COLD WAVES IN THE ROMANIAN CARPATHIANS, AN INDICATOR OF NEGATIVE TEMPERATURE EXTREMES

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ABSTRACT. – Cold waves in the Romanian Carpathians, an indicator of negative temperature extremes. Cold waves are a representative indicator frequently used to analyze the incidence of cold extremes in a given area. This study was undertaken on these cold extremes in the Romanian Carpathians defined by the STARDEX project. Investigations had in view mountain weather stations located >1,000 m a.s.l. (15 sites) over the 1961-2003 period of available daily temperature records. Long-term records of daily minimum temperature (blended) were also studied from the available ECA&D data sets at Omu Peak station (1928-2011). Regional patterns of cold waves were expressed by comparing their frequency, duration and intensity at the weather stations located in the alpine, sub-alpine and forest vegetation belts. There is an evident inter-annual variability of cold wave duration, showing a significant increase particularly in some forest belt locations in the Southern Carpathians. However, the long-term variability trend (83 years) at Omu Peak alpine station showed quite an opposite trend, corresponding to the warming process in terms of minimum temperature values. Cold waves are usually associated to a high number of consecutive frosty nights and freeze days, but they have low effects on the characteristics of snow season.

Keywords: cold extremes, cold wave duration index, variability, mountain region.

1. INTRODUCTION

The incidence of climate extremes has a two-fold significance, being associated both with climatic and moreover with the natural variability of climate and with general climate warming, particularly obvious in the second half of the 20th century and the beginning of the 21st century. The ever greater frequency and intensity of extreme climatic events called for the elaboration of a common methodological and terminological framework, in order to facilitate a variability assessment of climate extremes in regions with distinct climatic conditions (Katz, Brown, 1992; Folland *et al.*, 1999; Peterson, 2005; Frich *et al*., 2002).

The indexes/indicators put forward by WMO-CCL/CLIVAR/ETCCDMI and promoted under some international projects (e.g. STARDEX) are considered to be representative for an analysis of climate worldwide. The analysis would be the more representative for assessing the effects of local climate change as mountains are considered to be early indicators of global climate change (UNEP Conference, April 2008, Padova).

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Cold waves are assumed to be a suggestive indicator of negative thermal extremes, often associated with massive cooling spells, frequently growing into absolute negative thermal records. The aim of this paper is to make a climatological characterisation of persisting cold extremes by looking at their duration, frequency and intensity, with highlight on the rough mountain climate at altitudes above 1,000 m. The study has also in view the mid-term (1961-2003) and long-term (1928-2011) variability trends of cold wave duration and the corresponding shifting years in their regime.

2. DATA AND METHODS

The cold waves and their specific parameters have been analysed based on rows of continuous and sufficiently long observation data recorded at 15 weather stations listed in the national network (>1,000 m a.s.l.). Hypsometrically, the meteorological measurement points are placed mostly in the forest (9) rather than in the sub-alpine (4) and alpine belts (2) (Figure 1).

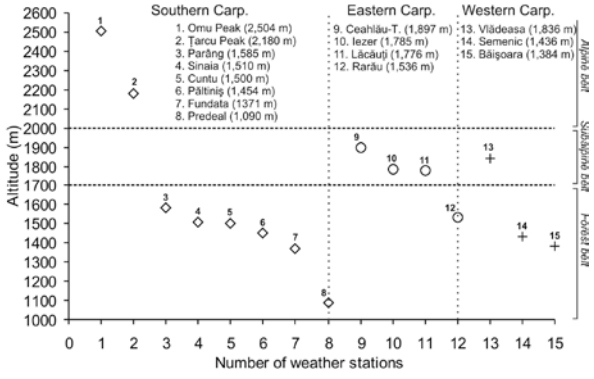

Fig. 1. ***Altitudinal distribution of mountain weather stations in the Romanian Carpathians located above 1,000 m a.s.l.***

The cold wave study uses daily air minimum temperature data recorded over a 43-year period (1961-2003). In order to assess the perennial character of the rough mountain climate at over 2,500 m, more directly in contact with the free troposphere, the variability of cold wave duration at Omu Peak station was followed based on daily minimum temperature blended data (1928-2011), available from the European Climate Assessement and Dateset (ECA&D).

In the present study, cold waves have been evidenced according to the definition put forward the by the STARDEX project*, corresponding to an interval of at least 6 consecutive days with negative deviations of at least 5°C from the normal value of each calendar day, computed for the 1961-1990 reference period (in terms of the WMO recommendation). The same definition was also adopted by the National Meteorological Administration (Busuioc *et al*., 2010).

* Statistical and Regional Dynamical Downscalling of Extremes for European Regions.

3. RESULTS

3.1. Cold wave duration

Cold waves in Romania last less than heat waves do (Busuioc *et al.*, 2010). In the Romanian Carpathians this happens only at the weather stations situated below 1,900-2,000 m altitude. It is only in the alpine realm (at over 2,200 m) that things look the-other-way-round, because altitude is restrictive, moderating intense heat. In terms of multiannual regime, cold waves last on average 9.7 days (Omu Peak station) and 10.8 days (Ţarcu Peak station) in the alpine belt; 6.4 days (Predeal) and 12.2 days (Parâng) in the forest belt. Looking at the three Carpathian branches, it appears that the average length of cold waves is the shortest in the Western Carpathians (ca. 9.9 days), with maximum values in the Eastern and Southern branches (ca. 10.5 days).

Whatever the altitude or Carpathian branch, the annual duration, in terms of multiannual regime, little or moderately persistent cold waves are the best represented ones (50-75% and 20-45% of cases, respectively) (Table 1). At the other end of the spectrum stand persistent (2-10%) and very persistent cold waves (2-7%), characteristic mostly of high mountain areas (>1,800 m), very windy, or locally favourable to strong thermal inversions.

Table 1. ***Frequency (cases) of cold waves by annual duration classes (1961-2003)***

Weather stations	Little persistent	Moderately persistemt	Persistent	Very persistent
	<10 days	11-30 days	31-50 days	>50 days
Omu Peak	60.5	37.2	2.3	0.0
Ţarcu Peak	55.8	39.5	4.7	0.0
Ceahlău-Toaca	55.0	42.5	2.5	0.0
Vlădeasa	62.8	37.2	0.0	0.0
Iezer	60.5	39.5	0.0	0.0
Lăcăuţi	55.8	41.9	2.3	0.0
Parâng	58.1	32.6	7.0	2.3
Rarău	55.0	45.0	0.0	0.0
Sinaia	60.5	37.2	2.3	0.0
Cuntu	48.8	39.5	4.7	7.0
Păltiniş	58.1	32.6	9.3	0.0
Semenic	74.4	23.3	2.3	0.0
Băişoara	67.4	32.6	0.0	0.0
Fundata	60.5	39.5	0.0	0.0
Predeal	76.7	23.3	0.0	0.0

Source: Data computed from the NMA Archive.

Maximum duration was of 38 days (Omu Peak and Ţarcu Peak stations, 1997) in the alpine belt, down to 27 days (Iezer, 1963) and 35 days (Ceahlău-Toaca, 1995 and Lăcăuţi, 1987) in the sub-alpine belt and 27 days (Predeal, 1963) and 65 days (Parâng, 1965) in the forest belt. The average and particulary the maximum length of cold waves is not visibly dependent on altitude, but rather on synoptic causes. The monthly frequency and persistence of cold waves led to an annual maximum of only 31 days in the Western Carpathians (Semenic, 1991), 35 days in the Eastern Carpathians (Ceahlău-Toaca, 1995) and over 60 days in the

Southern Carpathians (Parâng 65 days, 1965). Annual duration over a longer period of time (Omu Peak, 1928-2009) reached a maximum of 74 days due to the cumulated persistence of some successive waves of cold registered over the April-June interval of 1940.

The cold waves recorded over the 1961-2003 interval lasted the longest, especially in the cool and cold years (1963, 1985, 1987, 1991, 1997) with a higher incidence of cold air advections.

3.2. Frequency and intensity of cold waves

Cold waves in the Romanian Carpathians may occur throughout the year, particulary during the cold season, when snow season months* alone add 51-99% to the overall annual number of cases (Table 3). The months with the greatest cold wave frequency at over 1,000 m altitude are November and February, totalling up to 11-15 cases over the 1961-2003 period. Lowest frequencies are generally reported in April, irrespective of altitude (up to 5-6 cases). And yet, special synoptic conditions may generate cold waves in autumn (March and May), and spring (March and May), seldom in summer (mostly in June), but the frequency, persistence and intensity of these extremes is visibly reduced.

Table 3. Annual and monthly number of cold wave cases in the Romanian Carpathians

Weather stations	VIII	IX	X	XI	XII	I	II	III	IV	V	VI	VII	Annual
Omu Peak	0	2	5	**11**	6	7	**11**	8	4	1	0	0	55
Ţarcu Peak	2	4	9	6	8	7	7	**9**	5	2	1	0	60
Ceahlău-Toaca	0	3	10	8	9	5	**11**	7	2	0	1	0	56
Vlădeasa	0	3	5	**8**	**8**	5	**8**	6	4	0	1	0	48
Iezer	0	2	4	6	7	7	**11**	7	3	1	0	1	49
Lăcăuţi	0	2	5	**11**	7	9	9	10	2	0	1	0	56
Parâng	4	6	**11**	6	7	6	5	5	3	2	3	0	58
Rarău	0	1	6	10	6	7	**14**	7	2	0	0	0	53
Sinaia	0	2	5	**13**	5	7	8	10	6	1	0	0	57
Păltiniş	0	1	7	9	7	**11**	8	10	3	2	1	0	59
Semenic	0	0	2	8	5	5	**10**	5	1	2	1	0	39
Băişoara	0	3	6	5	6	**8**	**8**	4	3	1	1	0	45
Fundata	0	0	4	**10**	6	6	8	9	2	1	0	0	46
Predeal	0	1	2	5	7	7	**8**	4	0	0	0	0	34

Source: Data computed from the NMA Archive.

The lengthiest monthly cold waves (16-21 days) were registered usually in January (Vlădeasa, Iezer, Rarău, Semenic, Băişoara and Fundata) and March (Omu Peak, Ţarcu Peak, Ceahlău-Toaca, Lăcăuţi, Sinaia, Păltiniş and Predeal) (Figure 3):
- *January*: between 19 days (Iezer, Semenic and Fundata) and 21 days (Vlădeasa, Rarău and Băişoara), especially in 1963;
- *March*: between 16 days at Păltiniş (1987) and 21 days at Ceahlău-Toaca (1995).

* The snow season corresponds to the interval of high snow pack persistence and thickness at over 1,000 m a.s.l., basically from the 1st of November to the 30th of April.

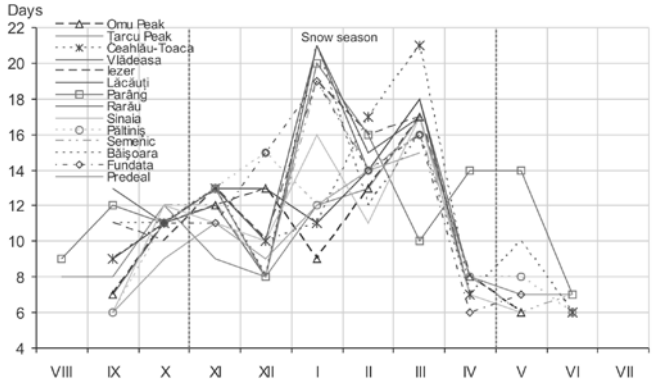

Fig. 3. ***Monthly maximum duration of cold waves in the Romanian Carpathians.***

In the warm period of the year, the monthly maximum duration of cold waves is generally shorter than 10 days during the calendaristic summer months, as well as in early autumn – September (with a few exceptions: Vlădeasa 13 days/1972, Iezer 11 days/1972, Parâng 12 days/1991, Cuntu 18 days/1999 and Băişoara 11 days/1972) and at the end of spring – May (with the exception of Parâng 14 days/1965). In general, at most stations, the monthly persistence threshold ($\geq$10 days) is often surpassed from October to March (Omu Peak, Ţarcu Peak, Ceahlău-Toaca, Lăcăuţi, Rarău, Sinaia, Păltiniş, Semenic and Fundata stations), September to March (Vlădeasa, Iezer, Parâng and Băişoara stations) and November to March (only at Predeal station), but over a less extended mountain area.

In the Romanian Carpathians, ***the most persistent cold waves*** (21 days) were registered in some mountain areas, exposed to dynamic air flows and cold air advections (arctic or polar), of the Eastern Carpathians (Ceahlău-Toaca/March 1995 and Rarău/January-February 1963), as well as in the windy ridge area of the Apuseni Mountains – Western Carpathians (Vlădeasa/January-February 1963) (Table 3). It is worth mentioning that those lengthy cold intervals occurred mostly in February and March in the particularly cold years of the study-period: 1963, 1985 and 1987.

The highest thermal negative deviations of minimum temperatures registered during a cold episode were -22.8ºC (Ţarcu Peak, 3.I.1979) (Tabel 3).

The lowest minimum temperatures during a cold episode showed massive cooling ($\leq$-30.0ºC) only at the weather stations located in the alpine belt of the Southern Carpathians (Ţarcu Peak, -34.4ºC/3.I.1979 and Omu Peak, -32.3ºC/18.I.1964) (Table 3).

Over the long-term observation period (1928-2011), at above 2,500 m altitude (Omu Peak station), the lowest minimum occurred in 1929 during a cold wave that lasted from January 31 to February 17, an interval in which the absolute thermal minimum record in all the Romanian Carpathians was recorded (-38.0ºC/10.II.1929), a value by only 0.5ºC lower than the absolute thermal minimum in this country.

Table 3. ***Main climatic characteristics of cold waves in the Romanian Carpathians***

Weather stations	Lengthiest cold wave		Highest negative deviation		Lowest minimum temperature	
	No. of days	Cold wave	ºC	Cold wave	ºC	Cold wave
Omu Peak	17	III.1987	-18.4	II.1965	-32.3	I.1964
Ţarcu Peak	17	III.1987	**-22.8**	**I.1979**	**-34.4**	**I.1979**
Ceahlău-Toaca	21	III.1995	-18.3	II- III.1982	-28.2	II.1962
Vlădeasa	21	I-II.1963	-19.3	I-II.1963	-25.9	II.1965
Iezer	19	I-II.1963	-18.0	II.1965	-29.0	II.1965
Lăcăuţi	18	III.1987	-17.1	I.1963	-28.7	I.1963
Parâng	20	I-II.1963	-17.7	II-III.1963	-25.5	XII.1967
Rarău	21	I-II.1963	-18.4	III.1987	-28.0	I-II.1963
Sinaia	17	III.1987	-17.5	II.1985	-26.5	I.1963
Păltiniş	16	III.1987	-17.9	I-II.1963	-24.0	I-II.1963
Semenic	19	I-II.1963	-16.6	II.1985	-24.5	I-II.1963
Băişoara	20	I-II.1963	-18.8	I-II.1963	-25.3	I.1964
Fundata	19	I.1963	-16.9	I.1963	-25.9	I.1963
Predeal	15	II.1987	-17.8	I-II.1963	-17.8	I-II.1963

Source: Data computed from the NMA Archive.

3.3. Cold wave duration variability and shifting years

The multiannual analysis has shown that cold waves had occurred more frequently in the 1961-1970 and 1991-2000 decades (7-21 cases and 9-28 cases, respectively). On the other hand, in the 1971-1980 and 1981-1990 decades (7-13 cases and 7-15 cases, respectively) and especially after 2000, the frequency of these extremes dropped to 5 cases/3 years (Figure 4).

In the decades when cold wave frequency was at its pek, large mountain areas were simultaneously affected, expecially in the extremely frosty or very cold months of certain years, e.g. January 1963, January and February 1985, March 1987 and October 1991. In many cases cold waves lasted only 3-5 consecutive days, even though the intensity criterion was met in terms of deviations from the normal (e.g. 18-21.I.1961, 3-8.III.1980, 13-17.II.1981). This supports the idea of such manifestations being associated with the natural variability of the mountain climate and not necessarily with some lengthy and severe cooling episodes of extreme climatic events.

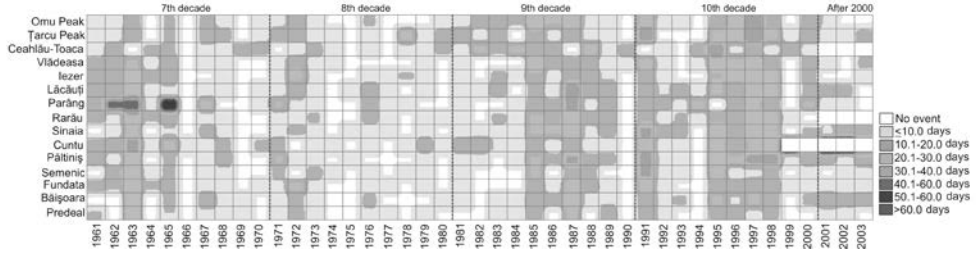

Fig. 4. ***Variability of the annual cold wave duration in the Romanian Carpathians.***

The annual duration of cold waves is one of the most suggestive variables of the extreme character of cooling episodes, being considered an indicator of extreme climate-related events worldwide (i.e. cold extremes). In order to investigate trends and rates of change, the non-parametric Mann-Kendall (MK) test

in the sequential version (Sneyers, 1992) and a regime shift indicator test (Pettitt test) were applied to the annual data.

Evolution trends in Romania, assessed for the 1961-2007 period (Busuioc *et al.*, 2011) indicate that cold wave duration is on the decrease, mainly in the Extracarpathian region where heat waves tend to last longer over the year. On the other hand, a shorter period of observations (1961-2003), which did not include the warm winter of 2006/2007, revealed a generalised annual increase of such extreme events (to over 20 and 30 days even) in the Carpathian region, due to the concentration of some cold years in the second half of the study-period (1985, 1987, 1991 and 1995-1998). However, looking at the rates of change in annual cold wave duration (less than 3.0 days/decade), increases appear to be significant (p-value<0.05) only in a few mountain areas of the Southern Carpathians (corresponding to Sinaia, Cuntu, Fundata and Păltinş stations). This variation trend was found also in the alpine belt stations, even though the rates of change were more reduced and not statistically significant (0.8-0.9 days/decade) (p-value>0.05).

At regional level, this aspect does not fully correspond to the observed trend of minimum temeprature evolution which, despite showing a slight increase (0.1-0.2ºC/decade), proved to be statistically significant only at half of the 15 weather stations studied (Iezer, Lăcăuţi, Cuntu, Semenic, Băişoara and Fundata).

Shifting years in the annual duration of cold waves (1961-2003) are visibly concentrated during the 1980s (covering the 1981-1985 interval), with only 1985 holding about 50% of shifting years cases (Vlădeasa, Lăcăuţi, Parâng, Rarău, Sinaia, Păltiniş, Fundata and Predeal stations) and even less in the tenth decade of the last century (1991/Semenic station and 1995/Ţarcu Peak, Iezer and Băişoara stations).

The long-term analysis of variability in cold wave duration at over 2,500 m altitude (Omu Peak, 1928-2011) indicates that this extreme event is less persistent over the year. Even though this finding is not statistically significant (p-value>0.05), it is a first signal of the local effects of climate warming in the high mountain region over the long period of observation, as evidenced by a minimum temperature rise at a rate of about 0.8ºC, significant for the 99% confidence level (Figure 5). Long-term temperature change signals revealed for Omu Peak site, where the climate is usually severe (cold, humid and windy) and unpredictable, could be viewed both as an elevation response to the observed warming process and a climate change indicator for all the alpine areas of the Romanian Carpathians.

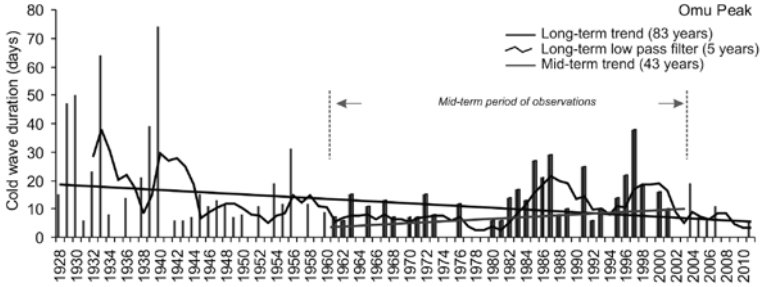

Fig. 5. ***Long-term (83 years) and mid-term (43 years) variability of cold wave duration at Omu Peak site (2,504 m).***

4. CONCLUSIONS

Altitudes in the Carpathian mountain region makes it prone to cooling. However, the frequency of massive coolings ($\leq$-30ºC) is fairly low in most of the mountain area (except for the alpine belt). The climatic specificity of the most severe cold waves that affected the Romanian Carpathians (1961-2003) consists in lasting persistence (at least 17 days), high negative thermal deviations (over 15-20ºC) and low minimum temperatures (under -25ºC).

In general, mountain areas below 1,500 m altitude are the ones most frequently affected by little and moderately persisting cold waves, while at over 1,700-1,800 m, although such cold episodes occur rather seldom they may persist for a long and very long time. These thermal extremes can be registered throughout the year, but more frequently in November and February (11-15 cases). In very cold or frosty months, cold waves rage simultaneously over very large areas of the Romanian Carpathians (e.g. January 1963, March 1987, October 1991 s.o.).

Even though medium-term trends (43 years) in cold wave duration variability show an increase, significant for some mountain areas in the Southern Carpathian forest belt, yet long-term records (83 years) made at the weather station situated at top altitude (Omu Peak) indicate a slight decrease. This would signal local-scale effects triggered by the general climate warming.

No direct or statistically significant relationship was noticed between the seasonal duration of cold waves, the length of the snow cover interval and the number of snow cover days. The negative extremes develop against the background of some very cold continental polar air pulsations in the north or east of Europe in the conditions of a dominant anticyclonic regime which generally does not stimulate precipitation, nor snowfall either. Noteworthy, years with lasting cold waves were generally associated with highly negative NAO phases. This would support the idea of a dominant synoptic causality of these cold extremes and implicitly their manifestation over large areas of the Romanian Carpathians.

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