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# Air temperature as a determinant of the forest line in the Tatras

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## Abstract

The forest line has been widely studied by a number of scientists representing various research disciplines. Changes in its position are an indicator of climate change. However, despite numerous studies, it is not always known what has the greatest influence on the position of the forest line. In the Tatras, which are Alpine moun-tains, the position of the forest line in places not disturbed by human activity or slope processes mainly depends on the annual mean air temperature and the number of days with negative temperature and its value in the warm season. The most unfavourable thermal conditions are found at the bottoms of concave landforms, just above the forest line. This thermal barrier effectively limits the upward movement of the forest line, even if the average annual temperature increases. Small concave landforms may have a higher vertical temperature gradient and lower air temperature values at their bottoms than larger and higher-lying forms.

## Key words

forest line, air temperature, concave landforms, the Tatras

## Introduction

The forest line is not only of interest to foresters or, more generally, botanists, but also to researchers dealing with inanimate nature, for example geomorphologists and climatologists (Fabijanowski 1955; Myczkowski 1964; Pawłowski 1972; Balon 1991a, 1991b, 1995; Barry 1992; Heikkinen et al. 1995; Kotarba 1987; Krzemień et al. 1995; Piękoś-Mirkowa and Mirek 1996; Barber et al. 2000; Kirchhefer 2000; Becker and Bugmann 2001; Jodłowski 2007; Körner 2009; Lebourgeois et al. 2010; Jochner et al. 2018; Kelsey et al. 2018; Zhimova et al. 2019). The latter group of researchers, in particular, have closely followed changes in the position of the individual vegetation zones, including the forest line, as indicators of climate change. In the Holocene, the forest line changed its position many times, mainly moving upwards. However, the climatic conditions at the forest line are also strongly influenced by the landform (Guzik 2008). In his studies on the Polish part of the Carpathians, M. Hess demonstrated that differences in the annual mean air temperature between concave and convex landforms can be as high as 1ºC (Hess 1965, 1966, 1974). However, while M. Hess's calculations were made for large landforms such as the bottoms of basins or mountain valleys, the impact of small terrain forms on the forest line has largely been dis-



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regarded. Usually instances of local lowering of the forest line have been attributed to geomorphological slope processes or soil conditions. There has been no detailed research on the distribution of air temperatures either just above or just below the forest line.

In 1997, Baranowski began the first detailed study of variations in air temperatures within small landforms in the Dolina Suchej Wody valley in the Tatra Mountains. In his measurements, which continued for several years, the author focused on measuring extreme temperatures. The results of his research show that even small landforms of the order of less than 20 metres in size have a large impact on the air temperature inside these forms (Baranowski 2003a, 2003b).

In the warm season of 2007, based on the results of Baranowski's research, Kędzia carried out temperature measurements along the forest line in the area of Hala Gąsienicowa using digital data loggers with thermistors (Kędzia 2011). The results encouraged the authors to continue research using more recorders placed along a longer section of the forest line. The aim of this study is to investigate the relationship between air temperature and landforms and their influence on the position of the upper forest line.

## Material and methods

### Study area

The study area included the upper closed canopy forest line along the section from the Karczmisko Pass to the bottom of the Pańszczyca Valley in the Sucha Woda Valley (Fig. 1). The choice of the research area was guided by the presence of suitable landforms and

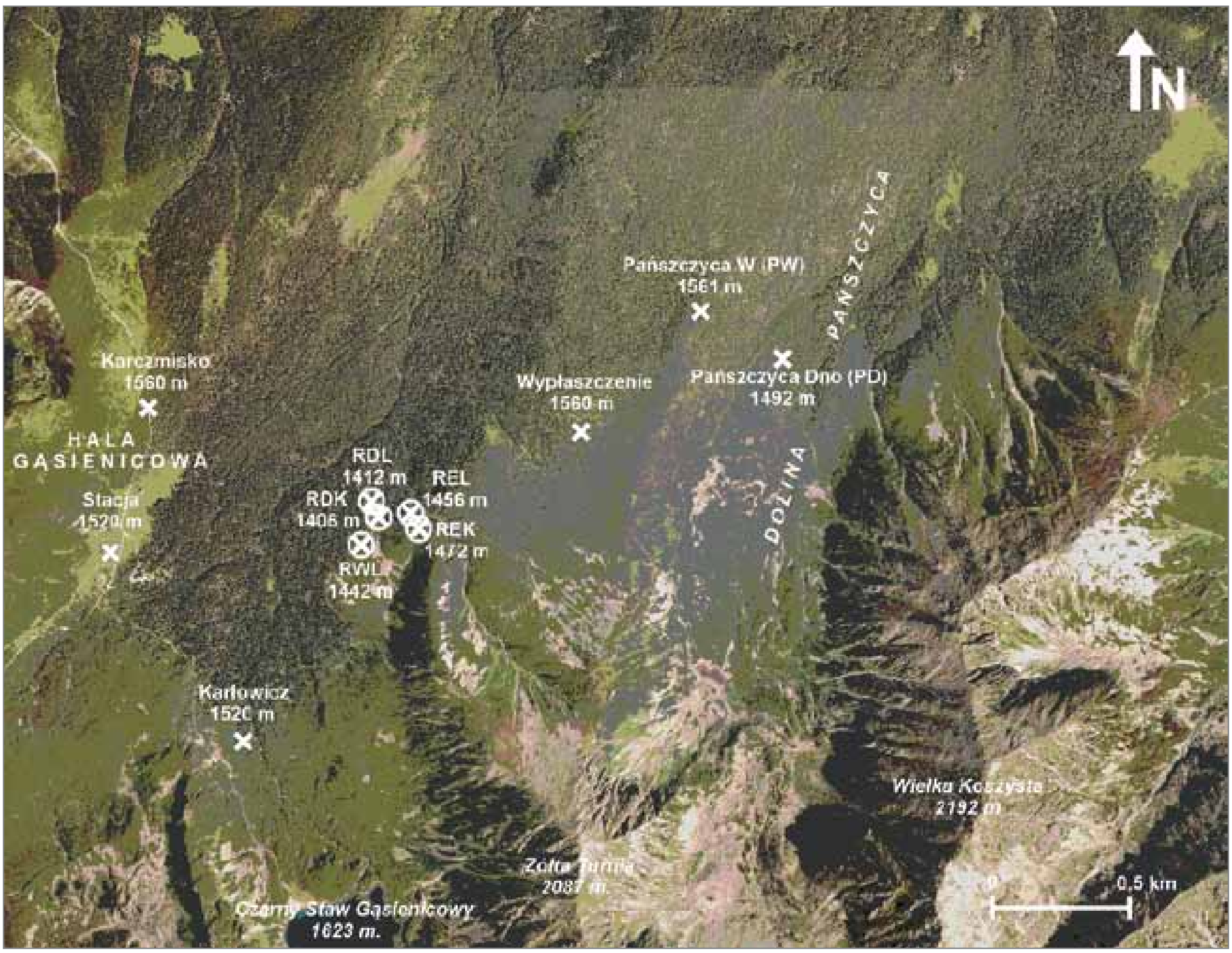


**Figure 1.** Position of the measuring sites in the Sucha Woda Valley in the Tatra Mountains in 2009–2010 (×) and in 2011 (○).

**Table 1.** Characteristics of the measuring sites

| Name of sites | Altitude [m a.s.l.] | Landform description |
|---|---|---|
| Karczmisko | 1560 | Upper closed forest boundary, convex SE-facing slope, forest site |
| Karłowicz | 1520 | Upper closed forest boundary, valley bottom with SN orientation, forest site |
| Wypłaszczenie -Flattening | 1560 | Upper closed forest boundary, non-fragmented slope with small inclination, NW exposure, forest site |
| Pańszczyca W (PW) | 1561 | Upper closed forest boundary, upper section of the western slope of the valley, forest site |
| Pańszczyca Dno – Pańczyca Valley Bottom (PD) | 1492 | Upper closed forest boundary, valley bottom with SN orientation, forest site |
| Rynna Dno Las – Gully Bottom Forest (RDL) | 1412 | Upper closed forest boundary, valley bottom on the slope, NW exposure, forest site |
| Rynna Dno Kosodrzewina – Gully Bottom Dwarf Mountain Pine (RDK) | 1406 | Upper closed forest boundary, gully bottom on the slope, NW exposure, dwarf mountain pine site |
| Rynna E Las – Gully E Forest (REL) | 1456 | Upper closed forest boundary, eastern edge of the gully, forest site |
| Rynna E Kosodrzewina – Gully E Dwarf Mountain Pine (REK) | 1472 | Upper closed forest boundary, eastern edge of the gully, dwarf mountain pine site |
| Rynna W Las (RWL) | 1442 | Upper closed forest boundary, western edge of the gully, forest site |

the distance from the Hala Gąsienicowa meteorological station, as well as by the degree of transformation of the forest line by humans. The forest line along the section under scrutiny, with the exception of Hala Gąsienicowa, has undergone so little change, that it could sometimes be disregarded. As a result of further surveys, the position of the upper forest line was not found to have been affected by any significant slope processes or soil-related conditions. During the period from 1 June 2009 to 31 May 2010, measurements were carried out at 8 points located within various landforms at altitudes ranging between 1412 and 1561 m a.s.l. (Tab. 1). The measuring points were located in places where the position of the upper forest line was not exposed to major and direct landform-related impacts, such snow avalanches, debris flows, landslides, etc. All measuring points had similar exposure to minimize the difference in solar radiaton (Buffo 1972; Zhimova et al. 2019). In addition to the 8 measuring points mentioned above, air temperature measurements were carried out at the Hala Gąsienicowa research station, which is located at 1520 m a.s.l. Since all the measuring sites over the above period were located below the forest line, it was decided that the measurements that were to follow in 2011 would be carried out both just below the forest line and beyond it, i.e. within the areas of dwarf mountain pine. The 2011 measurements were conducted in a concave landform knows as "Rynna" (gully or couloir) at 5 measuring sites. The measuring sites used in 2009–2010 and 2011 are described in Table 1. Out of the eight measuring sites used in 2009–2010, two were located in the bottoms of valleys, one in a small concave gully-shaped form, while the remaining five were situated on the mountainsides or slopes (Tab. 1).

The forest line along nearly the entire section under study is formed by spruce (*Piceetum myrtillosum*), with a small admixture of Arolla pine (*Pinus cembra*), mountain ash (*Sorbus aucuparia*.), and larch (*Larix decidua*).

### Measurement method

All air temperature measurements were carried out using digital HOBO Pro data loggers from Onset Computers which were fitted with thermistors and had a measurement uncertainty of ±0.2°C and resolution of 0.02°C. Before they were installed onsite, each logger was calibrated. The differences between the devices in question did not exceed 0.1°C. Measurements were carried out every 30 minutes on a 24/7 basis. Each logger was placed in a shield, which protected it from precipitation and direct solar radiation. At the forest measuring sites, the loggers were suspended at a height of 2 m under tree branches on the north side of the trunk and at a distance of at least 0.5 m from it. The loggers placed within dwarf mountain pine were mounted on thin aluminum masts (Fig. 2). The measuring points were distanced a dozen or so metres from the forest line. The coordinates of the measuring points were determined using Garmin Legend HCx GPS and Oregon 300 GPS devices. The coordinates of the forest measuring points may have a slightly larger error than the dwarf mountain pine sites.

**Figure 2.** View of the RDK measuring site

## Results

Figure 2 presents the relationship between the mean air temperature from twelve consecutive months (1 June 2009 – 31 May 2010) and the altitude and landform. Since the points were situated at different elevations, they were characterised by different temperatures, which results, *inter alia*, from their altitude. In order to eliminate variations in temperature resulting from different altitudes, all the measured temperature values were recalculated for the level of 1560 m (the highest point of the upper forest line along the section under study), assuming a drop in temperature with altitude of 0.6$^{o}$C/100 m. Figure 3 shows the differences in the elevation of the measuring points and variation in the average temperature as recalculated for 1560 m a.s.l.

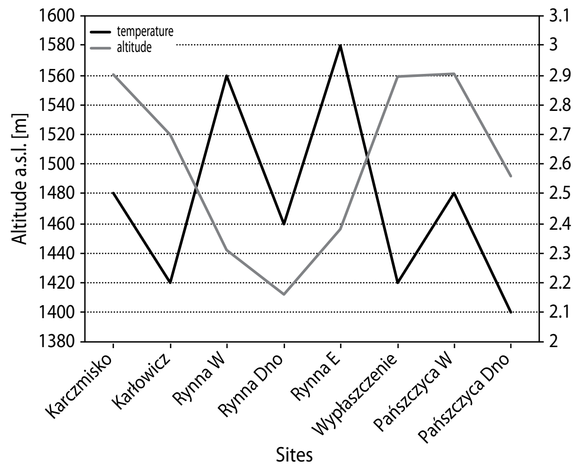


**Figure 3.** Relationship between the mean air temperature over twelve consecutive months and the altitude and landform

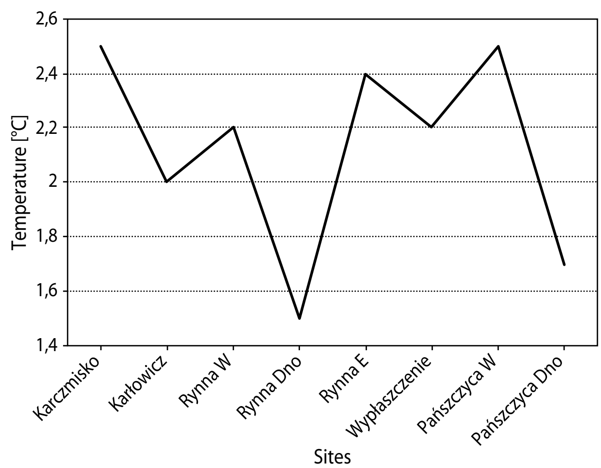


**Figure 4.** Mean air temperature over twelve consecutive months recalculated for 1560 m a.s.l.

When analysing the pattern of mean air temperature recalculated for the above altitude, there is a noticeable relationship between the measuring sites located in the bottoms of concave landforms and those situated on the slopes of the same (Fig. 4, 2), with the bottoms having a much lower temperature than the slopes. The differences in temperature range from 0.5 to 0.9°C. The smallest of the landforms, a gully known as "Rynna", is particularly interesting in terms of the distribution of temperature. Even though it is approximately 40 m deep, which is nearly half as deep as the deepest of the forms studied, namely the Pańszczyca Valley, the "Rynna" gully demonstrates the largest differences in temperature between the bottom and slope.

The sites within the "Rynna" gully lie at the lowest altitude of all the measuring locations and should have the highest daily mean air temperatures. Meanwhile, "Rynna" proved to be the coldest landform of all. The 12-month mean temperature recalculated for the common altitude of 1560 m was lower in its bottom (RDL) and on the slopes (REL and RWL) than on the bottoms and slopes of the other gullies.

Since the position of the upper forest line is not only influenced by the annual mean air temperature, the minimum temperatures and the temperature of the warmest months were also analysed (Tab. 2 presents the average minimum temperature, the average minimum temperature recalculated for 1560 m a.s.l., and the average temperature in June-August). As in the case of the 12-month mean temperature recalculated for the common altitude, the recalculated mean minimum temperature recorded at the bottom of the "Rynna" gully (RDL) also proved to be the lowest (Tab. 2). Its value was 0.6 – 0.7°C lower than in the bottoms of the other large concave forms, namely "Pańszczyca Dno" and "Karłowicz". As regards the average temperature of the hottest months, the lowest values were also recorded at sites located in the bottoms of concave forms, with the "Gully Bottom Forest" site having a temperature 0.3°C higher than the temperature at the bottoms of the other gullies: „Pańszczyca Bottom" and „Karłowicz".

Because previous studies of the distribution of air temperatures at the forest line had been conducted in the forest (just below its upper line), in 2011 the study was expanded to include measurements in dwarf mountain pine (just above the upper forest boundary). A concave form known as "Rynna" was chosen for the detailed study since it had recorded the greatest variations in air temperatures of all the measuring points used in the previous research. The sites are described in Table 1. Air temperature measurements were carried out in the period from 26.05.2011 to 24.10.2011.

The following figures show the characteristics of the daily mean, the mean maximum, the mean minimum as well as the maximum and minimum temperatures at five sites distributed across the "Rynna" gully

**Table 2.** Values of selected temperature parameters at the individual measuring sites

| Name sites | Karcz-misko | Karłowicz | Rynna W | Rynna Dno | Rynna E | Wypłasz-czenie | Pań-szczyca W | Pań-szczyca | Stacja |
|---|---|---|---|---|---|---|---|---|---|
| Altitude [m a.s.l.] | 1560 | 1520 | 1442 | 1412 | 1456 | 1560 | 1561 | 1492 | 1520 |
| 12-month mean temperature [°C] | 2.5 | 2.2 | 2.9 | 2.4 | 3.0 | 2.2 | 2.5 | 2.1 | 2.8 |
| Mean temperature recalculated for 1560 m [°C] | 2.5 | 2.0 | 2.2 | 1.5 | 2.4 | 2.2 | 2.5 | 1.7 | 2.6 |
| Mean minimum temperature [°C] | –0.7 | –1.3 | –0.3 | –1.2 | 0.3 | –0.8 | 0.0 | –1.0 | –0.3 |
| Mean minimum temperature recalculated for 1560 m [°C] | –0.7 | –1.5 | –1.0 | –2.1 | –0.3 | –0.8 | 0.0 | –1.4 | –0.5 |
| Mean VI, VII, VIII temperature [°C] | 11.1 | 10.6 | 11.4 | 10.9 | 11.3 | 10.5 | 10.8 | 10.6 | 11.5 |

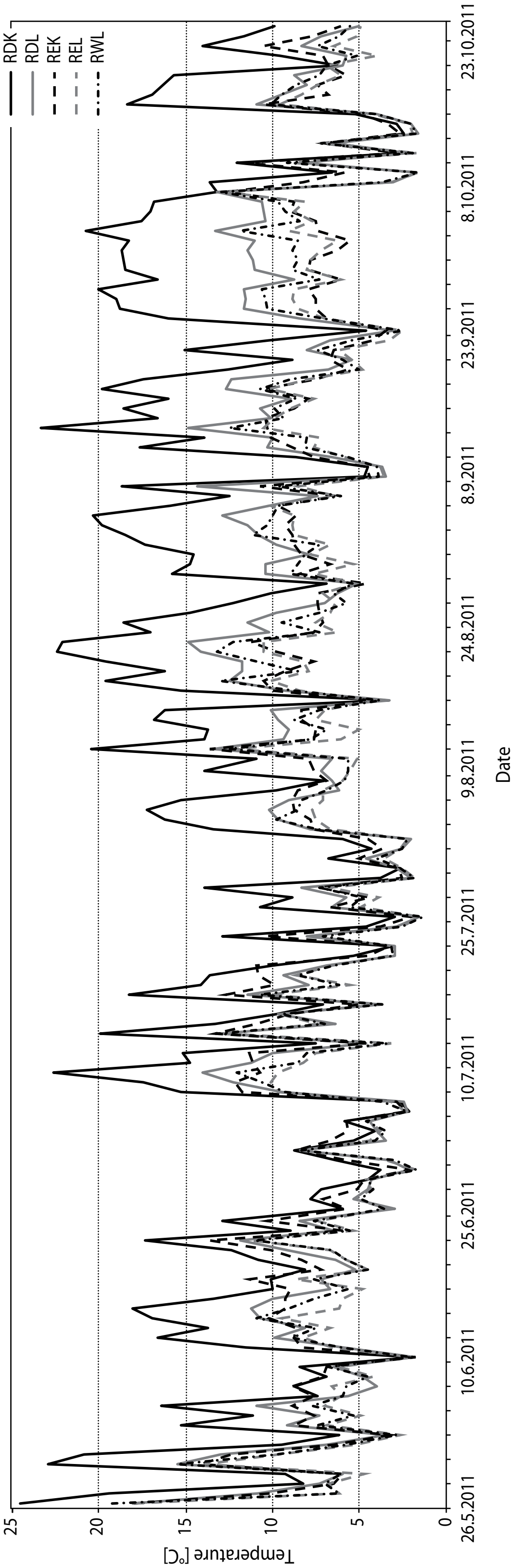


**Figure 5.** Daily mean air temperatures at individual sites within the "Rynna" gulley (Baranowski, Kędzia 2015 – modified)

(Fig. 5, 6). When analysing the values of these temperatures, it can clearly be seen that the site located at the bottom of the gully in dwarf mountain pine vegetation (RDK) observes the highest maximum and mean maximum air temperatures and the lowest minimum and mean minimum temperatures. The difference between the maximum temperature at the "Gully Bottom Dwarf Mountain Pine" (RDK) site and the other locations ranges from 3.4ºC to 6.2 ºC, while for the maximum mean temperature this difference is in the range of 2.2ºC – 3.2ºC. The same applies to the minimum temperature at this site – the difference is from 2.7ºC to about 4.5 ºC, while for the mean minimum temperature it is from 1.3 ºC to 2.9 ºC. The bottom of the gully, especially the dwarf mountain pine (RDK) site, is characterised by the largest air temperature amplitudes. Regarding daily mean temperature, the abovementioned sites are among the coldest ones, even though they lie from about 30 to about 60 m lower than the other sites (Tab. 1) and should be the warmest given the vertical distribution of temperatures. The daily mean air temperature value recorded there is 0.4 to 0.7 ºC lower than at the other locations (Tab. 2, Fig. 6). Such a vertical

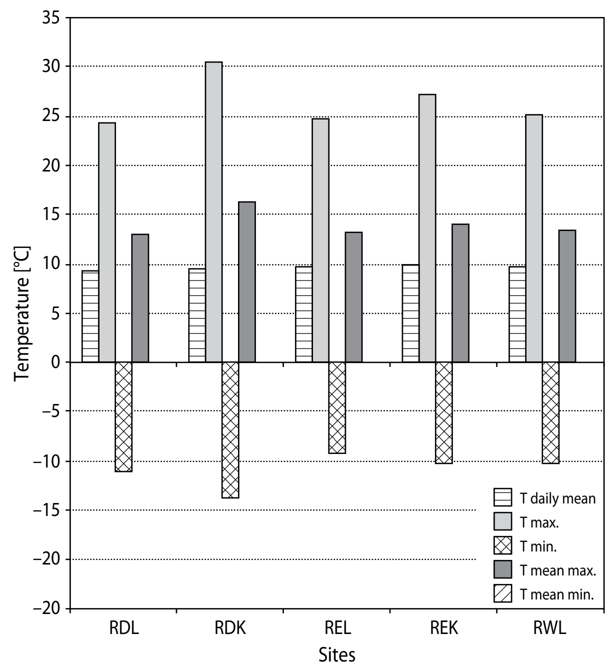


**Figure 6.** Daily mean, maximum and minimum mean, and maximum and minimum temperatures recorded at the measuring sites (Baranowski, Kędzia 2015 – modified)

**Table 3.** Selected temperature parameters at sites within the "Rynna" gully and at the Hala Gąsienicowa meteorological station

| Parameter | Sites | | | | | |
|---|---|---|---|---|---|---|
| | RDL | RDK | REL | REK | RWL | Stacja |
| Daily mean temperature [°C] | 9.2 | 9.4 | 9.8 | 9.9 | 9.8 | 9.9 |
| Maximum temperature [°C] | 24.3 | 30.5 | 24.8 | 27.1 | 25.2 | 29.5 |
| Minimum temperature [°C] | –11.1 | –13.8 | –9.3 | –10.2 | –10.3 | –11.2 |
| Mean maximum temperature [°C] | 13.1 | 16.3 | 13.2 | 14.1 | 13.4 | 15.7 |
| Mean minimum temperature [°C] | 5.1 | 3.8 | 6.7 | 6.4 | 6.2 | 5.5 |
| Number of days with minimum negative temperature | 16 | 29 | 15 | 15 | 16 | 19 |
| Share of days with minimum negative temperature [%] | 10.6 | 19.2 | 9.9 | 9.9 | 10.6 | 12.5 |

distribution of temperatures is proof of the frequent occurrence of inversion, despite the small size of the "Rynna" gully. Table 3 shows the number of days with a negative minimum temperature and the percentage of these days. At the site at the bottom of the "Rynna" gully in dwarf mountain pine (RDK), the number of days with a negative minimum temperature was about twice as high as at the other locations. Fig. 7 demonstrates at

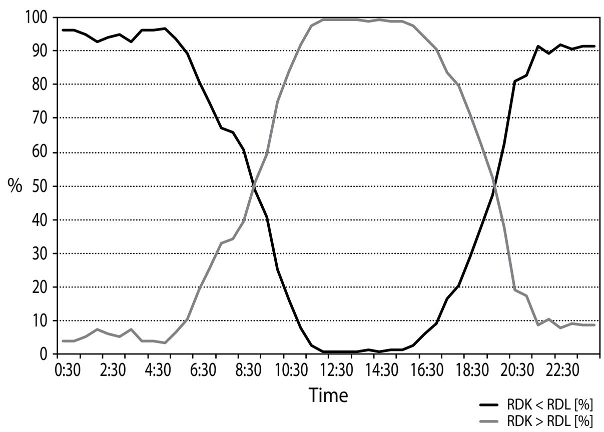


**Figure 7.** The percentage share of all measurements with the RDK site temperature lower than that at the RDL site and vice versa

which times of day the temperatures in the bottom of the "Rynna" gully in the dwarf mountain pine area were higher or lower than in the forest. At night, from about 21h.00 to about 5h.30, over 90% of the measurements revealed lower temperatures in the dwarf mountain pine than in the forest. In the summer, the situation was reversed. From around 9h.00, half of the measurements at the dwarf mountain pine site showed temperatures that were higher than those in the forest, and the other half – lower temperatures. From about 12h.00 to about 15h.30, nearly all the measurements indicated higher temperatures in the dwarf mountain pine zone than in the forest. Between 19.00 and 19.30, approximately half of the measurements showed higher temperatures in the dwarf mountain pine, and the other half in the forest. The percentage share of measurements indicating a higher temperature in the forest increased until 21h.00. The most noticeable differences in temperature between the sites in question at the bottom of the "Rynna" gully was recorded at times of high insolation, while the least pronounced were seen on cloudy and rainy days. Wind reduced the variations between the sites.

## Discussion

Measurements of air temperature carried out at eight sites along the forest line in the period from June 2009 to May 2010 reveal large variations between the landforms researched. The widest and at the same time deepest concave forms were not the coldest ones. The lowest mean temperature values for the 12-month period recalculated for the altitude of 1560 m a.s.l. were found in the bottom of the smallest and lowest form – "Rynna Dno" – gulley bottom (Tab. 2). This was also the case with the mean minimum temperature recalculated for the above elevation. This proves that the bottoms of large landforms do not necessarily have the lowest temperatures (Rosenberg et al. 1983; Saunders et al. 1998; Chen and Brosofske 1997; Dong et al. 1998; Chen et al. 1999; Oberhuber and Kofler 2000; Zhang et al. 2015). Smaller and lower-lying forms can be colder than larger ones situated at higher elevations.

The "Rynna" gully also stands out from the other concave forms by demonstrating the largest differences in temperature between the slopes and the bottom. Between the "Rynna Dno Las" (Gully Bottom Forest) site and the "Rynna W Las" (Gully W Forest) site, which is located on the upper part of the slope, the difference in the 12-month mean temperature was 0.5ºC with an elevation difference of only 30 m. Meanwhile, the difference in temperatures between the "Rynna E Las" (Gully E Forest) site, which lies on the other slope of the landform in question, and the bottom was 0.6ºC with an elevation difference of 44 m. Neither of the other two large concave forms recorded such great differences in temperatures between the bottom and the slope. For the "Pańszczyca" landform, the difference in temperature between the bottom ("Pańszczyca Bottom Forest") and the slope ("Pańszczyca W Forest") was 0.4ºC, but the difference in elevation amounted to 69 m. Meanwhile, the difference between the bottom ("Karłowicz") and the slope ("Karczmisko") in the other large concave form was 0.3ºC. The above results demonstrate that small concave landforms can not only be colder than large ones, but they can also have a much higher temperature gradient than the latter.

It is difficult to determine unambiguously the key underlying factor. For certain, the large inclination of the bottom and slopes accelerates the downward movement and pooling of cold air and the "Rynna" gully is characterised by the largest inclination of the bottom and slopes of all the landforms surveyed.

However, for fauna and flora the actual temperature, rather than that recalculated for a specific altitude, is of key importance. In this context, the differences in the mean and mean minimum temperature values between the bottoms of the landforms investigated are very small and amount to 0.3ºC, even though the differences in altitude reach about 150 m (Tab. 2). On slopes, the differences in the mean and mean minimum temperature between the landforms investigated are larger and fluctuate between 0.5ºC and 0.7ºC respectively, with a difference in elevation of about 120 m. The same is true for the average temperature of the warmest months. The difference between the bottoms is also 0.3ºC, while that between the slopes is up to 0.6ºC.

Although the landforms in question differ in size and their bottoms lie at different elevations, the differences in mean daily temperatures, the mean minimums and the means from the warmest months between the bottoms of the individual forms at the forest line are very similar. Even at the site located on the "Flattening", i.e. on a non-fragmented slope with a low inclination, the daily mean temperature is nearly the same as on the valley bottoms (Tab. 2). The above measurement results justify the conclusion that in the bottoms of valleys and on non-fragmented slopes, the forest line is strongly related to temperature. The 12-month temperature average for all the sites (on the valley bottoms and slopes) is 2.2ºC. Given that the mean air temperature in the 12 months analysed was 0.4ºC higher at the Hala Gąsienicowa meteorological station (Tab. 2) than the annual mean of 2.4ºC (as calculated for 1952–1961 by Hess 1965 and for 1980–1999 by Błażejczyk et al. 2013), it can be concluded that the annual mean air temperature at the forest line in the bottoms of valleys and on non-fragmented slopes is 1.8ºC. This is 0.2ºC lower than the value calculated by M. Hess (1965) for the upper forest line in the Tatras.

The situation on the slopes of the valleys included in the study is slightly different. The 12-month temperature averaged for all the sites on the slopes is 2.7ºC. After deducting 0.4ºC, i.e. the value by which the temperature at the Hala Gąsienicowa weather station was higher than the long-term one, we get 2.3ºC, which is the long-term mean temperature at the forest line on the slopes of valleys. This raises the obvious question of why the annual mean temperature at the forest line on the slopes of valleys is higher than the annual average temperature at the forest line on the bottoms of valleys and on non-fragmented slopes?

To answer this question, reference should be made to research carried out from 26/05/2011 to 24/10/2011 in the smallest of the previously studied landforms, namely the "Rynna" gully. The measuring sites in the gully were located not only in the forest just below the forest line, but also in dwarf mountain pine just above the forest line (Tab. 3). When analysing the results of the measurements presented in Table 3, it can be seen that the measuring point in the bottom of the "Rynna" gully clearly stands out. The temperature values recorded here are the most extreme, both as regards the daily mean, maximum, and mean maximum temperatures, but also as regards the minimum and mean minimum temperature. The greatest difference between the site in question and other locations is observable for the number of days with a negative minimum temperature. While at the remaining sites the number of days with a negative minimum temperature ranges from 15 to 16 days, the dwarf mountain pine site at the bottom of the "Rynna" gully sees nearly twice as many such days, i.e. 29, which represents 19.2% of the measurement timespan. Considering that the measurements were carried out exclusively in the warm period of the year, i.e. they covered the vegetation period, such a high number of days with negative temperatures and with such low temperature minima obviously affects the position of the upper forest line. To sum up, it can be concluded that the most adverse thermal conditions occur at the bottoms of concave forms, just before the upper forest boundary. Therefore, at the forest line, the bottoms of concave landforms record lower annual mean air temperatures than on the valley slopes or non-incised slopes at the forest line.

## Conclusions

Air temperatures and the vertical temperature gradient recorded in concave landforms do not necessarily correspond to the altitude of the landform and its size. Small concave landforms may have a higher vertical temperature gradient and lower air temperature values in their bottoms than larger and higher-lying forms. Most likely, this is attributable to the inclination (of the bottom and slopes), which influences the rate of downward movement and pooling of cold air.

The position of the forest line (the upper borderline of closed canopy forest) depends mainly on the annual mean air temperature and the number of days with a negative temperature and its value in the warm season. The most unfavourable thermal conditions prevail at the bottoms of concave terrain forms, just above the forest line. This thermal barrier effectively limits the potential for the forest line to migrate up the slope, even when the average annual temperature increases.

The upper boundary of closed canopy forest aligns with the 2ºC isotherm, i.e. the value that M. Hess determined for the Carpathians in 1965. At the bottoms of valleys and on non-fragmented slopes, the forest line runs slightly below the 2ºC isotherm, while on the slopes of valleys it runs slightly above it.

Any conclusions regarding the position of the upper forest line based on interpolation and extrapolation of temperature data from meteorological stations without measurements of temperature on the actual landforms (slopes, bottoms and sides of concave landforms regardless of their size) are not justified because they involve interpolation and extrapolation errors that are too high, and do not take into account changes in temperature depending on the landform.

There is a need for further research on the relationship between the microclimate, landforms, and the position of the forest line.

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