eISSN 2082-8926
Leśne Prace Badawcze (*Forest Research Papers*),
December 2014, Vol. 75 (4): 367–374
DOI: 10.2478/frp-2014-0034

ORIGINAL RESEARCH ARTICLE

The effects of frost conditions on forest management based on the example of the July 1996 period at Hala Izerska in the Izera Mountains

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Abstract. This paper presents the characteristics of a frost episode that occurred July, 20–23, 1996 in the centre of the Izera Mountains and its effects on forest management. Source data consisted of air temperature measurements originating from the author's own and archival databases of the Institute of Meteorology and Water Management (IMGW), Voivodeship Inspectorate of Environmental Protection (WIOŚ), University of Wrocław (UWr) and the Bureau of Forest Management and Geodesy in Brzeg (BULiGL). The intensity, time of occurrence and effects of this particular episode were extreme. The estimated probability of frost in the centre of the mountain dale Hala Izerska in July at a temperature of -5.5°C two meters above ground level is 2.4%. Therefore, it can be stated that such a sharp decline of T_{min} in the middle of the growing season can occur in this area once every 40–50 years. Strong, nocturnal decreases of T_{min} below 0°C during the growing season occur in the Izera Mountains almost every year, causing significant damage to silviculture. The interior of the Izera Mountains, represented by mountain dale Hala Izerska, is one of the coldest or even the coldest site in Poland in terms of absolute minimums of air temperature during the growing season.

In the mountain areas, knowledge of the impact of climate, such as thermal factors, on tree stands enables silviculture work to be optimised, ultimately allowing funding to be rationalised. The distinct climatic conditions of mountain basins and valleys, slopes and plateaus located at similar altitudes need to be considered.

Key words: frost, growing season, damage to forests, the Izera Mountains

1. Introduction

Climatic conditions impact forest ecosystems in many ways. The main meteorological factors causing abiotic injury to forests include: strong wind, heavy snowfall, drought, extreme drops in air temperature, and icing or hard rime.

The issue of forest damage from atmospheric factors has been presented in many studies (Zajączkowski 1984, 1991; Mikułowski 1998, 2002, Urban 2002, Urban et al. 2000, 2005, 2011; Zachara 2006; Gil and Zachara 2006; Zachara et al. 2007). In forests, aside from the most common and most spectacular damage caused by wind and snow, other factors also result in significant economic loss in forestry, such as when air temperatures drop below 0°C during the growing season.

Extreme temperatures are an important factor affecting the ecological conditions in mountain ecosystems, particularly the lowest temperature occurring at different times of the year. Plants, including relatively resistant spruce trees, can suffer damage from low air temperatures during the growing season quite quickly – within several hours. This particular type of weather is formed by high-pressure systems, with radiational cooling of the ground and lower atmosphere layers. Such weather conditions are associated with specific synoptic situations and terrain morphology, which will be described later in this paper.

Received 16 April 2014, accepted after revision 25 June 2014.

While taking weather measurements in 1995 in the Izera Mountains, the air temperature dropped many times below 0°C at a height of 2 m above ground level.

One of the most significant summer frost occurrences, in terms of damage to reforesting work in the Izera Mountains, was the episode of July 20–23, 1996. In view of its extraordinary character (intensity) in terms of the sharp air temperature drop and time of year (middle of the growing season), this frost episode should be fully documented and related to areas beyond the Izera Mountains.

2. Study area

The Izera Mountains comprise the western extremity of the Sudetes Mountains, characterised by an exceptionally extensive area of flat-topped mountains over 800 m above sea level. In contrast to other Sudetes ranges, the higher regions of the Izera Mountains are not dissected by river valleys, which are wide and shallow here, and in many intermontane locations, have the characteristics of an extensive, high-altitude intermontane basin, as exemplified by the vast mountain dale Hala Izerska. The Hala Izerska occupies an area of approximately 400 ha and is found at an altitude of 820–880 m above sea level (ASL). The morphology of the terrain and the Jagnięcy Potok (JP) weather station are shown in Photograph 1.

The specific features of the Izera Mountain terrain (a more detailed description is provided below) favour exceptionally strong and frequent thermal inversions, which are related to intense frosts that are particularly dangerous for tree stands during the growing season.

After the frost of July 1996, more than 50% of spruce plantings were damaged in the forests of Świeradów and Szklarska Poreba, and in extreme cases – at intermountain valley floors – up to 90% (BULiGL 1998, 1999, photographs 2 and 3). The inversion layer with a very low ambient T_{min} was so intense that the apical shoots of spruce were damaged even at a height of 2 m above ground level. Damage also extended to the outer crown shoots of mature (decades old) spruce trees, which were already dwarfed (bushy) due to the almost annual dam-age caused by frost.

Intense minimum air temperature drops below 0°C in the middle of summer are very disruptive to the vital functions of forest ecosystems. Damaged and weakened tree stands are more susceptible to the effects of biotic factors, which in turn can lead to complete die-off.

Photograph 1. Radiation fog at mountain dale Hala Izerska, the Jagnięcy Potok measurement station (825 m), view towards direction North-North-West (photograph by G. Urban; June 4, 1999).

Photographs 2 and 3. Damage to spruce trees after the frost episode of July 20–23, 1996, at mountain dale Hala Izerska in the Izera Mountains, near the estuary of Jagnięcy Potok (photograph by M. Sobik, August 1, 1996).

3. Source data and methods

The analysis was based on the results of measurements of air temperature I collected in the Izera Mountains for a study conducted by the Department of Meteorology and Climatology, University of Wroclaw (ZMiK UWr 1995–2000). In addition, meteorological data for July 1996 were used from the weather station of the Institute of Meteorology and Water Management (IMGW) and from the Voivodeship Inspectorate for Environmental Protection (WIOŚ) in Jelenia Góra (JG), located in the Izera Mountains and their vicinity. Data from these stations provided the situational background and the opportunity to verify and supplement my own measurements. The spatial distribution of the measurement stations used in this study and the characteristics of their locations are illustrated in Figure 1 and Table 1.

Analysis of the barometric and weather conditions in Europe and Poland, with particular emphasis on the Izera Mountains region, was carried out on the basis of:

synoptic maps for the period of July 19–22, 1996, daily IMGW meteorological bulletins for July 19–23, 1996, the National Hydrological and Meteorological Service bulletin of IMGW for July 1996, diagrams and data from weather balloon soundings for Wroclaw and Prague, and information from the following websites: www.knmi.nl, www.imgw.pl, www.chmi.cz, www.weather.uwyo.edu.

Indispensable data on the extent of damage in the tree stands were obtained from the Bureau of Forest Management and Geodesy in Brzeg (BULiGL, 1998 and 1999).

I defined the probability of a frost occurrence in July at mountain dale Hala Izerska with a daily T_{min} equal to -5.5°C, the lowest recorded temperature during the frost episode under study. The probability was calculated based on available July daily T_{min} data for four years: 1998, 1999, 2004 and 2006. It was found that the level of T_{min} is subject to a normal distribution with the following parameters: mean equal to 6.68°C and a standard deviation equal to 3.842°C. This was established with the use of the Chi-square test of compatibility. The calculated probability was 2.4%, providing a repeatability rate for the phenomenon of every 40–50 years.

4. Results and discussion

4.1. Meteorological and morphological conditions of the weather episode of July 20–23, 1996

On July 20–23, 1996, Poland was in an area of high pressure with a North-East to South-West axis. An arctic air mass (AAm), characterised by low relative humidity and very clear skies, was associated with this baric system (with a very weak horizontal gradient of atmospheric pressure) and fostered intense thermal radiation from the ground, consequently resulting in very intense radiational frost.

The nature of the air mass was well reflected in data retrieved from the weather balloon above Wrocław on July 21, 1996 (Table 2). The data shows a barometric pressure of 925 hPa at 875 m ASL, which is the same height as the altitude of the mountain dale Hala Izerska; the air mass was relatively dry (relative humidity of 57%, a saturation deficit of 5.03 hPa, determined from psychrometric tables) with a wind speed of 4 m/s from the North (Table 2).

Table 1. Measurement stations in the Izera Mountains and surrounding area

Location of weather station	Abbreviation	Altitude [m ASL]	Operator*	Type of terrain
Jelenia Góra	JG	341	IMGW	Concave landform, JG Basin floor
Świeradów Zdrój	ŚW	543	IMGW	Convex landform, hilltop with a North-East exposure, about 80 m above the Kwisa Valley floor
Szklarska Poręba	SP	650	IMGW	Concave landoform, lower N portion of Szrenica slope, right side of the Kamieńczyk Valley, about 20 m above the Kamieńczyk stream bed
Rozdroże Izerskie	RI	770	WIOŚ	Convex landform, slope just above a broad open mountain pass connecting Wysoki Ridge and Kamienicki Ridge
Jagnięcy Potok	JP	825	ZMiK UWr	Concave landform, flood plain at mountain dale Hala Izerska, left bank of the Izera and left bank of the Jagnięcy Potok, about 100 m from these watercourses, about 3–4 m above the water level of the Izera, open, grassy area
Chatka Górzystów na Hali Izerskiej	CG	840	ZMiK UWr	Concave landform, lower part of the slope of the Izera Valley, open and grassy
Jakuszyce	JK	860	IMGW	Concave landform, in the vicinity of a broad mountain pass, right bank of the Kamienna River, flood plain
Szrenica	SZ	1332	ZMiK UWr	Convex landform, upper part of the slope WSW

*IMGW – Institute of Meteorology and Water Management, WIOŚ – Voivodeship Inspectorate of Environmental Protection, ZMiK UWr – Department of Meteorology and Climatology, University of Wrocław.

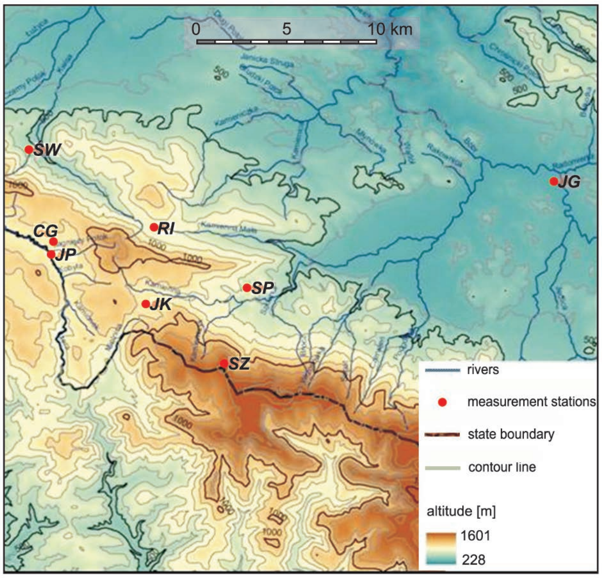

Figure 1. Location of measurement stations in the area. Key to abbreviations is presented in Table 1.

A vertical sounding of the atmosphere was also performed above Prague (Czech Republic, situated at an altitude of 305 m ASL on the other side of the Izera Mountains). It showed that the humidity parameters of the air mass at a barometric pressure of 925 hPa were similar to the readings from Wrocław (the saturation deficit determined from psychrometric tables reached 6.2 hPa). The mass was therefore relatively dry, which helped to radiate heat from the ground.

On July 21, 1996, the middle of the growing season, the recorded air temperature at a height of 2 m above ground level was −5.5°C at the JP measurement station, and below 0°C for the next 4 days. During those same days, in the stations where conditions were conducive to the formation of extended frosts, such as Jakuszyce (JK) or JG, minimum temperatures were a few degrees higher. However, the T_{min} at JK on July 21, 1996, fell below 0°C and amounted to −0.3°C (Figure 2).

An all-night radiational thermal inversion marked the course of this weather episode, clearly visible for the next four nights, between stations JP and Szrenica (SZ). The inversion also occurred between stations JG and SZ, but was of slightly shorter duration and weaker because it only lasted for a few hours of the last 3 nights – for 5, 2 and 4 hours respectively. The thermal inversion disappeared in the morning hours, while the decrease in air temperature as the height ASL increased was similar to the dry adiabatic lapse rate, that is, approximately 1.0°C per 100 m of increase in altitude (Figure 2).

Table 2. Data from a weather balloon above Wrocław on July 21, 1996, at the hour of 00:00 Coordinated Universal Time (UTC) [source: www.weather.uwyo.edu/upperair/sounding.html]

P	H	T	Td	U	Mixr	V	L
[hPa]	[m ASL]	[°C]	[°C]	[%]	[g/kg]	[m/s]	[0–360°]
1012.0	119	12.2	6.2	67	5.91	0	0
1001.0	211	11.8	6.,8	71	6.23	5	10
996.0	253	12.8	6.8	67	6.26	7	15
991.0	296	13.8	6.8	63	6.29	8	40
985.0	347	13.4	6.3	62	6.12	8	60
925.0	**875**	**9.4**	**1.4**	**57**	**4.60**	**4**	**5**
903.0	1073	7.7	0.7	61	4.48	3	40
850.0	1572	3.4	−1.0	73	4.20	5	355
811.0	1947	0.6	−2.8	78	3.85	5	25
792.0	2136	−0.8	−3.7	81	3.69	5	10
750.0	2570	−4.1	−5.8	88	3.32	6	40
723.0	2862	−6.3	−7.2	93	3.09	5.5	26
719.0	2960	−6.7	−11.6	68	2.20	5.5	24
707.0	3038	−4.5	−25.5	18	0.68	5	17
703.0	3082	−4.6	−25.6	18	0.68	5	15
700.0	3116	−4.7	−25.7	18	0.68	6	5

Key: P – atmospheric pressure, H – altitude, T – air temperature, Td – dew point temperature, U – humidity, Mixr – mixing ratio of water vapor, V – wind velocity, L – wind direction

It is worth noting that at the Rozdroże Izerskie (RI), also located in the interior of the Izera Mountains and only approximately 50 m lower than the JP site, the minimum temperature never fell below +5.0°C. On July 21, 1996, it reached a temperature of +5.4°C. It is clear that the terrain influenced the distribution of minimum air temperature. In the case of JP, the flat-bottomed intermontane basin favoured the formation of stagnant cold air, while the mountain pass at RI enabled the cold air to flow out and down the valley.

Based on the relationship of the minimum air temperature at heights of 2 m and 0.05 m above ground level with anticyclonic circulation at the Chatka Górzystów (CG) site of mountain dale Hala Izerska, the T_{min} at ground level on July 21, 1996, could have reached even −10.0°C (Urban 2002). The level of minimum air temperature recorded for July 20–23, 1996, at other IMGW measurement stations in Poland never dropped as low as the values obtained from the centre of the mountain dale

Hala Izerska at the JP station (Table 3). Even at the JG basin floor, at the JG synoptic station, where the absolute minimum air temperature of −36.9°C was recorded in Poland after World War II (Kuziemska 1983), the T_{min} for that day was +3.0°C (Table 3).

The key features of the Izera Mountain terrain result in different climatic conditions than in the other ranges of the Sudetes Mountains. These include: steep slopes of high relative altitudes to the west and north; in the central part of the mountains, the presence of extensive, flat-bottomed depressions with very gradual decreases in altitude along their longitudinal axes, which in many places resemble broad intermontane basins. The enclosed depressions at altitudes of over 750 m ASL are a unique part of the Sudetes Mountain terrain (Migoń 1998).

During anticyclonal radiational weather conditions, the depressions in the higher regions of flat-topped mountains are places where cold air collects as it flows from the surrounding slopes, creating stagnant pools. These cold air pools play a significant role in shaping the ecology of plant communities. An additional factor favouring the development of the intensive radiational

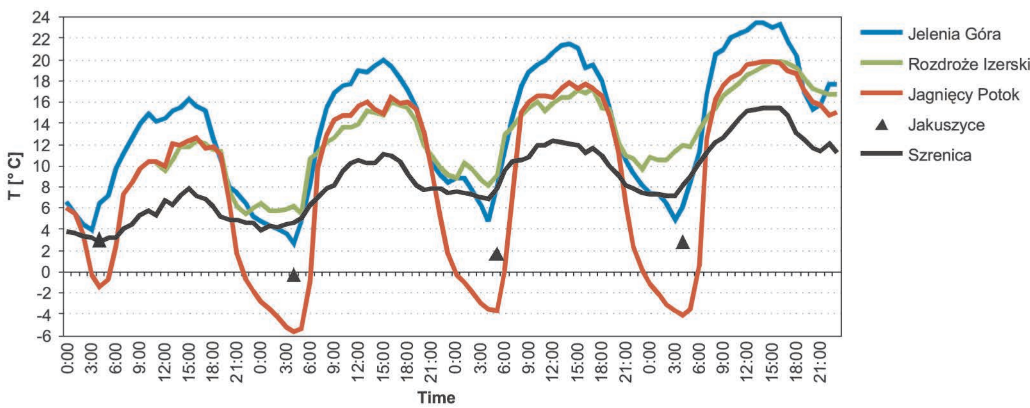

Figure 2. The daily course of air temperatures at selected measurement stations for July 20–23, 1996. Key to abbreviations is presented in Table 1.

Table 3. Minimal air temperature [°C] at a height of 2 m (T_{min}) and 0.05 m (T_{min+5}) above ground level at selected IMGW synoptic stations in Poland for July 20–23, 1996 [source: IMGW Daily Meteorological Bulletin]

Stations	July 20, 1996 T_{min}/T_{min+5}	July 21, 1996 T_{min}/T_{min+5}	July 22, 1996 T_{min}/T_{min+5}	July 23, 1996 T_{min}/T_{min+5}
Białystok	10/9	7/6	8/6	8/3
Jelenia Góra	4/1	3/1	5/2	5/2
Kasprowy Wierch	0/×	−1/×	4/×	1/×
Kłodzko	6/3	4/2	6/4	6/3
Lębork	13/13	12/10	4/1	7/4
Przemyśl	10/9	9/8	8/7	9/7
Resko	5/1	6/3	6/3	8/6
Siedlce	10/10	6/5	6/4	5/3
Suwałki	10/9	6/4	7/5	8/2
Śnieżka	1/×	2/×	5/×	6/×
Wrocław	8/6	6/3	9/5	7/4
Zakopane	7/7	4/3	4/4	4/2

× – measurements not taken

inversion was the extensive deforestation of the mountain uplands and slopes as a result of extremely detrimental environmental conditions. This facilitated the gravitational flow of cold air into the valley. Of equal importance is also the lack of settlements in the Izera Mountain interior, which in other areas – through emissions of home heating systems – helped to reduce nocturnal heat loss of far infrared radiation (Sobik 1998).

These factors cause frequent and intense thermal inversions, which, in the warm part of the year, are limited to nighttime and relate primarily to minimum temperature (T_{min}). During the cold part of the year, such temperature inversions are much more frequent, stronger and last longer; aside from the T_{min}, they also include mean daily temperature (T_i), and even the average monthly minimum temperature and monthly average, and occasionally also the maximum temperature T_{max} (Sobik and Urban 2000, Urban 2002). Due to the relatively small horizontal dimensions of the intermontane depressions, of which mountain dale Hala Izerska is an example, the air temperature is further reduced by the absence of the warming influence of foehns, important in the formation of thermal conditions on the northern slopes of the Karkonosze and the Izera Mountains, as well as the neighbouring, broad JG Valley.

In order to verify the frequency and intensity of temperature drops below T_{min} of 0.0°C in the middle of the growing season, an analysis was performed of available meteorological data near the centre of the Izera Mountains (1934–1938 German Meteorological Yearbook; IMGW, University of Wrocław). Temperature drops below T_{min} of 0.0°C at a height of 2 m above ground level occurred constantly in this area, but were not nearly as intense as in 1996. The lowest measured T_{min} in July at mountain dale Hala Izerska from the 1934–1938 records was −1.5°C in 1935; from 1972 to 2013 at the IMGW JK weather station, it was −0.7°C in 1976; and at the University of Wrocław measurement stations operating since 1995 (JP, Chatka Górzystów at mountain dale Hala Izerska), −5.5°C in 1996 at JP.

Temperature records have been recorded over the longest period of time – since 1972 – at the IMGW JK weather station, which has conditions similar to those in the centre of the Izera Mountains. The average annual air temperature in both locations is approximately 4.0°C. However, the average annual minimum temperature is lower, and the average monthly minimums are lower in almost every month in the centre of the mountain dale Hala Izerska, as recorded by the JP or CG measurement stations. The largest warm season differences in mean monthly minimum air temperature between JP or CG and JK is about 1.0°C, with a maximum in August and September of 1.4°C and 1.3°C respectively (Urban 2002). However, when anticyclonal weather occurs in the warm season (during which the differences are greatest), the daily T_{min} in the centre of the mountain dale Hala Izerska is usually distinctly lower than in JK – on average by approx. 2.0°C to 2.5°C. In the case of JP, the T_{min} is lower than in JK by up to 2.7°C. The maximum difference between the interior of mountain dale Hala Izerska and the JK station even reaches 10.0°C–11.0°C (Urban 2002).

To date, the T_{min} recorded at JK in July fell below 0.0°C only five times, in 1972, 1976, 1989, 1990, 1996. During the analysed frost episode of July 1996, the temperature measured was −0.3°C. In section 3, I noted that the calculated probability of a July frost in the centre of mountain dale Hala Izerska with a value of −5.5°C is 2.4%. Therefore, it can be concluded that such intense drops in air temperature in the middle of the growing season occur there approximately once every 40–50 years.

4.2. The significance of the July 1996 frost in the Izera Mountains

Lindkvist et al. (2000) performed similar measurements in Sweden as those conducted in the Izera Mountains. They conducted topoclimatic measurements in the mountains of southern Sweden at an altitude of between 500 and 1200 m ASL in July–August 1996 in similar terrain and climate. While a temperature of −5.5°C was recorded at mountain dale Hala Izerska in July 1996, the T_{min} in Sweden did not fall below −4.0°C, either in V-shaped or U-shaped valleys at a height of approx. 650–800 m ASL (Lindkvist et al. 2000). This fact, taking into account the advection of the arctic air mass from the north, can only emphasize the depth of the T_{min} drop in July 1996 at mountain dale Hala Izerska and intensity of this phenomenon, conditioned by the specific morphology of the Izera Mountains.

In southern Sweden, between June and September of 1994 and 1995, the lowest air temperature at 1.5 m above ground level was recorded in July at −3.2°C and in August at −9.2°C (at an intermontane valley floor), although the period of the lowest minimum temperature (from −10°C to −15°C) associated with radiation frost in this region is usually at the end of September, the end of the growing season (Lindkvist and Lindqvist 1997). Radiation frosts described by Lindkvist lasted an average of a few hours.

It should be noted that only a light frost (from −2 to −3°C) lasting about 3–4 hours in the middle of the growing season is needed to seriously damage and dehydrate the tissues of the trees constituting the main species of mountain forests (*Picea abies, Pinus sylvestris, Betula sp*.) (Lindkvist and Lindqvist, 1997; Weiser, 1970). On July 21, 22 and 23, 1996, the frost at mountain dale Hala Izerska lasted 6, 3 and 5 hours, respectively.

The spruce trees growing in the Sudetes Mountains are highly resistant to winter frost. During winter dormancy, they can withstand air temperatures of up to −40°C, but during the growing season, they are not so hardy and their resistance drops to between −3°C and −7°C (Mikułowski 1997a, 1998). Late spring frosts cause more damage than those in early autumn (Giertych 1977). One- and two-year-old spruce needles are most susceptible to frost in June. This species grows relatively slowly in its first years of life, reaching a height of 0.5 m at 5 years of age and 1–2 m at about 10 years of age (Mikułowski 1997a). Until then, it is particularly vulnerable to ground-level frosts.

According to Modrzyński (1989) and Mikułowski (1997b), frost and other abiotic factors almost completely eliminate spruce ecotypes already at the stage of cultivation that were transported from very different environment.

The analysis of topoclimatic conditions in mountains shows that lower altitudes ASL are often unfavourable for tree growth, due to, among other reasons, temperature inversions that lead to the formation of cold air pools in depressed terrain. Due to the higher average annual air temperature at lower hypsometric altitudes, trees planted there start to grow earlier than at higher altitudes, and thus are more sensitive to dramatic changes in air temperature, especially in areas where there is formation of cold air pools, than trees growing at higher locations (Mikułowski 1995ab).

5. Summary

The frost episode of July 20–23, 1996, presented in this paper was conditioned by the specific morphology of the terrain in the central part of the Izera Mountains (trough-like, high altitude deforested flat-topped mountains, with minimal decrease in longitudinal drop of altitude) and the physical properties of the air mass (dry, Arctic, very clear skies).

The extreme decline of T_{min} below 0°C at a height of 2 m above ground level in the centre of the Izera Mountains over many hours, occurring over 4 days and nights (with a minimum on July 21, 1996, of −5.5°C) at the height of the growing season resulted in huge losses in managed forests. It is estimated that this frost episode damaged about 90% of the tree stand area in the interior of the Izera Mountains. The minimum temperature measured at the weather station of −5.5°C is thus far the lowest recorded value for this area in the middle of summer.

The calculated probability of a −5.5°C frost in the centre of mountain dale Hala Izerska in July is 2.4%. Therefore, it can be concluded that such an intense drop in air temperature at the height of the growing season (middle of summer) occurs at this site on average once every 40–50 years or less.

The interior of the Izera Mountains, represented by mountain dale Hala Izerska, together with adjacent valleys, such as JP, is one of the coldest or even the coldest site in Poland in terms of absolute minimums of air temperature during the growing season.

In summary, the July 1996 frost episode in the Izera Mountains was an especially extreme event in terms of the time of occurrence and intensity. Extreme nocturnal drops of T_{min} below 0°C during the growing season occur in the interior of the Izera Mountains almost every year, causing significant damage to silviculture.

This review of the climatic, botanical and forestry issues of the Izera Mountains shows that studying thermal conditions, especially in areas prone to cold air pooling, may not only have cognitive significance in enriching our knowledge about the climate of the Sudetes Mountain and Poland, but may also have practical application.

Knowledge about the impact of climate on tree stands in mountain areas, including thermal factors, should enable silviculture work to be optimised, and ultimately, allow funding to be rationalised. This may include such activities as adjusting species composition and the spatial structure of stock renewal, selecting the right kind of planting stock, and – in areas threatened by summer frosts, that is, in the zones of the most frequent and coldest frosts, even abandoning afforestation. Most importantly, the distinct climatic conditions of intermontane basins and valleys, slopes and plateaus located at similar altitudes must be taken into consideration.

Acknowledgements

This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.

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