CAO days, which is another outlier. We did not detect any clear regional patterns in winter, but in most decades the stations in the northern part of Hungary had more CAO days, than the southern stations. This is because the cold airmass usually arrives with north-westerly or north-easterly winds to the Carpathian Basin in this season.

We also investigated the distribution of cold air outbreak days with the same method in November, December, January, and February months to see if we can find any regional patterns below the seasonal scale (see *Figure 6*, b). November CAOs mainly occurred in three decades: 1900s, 1920s, and 1980s. Regional differences were present in some decades, but we did not find a clear trend. Looking at December, there were many CAO days in the 1930s and 1990s and a regional pattern in the 1960s, where the western stations had more event days. In some decades, the two north-eastern stations (Miskolc, Nyíregyháza) had more CAO days, implying a synoptic forcing from this direction. The greatest number of CAO days occurred in January, most frequently in a 30-year window from 1940 to 1970. In this period, most stations had over 60 CAO days per decade, Sopron station registered over 100 CAO days in the 1940s. Regional differences do appear in this month in a few

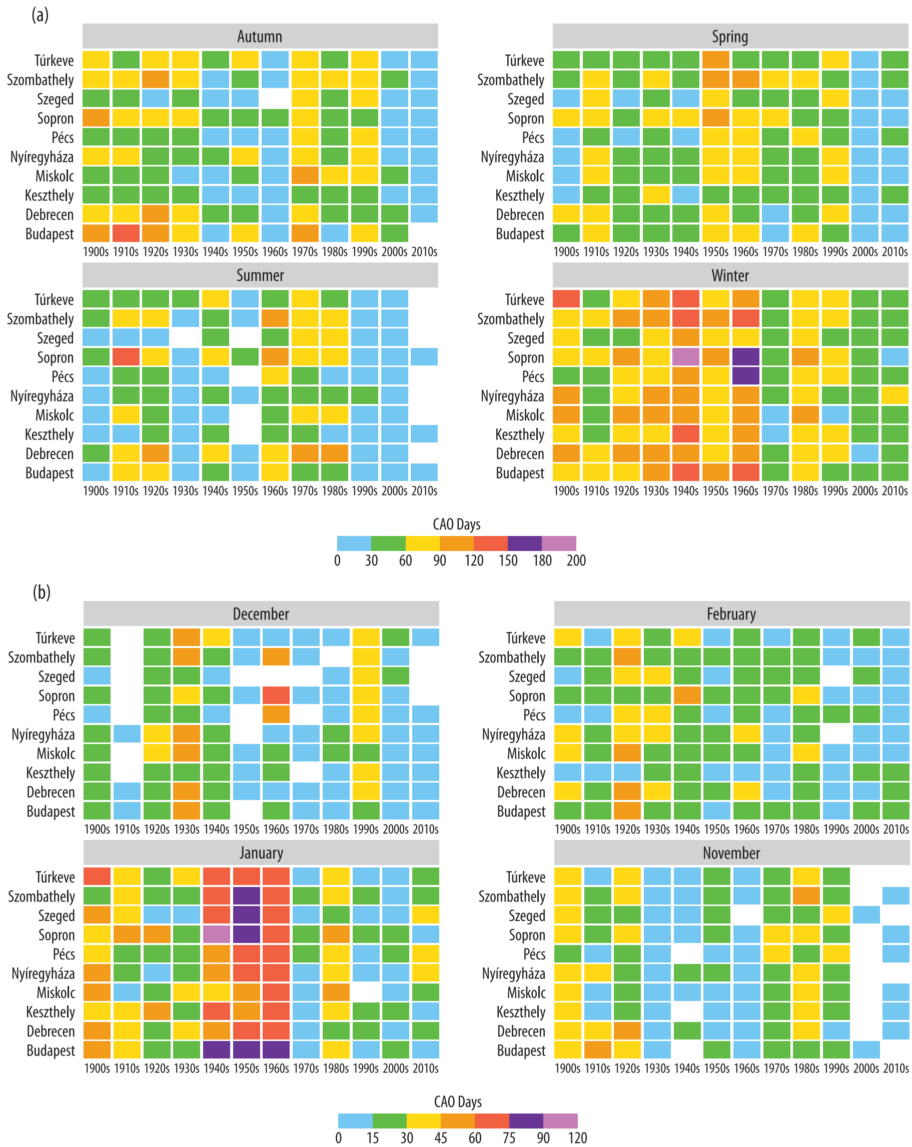


Fig. 6. Number of CAO days visualised at 10 Hungarian stations in the last 12 decades (1901–2020) across four seasons (a), and in November, December, January and February (b). *Source:* Authors' own elaboration.

decades, with the same east-west pattern we discovered previously. In February, we can see a great variability in event occurrence, the 1920s had the most CAO days in Hungary. No clear trend of a regional pattern was found in this month.

Finally, we created an overview for all stations like *Figure 7*, where we visualised all CAO events in a way that allowed us to see the seasonal and annual changes, the duration of events, and each event's peak intensity. We then selected Budapest station for a visual example.

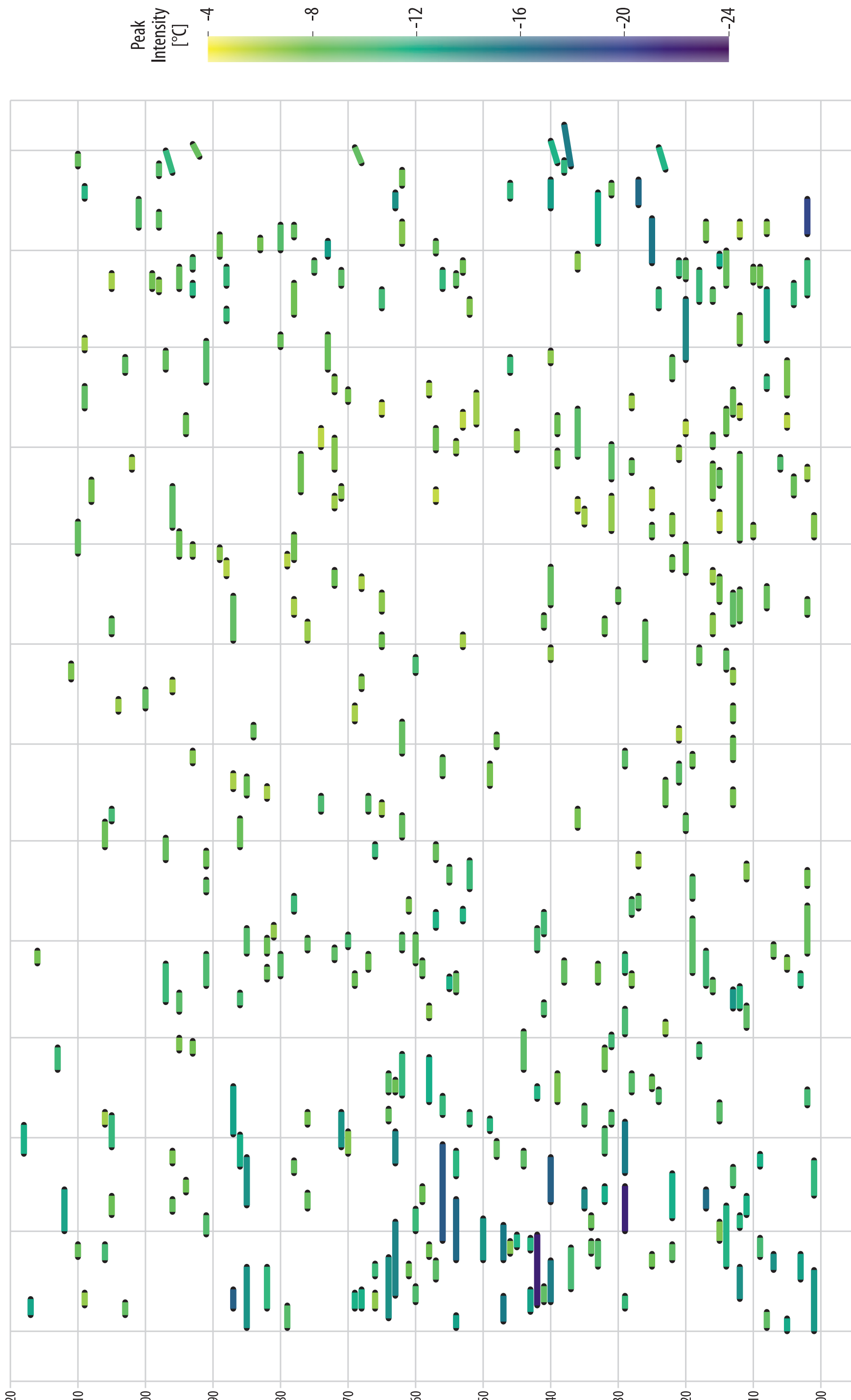


Fig. 7. An overview of all CAO events which occurred at Budapest from 1901 to 2020. We can see the distribution of events in the calendar year. Sloped lines at the end of the year represent events which lasted throughout the new year. *Source:* Authors' own elaboration.

Discussion

We compiled a climatology of cold air outbreaks in Hungary using station data during the last 120 years. In our method, we used 2-day non-CAO gap criteria, which allowed us to merge events together or increase event length in some cases where milder temperatures occurred for one- or two-days during CAOs. This way, we detected longer events, especially in summer and transition seasons, which could be the strength of our method. We analysed the characteristics and observed changes with carefully constructed graphs, which best represent the most important results obtained from this kind of data. Our intention with this study was only to thoroughly investigate cold air outbreaks, which affected Hungary, we did not want to compile or compare other cold weather phenomena within the boundaries of this research.

Our work differs from that of Spinoni, J. *et al.* (2015) in some ways, whose research was the closest to this investigation of CAOs in Hungary. They used "CARPATCLIM", a high-quality gridded dataset for the period 1961–2010 and a broad area surrounded by the Carpathian Mountain Range, in contrast to our station approach. They used a similar CAO (there: cold wave) definition of 5 consecutive days below the 10th percentile of the climatology (baseline period: 1971–2000), but for the night and daytime minimum/maximum temperatures. Also, the two-day gap between these days was not used as we did in our method. They also investigated these events on a seasonal basis and found an increasing trend in their statistics in autumn, which is opposite to what we found in spring. They also found that the rate of change is greatest in the winter season, similar to our results. Despite the differences between the methods, the decreasing trend of CAOs is still present in both investigations.

We could also use less robust cold indicators, like cold snaps or cold spells (CSPs), because these shorter events can also cause problems in the agricultural sector and road transport, like that experienced in March of 2013. The characteristics of these events at early spring are also important to understand better our changing climate and the shift of the seasons in Central Europe. The frequency of CSPs is also decreasing with the warming climate, but CSPs have been more frequent in recent decades than CAOs, so we are planning a comparison study between these indicators of cold weather.

Even though the number of CAOs (and the focus on them) has decreased in recent decades, investigating the changes in their seasonal distribution could be a research focus for the coming years. Understanding CAOs not just in the winter months may be critical to better predict the occurrence of these phenomena in the future. We also proved that cold air outbreaks represent a robust set of statistics relating to cold weather phenomena, and their reduction is a great indicator of a warming climate, so applying the methodology to different parts of the Earth where the rate of warming differs may be interested in research on recent decades.

Conclusions

This paper investigated Cold Air Outbreaks in Hungary using observational data from 10 Hungarian weather stations. We discovered some interesting facts using a robust CAO definition as well as the already-known effects of climate change in our region:

– Until the 1990s CAOs occurred with great seasonal variability, but in the last 30 years, their number declined rapidly (pointing to that we can use CAOs as an indicator of climate change because these long-lasting cold periods provide us with a robust set of statistics).
– Summer and autumn seasons have had the least number of events recently; only the winter months and early spring have had significant CAOs in the last decades.
– Almost all investigated statistics declined because of the warming in this region in the last 30 years. The only increasing trend was found in spring, where the mean and peak intensity had a slight increase in this timespan.

– We only found regional differences in the country in just a few decades, with no clear trend. These differences generally occurred between the western and the eastern part of Hungary, which could potentially reveal the origin of cold airmass.

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