



# Changes and variability of the physiological air humidity deficit index at Kasprowy Wierch (1971-2020) and the impact of atmospheric circulation

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**Abstract.** The paper examines changes and variability of the physiological air humidity deficit index (D) at the summit of Kasprowy Wierch in the period 1971-2020. The analysis comprised annual and long-term patterns of the average values, absolute minima and maxima, and the number and share of days with a perception of comfort and dryness. The conditional probability of the occurrence of conditions of perceptibility of air humidity for different air masses was calculated. The highest values of the D index occur at Kasprowy Wierch in winter, the lowest – in summer. The average, maximum and minimum values of the D index in the long-term distribution show a negative trend on an annual basis. Perception of humidity comfort occurs from April to October, peaking in August. Occasionally, days with index values interpreted as sultry do occur. In the long-term period covered in the study, the share of days with perception of physiological comfort of air humidity increases significantly, while days perceived as dry decreases significantly. The conditional probability of perceiving dryness in the air is the highest during the advection of arctic air over southern Poland. For comfortable air humidity it is highest when tropical air passes over southern Poland.

The high parts of the Tatra Mountains are unaffected by local anthropogenic impacts. Nevertheless, significant trends in the biometeorological index are observed, linked to air humidity conditions, which are a consequence of global climate change.

**Keywords:** bioclimatology, physiological air humidity deficit, Kasprowy Wierch, climate change.

## Introduction

Physiological air humidity deficit, as one of the bioclimatic indicators, is an interesting issue, especially in areas used for tourism and winter sports, such as Kasprowy Wierch. It is a place with unusual bioclimatic conditions mainly due to its location at high altitude and the features of the mountain climate.

Air humidity is studied by meteorologists and climatologists in a wide range of fields, including the analysis of long-term trends in the era of climate change. The trends of changes in air humidity in Poland coincide with the global trends, which are considered in many respects (Elliott, 1995; Mieruch et al., 2008; Wypych, 2021). Specific humidity increases with increasing air temperature; it is characterized by a positive trend in Central Europe (Wypych, 2021), in tropical latitudes and in the whole Northern Hemisphere (Willett et al., 2013). Relative humidity has been decreasing since the latter half of the 20th century, especially in south-eastern Poland. The lowest values of relative humidity in the annual distribution were observed in spring and summer (Wypych, 2021).

Bioclimatic conditions have been the focus of climatologists' interest for many years. Climate affects human functioning every day, all over the Earth, so it is worthwhile to explore these issues and endeavour to explain the correlation between climate and human health and well-being, i.e. the impact of climate on the human body. Bioclimatic conditions in the territory of Poland are already reasonably well comprehended, analysed e.g. by Błażejczyk (2006). A number of monographs and articles have been published showing the spatial variability of these conditions across the country (Kozłowska-Szczęsna et al., 1997; Arażny & Smukała, 2011; Kuchcik et al., 2021). The authors focused on various issues related to bioclimatology and biometeorology. Kozłowska-Szczęsna (1987) described the four types of bioclimate found in Poland and additionally created a corresponding map. An interesting aspect for Polish researchers is the bioclimate of Polish spas; this subject was addressed by Błażejczyk (1983), Kozłowska-Szczęsna et al. (2002), and Błażejczyk & Kunert (2011). They described spas located in different regions of Poland and their bioclimatic potential for health resort patients. There have also been detailed studies on bioclimatic conditions in Polish cities, including Poznań (Pótrolniczak et al., 2024), Wrocław (Sikora, 2008), Warsaw (Błażejczyk, 2002), Kraków (Matuszko & Piotrowicz, 2007), Lublin (Dobek & Krzyżewska, 2015) and some cities in the Baltic Coast region (Pótrolniczak et al., 2016).

Areas with particularly high variability in bioclimatic conditions include the Carpathian Mountains. When seen from the perspective of the climate severity index, the bioclimate of the Carpathians is characterised by an increase in the occurrence of conditions conducive to the cooling of the human body along with altitude. At Kasprowy Wierch there are 'severe' and 'very severe' conditions throughout the winter period. The 'very severe', 'severe' and 'extremely severe' conditions prevail, especially in December (80% of days). From November to March, 'severe' conditions are most common, with maximum frequency in December (38% of days) (Twardosz, 1994). A study of the bioclimate of the Tatra Mountains in terms of the subjective temperature index (STI) was conducted by Pelech (2013). With increasing altitude, there is a decrease in the number of thermal sensation classes, with 6 in Zakopane and 4 at Kasprowy Wierch. The most common sensations are 'cool' and 'cold'. The least favourable conditions are at the top of Kasprowy Wierch where the sensation of 'cold' in winter covers 70% of days. The highest STI value recorded at Kasprowy Wierch is 49°C ('hot').

From the perspective of recreation, the bioclimate of the Carpathians is the most favourable in the altitude range from 500 to 750 m asl (Obrębska-Starkłowa, 1997). A moderately stimulating bioclimate determines the optimal conditions for the average Polish tourist regardless of their age. The climate stimulating impact factor K for Kasprowy Wierch had the highest and therefore most stimulating values in 1951-1970, from March to May, as well as in September and October. In June and July, middle-ground values between those strengthening and moderately stimulating were observed (Obrębska-Starkłowa, 1997). Climatic and bioclimatic conditions of the Hala Gąsienicowa valley in the Tatra Mountains were described by Błażejczyk et al. (2013). They demonstrated that the climate and weather conditions there are highly variable from day to day. Field studies on climate and physiology show that mountain treks are more strenuous in winter than in summer due to the weight of warm clothes and the fact that some sections of the trails are snow-covered, which means that more caution should be exercised.

Studies of bioclimatic conditions of mountain areas in Poland typically concern the thermal characteristics of the air with much less emphasis on the air humidity condi-

tions. The aim of this study is to present the current status and the long-term changes in the physiological air humidity deficit index (D) at the summit of Kasprowy Wierch (Tatra Mountains) while distinguishing thresholds of perception of air humidity. In addition, an endeavour was made to explain the impact of atmospheric circulation on the different conditions of perceptibility of air humidity. The D index is an indicator of the amount of evaporation from the human upper respiratory tract and lungs. It is particularly important in low-temperature areas where the risk of dehydration due to excessive evaporation from the respiratory tract is very common. In high mountain areas respiratory heat loss (related to breathing) is greater than radiative loss (caused by longwave radiation from the human body; Krawczyk, 1993). According to the bioclimatic regionalisation carried out by Kozłowska-Szczęsna et al. (1997), Kasprowy Wierch belongs to Region VI – Foothill and Mountainous Areas which is characterised by a great diversity of bioclimatic conditions and a strong stimulating impact. Knowledge of changes in air humidity conditions, including D index in the summit parts of the Tatra Mountains, seems to be of great practical importance for tourism, trekking and skiing.

Research on the D index has been undertaken by a relatively small group of researchers, who have analysed its changes and variability in different areas, e.g. in the Norwegian Arctic (Araźny, 2005; Przybylak & Araźny, 2005) or in the south-east of Poland (Lesko; Wereski & Wereski, 2012). The studies on the D index in the Norwegian Arctic have shown that the perception of humidity comfort occurs in the area in summer and very rarely in autumn. Most often, i.e. throughout the year, a sensation of dryness is experienced. The most favourable perceptions of humidity are observed in summer during the advection of air masses from the southern sector. The least favourable situation occurs in winter during the advection of air masses from the north-eastern sector (Araźny, 2005). Maps showing the average values of the D index throughout Poland in the years 1961-1970 in January and July were included in the publication by Kozłowska-Szczęsna et al. (1997).

## Data and methods

The study period covers 50 years, 1971-2020 and concerns daily data recorded at 12:00 UTC at the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) station located at the summit of Kasprowy Wierch (h = 1991 m asl, 49°14'N and 19°59'E). Meteorological data were obtained from the public synoptic data of the IMGW ([https://danepubliczne.imgw.pl/data/dane\\_pomiarowo\\_obserwacyjne/dane\\_meteorologiczne/terminowe/synop/](https://danepubliczne.imgw.pl/data/dane_pomiarowo_obserwacyjne/dane_meteorologiczne/terminowe/synop/)). The time 12 UTC is often included in biometeorological studies as the baseline time point at which significant human activity is recorded (Krawczyk, 1993; Pórolniczak et al., 2024). At the summit of Kasprowy Wierch the highest number of tourists and skiers is precisely during the midday hours throughout the year.

Physiological air humidity deficit index (D) is an indicator of the amount of evaporation from the human lungs and upper respiratory tract. It was calculated according to the formula given in the monograph by Kozłowska-Szczęsna et al. (1997) as the difference between the saturated vapour pressure at 36.5°C (E), which equals 61.0 hPa, and the current vapour pressure (e):

$$D = E_{36.5^{\circ}\text{C}} - e$$

Three degrees of perception of humidity are distinguished, i.e. sultry (<45 hPa), pleasant/comfortable (45-53 hPa) and dry (>53 hPa) (Kozłowska-Szczęсна et al., 1997).

The data collected were complete. Three cases were found in the series where the water vapour pressure at 12:00 UTC was 0 hPa. These cases were controlled by comparison with values of adjacent hours of the day. On 16th January 1982 the adjacent values were close to or equal to 0 hPa. On 8th November 1982 the values before 12:00 UTC were equal to 0.5 hPa (6:00 UTC, 9:00 UTC) while after 12:00 UTC they were already 3.1 hPa (15:00 UTC) and 4.7 hPa (18:00 UTC). Similarly, on 6th December 1986 the values before remained at approx. 0-1 hPa (6:00 UTC, 9:00 UTC) while those after 12:00 UTC were 4.3 hPa (15:00 UTC) and 5.2 hPa (18:00 UTC). After such a detailed analysis, it was concluded that these values were correctly measured and recorded in accordance with the actual state of affairs. So, it was decided to take them into consideration in this analysis.

The following features of the D index were investigated: the annual distribution of the average value, the absolute maximum and the absolute minimum; the long-term course of the annual average, the annual absolute maximum, the annual average value of the monthly maxima, the annual absolute minimum, the annual average value of the monthly minima; the percentage of days with dryness (Ddry) and humidity comfort (Dcomf); the annual distribution of the monthly average number of days with dryness and humidity comfort.

The linear trends of the average, the annual average of the monthly maxima and the annual average of the monthly minima of the D index values were examined, as well as the number of days with a perception of humidity comfort and dryness from May to October. Their statistical significance was determined for a significance level of 0.05.

The *calendar of circulation types* by Niedźwiedź (2002, 2024) designed for southern Poland was used. Based on it, the conditional probabilities of the occurrence of conditions of perceptibility of air humidity at different air masses and circulation types were calculated. The conditional probability was calculated according to the method applied by Twardosz & Niedźwiedź (2001) as a quotient (expressed as a percentage) of the number of days with a particular condition of perceptibility of air humidity with a particular air mass and the total number of days with the occurrence of that air mass in the whole period of the study.

In the last part of the study, the conditions described by the D index at Kasprowy Wierch were compared with the conditions at the foot of the Tatra Mountains (in Zakopane) and on the peaks of the Karkonosze Mountains (Śnieżka) for two years: with the highest and lowest average annual value of the D index at Kasprowy Wierch in the period 1971-2020 (1978 and 2018, respectively).

## Results

The average annual value of the D index in the period of the study at Kasprowy Wierch is 55.1 hPa, which characterises the average conditions as dry air. The lowest values occur in July (an average of 51.1 hPa) and August (an average of 51.0 hPa), and the highest in the winter period, i.e. in January (58.1 hPa), February (58.0 hPa) and December (57.7 hPa) (Fig 1a). In the cold part of the year (October to May) the monthly average values of the index are within the range of perception of dryness (above 53 hPa), only from June to Sep-

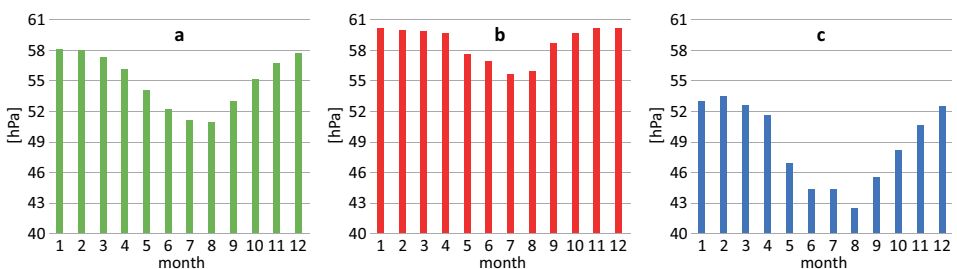
tember the averaged values belong to the range of perception of humidity comfort. The lowest values of the absolute maximum occurred in July (56.3 hPa on 27th July 1987). The highest values of the absolute maximum, and at the same time the highest possible (61.0 hPa), occurred three times, on 16th January 1982, 8th November 1982 and 6th December 1986 (Fig. 1b). Throughout the year, the maximum values are within the range of perception of dryness. The absolute minimum of D index occurred in August (42.6 hPa on 23rd August 2011). The highest values of the absolute minimum occurred in February (54.3 hPa on 12th February 1998) (Fig. 1c). From December to March, the minimum values of the index are in the range of perception of dryness. In April, May, September, October and November, the values are in the range of perception of humidity comfort while from June to August they are in the range of perception of sultriness.

The lowest annual average value of D index occurred in 2018 and was 54.3 hPa. The highest value (55.7 hPa) occurred in 1978 (Fig. 2a). The annual average values are characterised by a strong, statistically significant negative trend of  $-0.18$  hPa per 10 years (Table 1). The monthly average values show a negative trend in all months of the year, statistically significant in April, from June to August and in October and November.

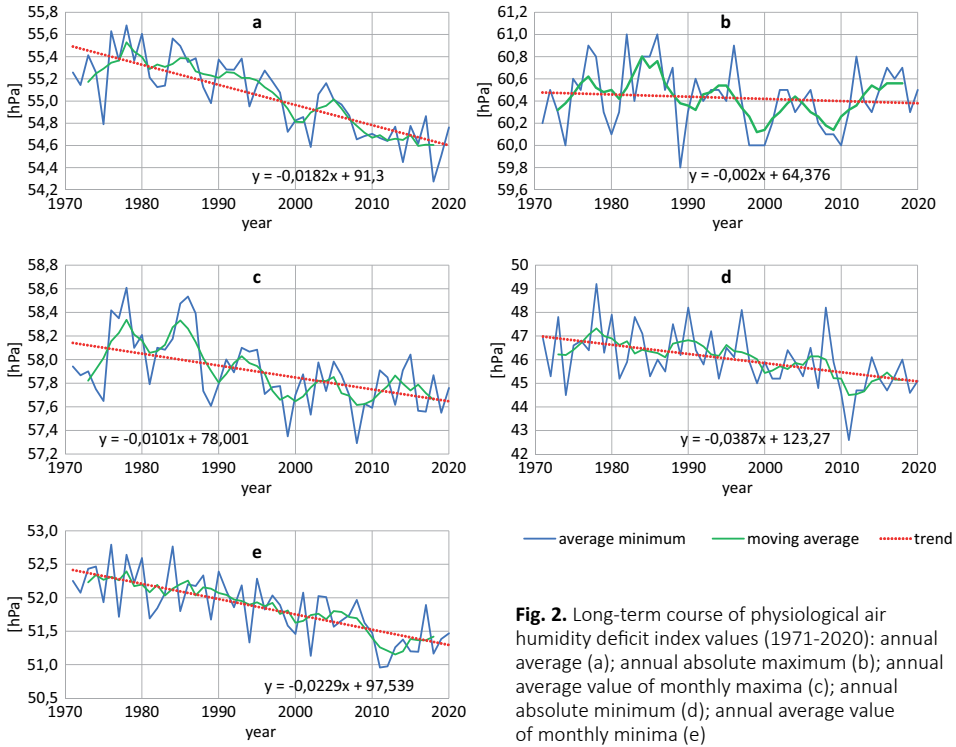
The lowest value of the absolute maximum (59.8 hPa) occurred in 1989. The annual absolute maximum reached the highest value, and at the same time the highest possible value (61.0 hPa), in the years 1982 and 1986 (Fig. 2b). This is associated with the occurrence of a water vapour pressure of 0 hPa at 12:00 UTC. The absolute maximum of the D index does not show a significant long-term trend at Kasprowy Wierch. The line of the 5-year moving average, however, shows a fairly clear, approximately 10-year periodicity of this characteristic. A very slight negative trend is shown by the values of the maxima in all months of the year. This trend proved statistically significant only in June and July (Table 1).

The annual average of the monthly maxima is within a small range of values, from 57.3 hPa in 2008 to 58.6 hPa in 1978 (Fig. 2c.). The long-term trend is negative and statistically significant (Table 1).

The absolute annual minimum is characterised by the lowest value of 42.6 hPa in 2011. This is the lowest value of the D ever recorded at the summit of Kasprowy Wierch at 12:00 UTC in the years 1971-2020. The highest value of the absolute annual minimum of 49.2 hPa occurred in 1978 (Fig. 2d). Slight negative trends of the minima were observed in all months of the year while statistically significant trends are observed in the period from April to August and in October (Table 1).



**Fig. 1.** Monthly average (a), monthly absolute maximum (b) and monthly absolute minimum (c) of physiological air humidity deficit index – annual distribution



**Fig. 2.** Long-term course of physiological air humidity deficit index values (1971-2020): annual average (a); annual absolute maximum (b); annual average value of monthly maxima (c); annual absolute minimum (d); annual average value of monthly minima (e)

**Table 1.** Ten-year trend values (hPa/10 years) of the average, the monthly maxima and the monthly minima of the physiological air humidity deficit index values. Trends that are statistically significant (0.05) are indicated in bold

Characteristic	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
average	-0.07	-0.08	-0.06	<b>-0.15</b>	-0.13	<b>-0.41</b>	<b>-0.34</b>	<b>-0.31</b>	-0.16	<b>-0.19</b>	<b>-0.24</b>	-0.05	<b>-0.18</b>
maximum	-0.04	-0.05	-0.06	-0.06	-0.01	<b>-0.36</b>	<b>-0.22</b>	-0.10	-0.09	-0.06	-0.09	-0.07	<b>-0.10</b>
minimum	-0.16	-0.10	-0.05	<b>-0.21</b>	<b>-0.29</b>	<b>-0.52</b>	<b>-0.54</b>	<b>-0.38</b>	-0.03	-0.14	<b>-0.30</b>	-0.04	<b>-0.23</b>

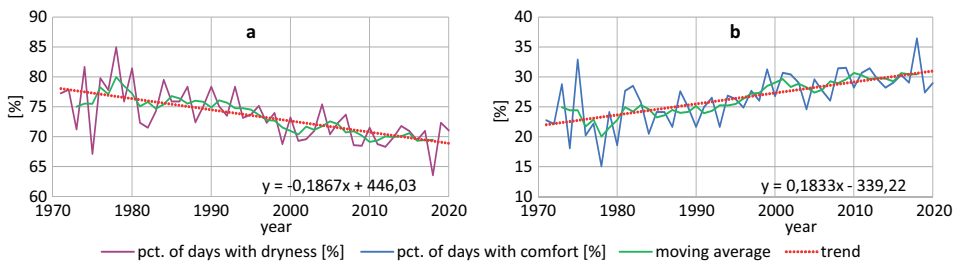
The annual average value of the monthly minima is characterised by a smaller range of values compared with the absolute minimum. The lowest value of 51.0 hPa was in 2011 and 2012 while the highest value occurred in 1976 and 1984 and was 52.8 hPa (Fig. 2e). The long-term trend is negative and statistically significant. The highest values were observed at the beginning of the long-term period in the analysis (in the 1970s and 1980s) while the lowest values were observed in the last decade.

The annual average values and annual maxima throughout the study period belong to a range that indicates a perception of dryness of the air; the average values of the minima throughout the period indicate a perception of comfort with regard to air humidity. The values of the absolute minima in the eight years belong to the range of the condition of perception of air sultriness.

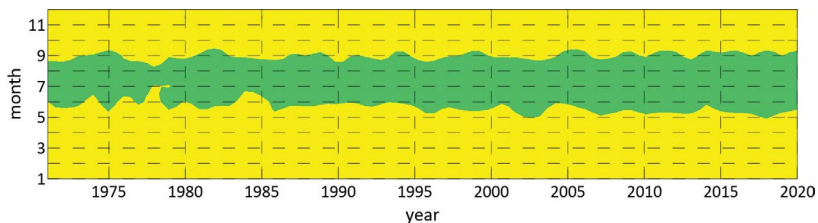
The annual percentage of days with a perception of dryness at Kasprowy Wierch in the period 1971–2020 systematically decreased over time, with some fluctuation of values throughout the study period, and a statistically significant trend was found. The lowest Dry (63.6%) occurred in 2018. The highest proportion of days with dryness (84.9%) occurred in 1978 (Fig. 3a). The annual percentage of days with a perception of comfortable air humidity increased systematically and significantly in the period 1971–2020. The values of the share of days with dryness and days with comfort mostly complement each other, which is due to the very small number of days belonging to the third range of perceptibility (perception of sultriness) in the period of the study at the summit of Kasprowy Wierch. Thus, the lowest Dcomf (15.1%) occurred in 1978, and the highest Dcomf (36.4%) was recorded in 2018 (Fig. 3b).

The average monthly D index at Kasprowy Wierch shows more and more often values belonging to the range of comfortable perception of air humidity (Fig. 4). The perception of dryness is consistently present in the months from January to April, as well as from October to December. In the months from May to September, the monthly average value of the index is variable, with the most significant changes between 1975 and 1980 where there was a decrease in the proportion of the comfortable perception of humidity to values only for the July–September period. Since the 1990s, the duration of comfortable conditions has been increasing steadily with a concomitant shortening of the dry period in both halves of the year. In 2018 the average monthly D continuously met the comfort criteria for five months (May to September).

As mentioned earlier, the number of days with comfortable perception of air humidity shows an increasing trend (Fig. 5). At the beginning of the long-term period of the study the occurrence of at least one day with a perception of humidity comfort was limited



**Fig. 3.** Percentage of days with a perception of dryness (a) and humidity comfort (b) per year between 1971 and 2020



**Fig. 4.** Average monthly physiological air humidity deficit index at Kasprowy Wierch in 1971–2020. Green colour denotes comfortable air humidity conditions, yellow colour – conditions of excessively dry air

to the months from April to October. In the second half of this period, an increase in the number of years was observed in which several days with a comfortable perception of humidity also occur in November. In the first half of the long-term period only few years showed the presence of months with 25-29 days with a perception of comfort. Since 1995 there has been a continuity in the occurrence of this number of days and an increasing proportion of months with 25-29 days with a perception of comfort. There have also been a few years when the perception of comfort in July and August occurred during the whole or almost the whole month (30 or 31 days).

The lowest monthly average number of days with a perception of dryness occurs in July (6.2 days) and August (5.7 days). The highest values occur from December to March when air perceived as too dry for the human body is observed every day (Fig. 6a).

The average monthly number of days with comfort is mostly complementary to the value of the average monthly number of days with dryness; thus the lowest values are 0 days with comfort in January, February, March and December. The highest values of the average monthly number of days with comfort occur in July (24.7 days) and August (25.2 days) (Fig. 6b).

During the 50-year period under study the number of days with a perception of comfort increased in the months from May to October while the number of days with a perception of dryness showed a decreasing trend. The statistically significant trends in both cases are those from May to August and, for the entire period, from May to October (Table 2).

The conditional probability of the occurrence of conditions of perceptibility of air humidity (comfort and dryness) with different air masses varies considerably (Fig. 7a). The highest probability of occurrence of dryness was observed in the case of advection

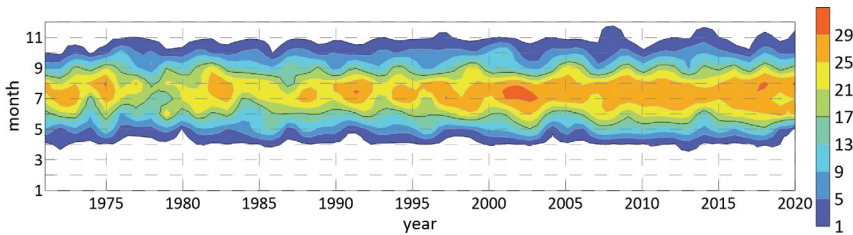


Fig. 5. Number of days with a comfortable perception of air humidity in 1971-2020

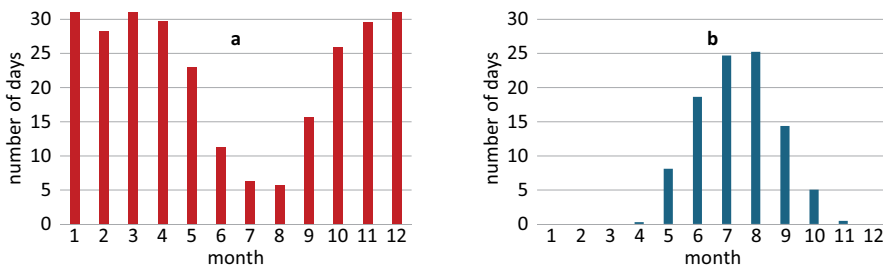
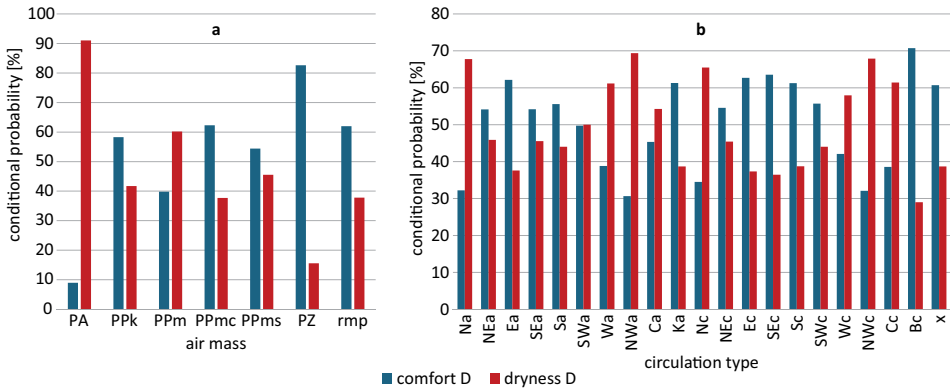


Fig. 6. Average monthly number of days with a perception of dryness (a) and humidity comfort (b) – annual distribution

**Table 2.** Ten-year trend values (hPa/10 years) for the number of days with perceptions of humidity comfort and dryness from May to October. Statistically significant trends ( $p < 0.05$ ) are indicated in bold

Degree of perception	May	June	July	August	September	October	May-October
comfort	<b>1.06</b>	<b>1.88</b>	<b>1.19</b>	<b>1.11</b>	0.74	0.49	<b>6.46</b>
dryness	<b>-1.06</b>	<b>-1.91</b>	<b>-1.25</b>	<b>-1.13</b>	-0.74	-0.49	<b>-6.58</b>

**Fig. 7.** Conditional probabilities of humidity comfort and dryness conditions occurring with: a) air masses from May to October, b) circulation types from May to October. Air masses: PA – arctic air, PPK – polar continental air, PPM – polar maritime air, PPMC – warm polar-maritime air, PPMS – transformed (old) polar maritime air, PZ – tropical air, rmp – various. Circulation types: N, NE, E, SE, S, SW, W, NW – direction of air mass advection; kind of pressure pattern: c – cyclonic, a – anticyclonic; Ca – center of high, Ka – anticyclonic wedge, Cc – center of low pressure, Bc – through of low pressure, x – unclassified situations or pressure col.

of arctic air masses over southern Poland (91%), and of polar maritime air mass (60.2%). The conditional probability of the occurrence of humidity comfort is more than 50% for tropical air (82.6%), warm polar maritime air (62.3%), various air masses (62%), polar continental air (58.3%) and transformed (old) polar maritime air (54.4%). The least significant difference in the conditional probability of the occurrence of the two conditions of perceptibility concerns the transformed polar maritime air, with a 54.4% chance of the occurrence of comfort and a 45.5% chance of the occurrence of dryness (Fig. 7a).

The conditional probability of dry days was the highest (above 60%) in cyclonic and anticyclonic types with air inflow from the northern sector (Na, NWA, Nc, NWC), from the west (Wa) and at the center of the low over southern Poland (Cc, Fig. 7b). On the other hand, the conditional probability of the occurrence of comfortable humidity conditions was the highest (over 60%) in cyclonic and anticyclonic situations with advection from the eastern sector (Ea, Ec, SEc) and from the south (Sc), at the anticyclonic wedge over southern Poland (Ka), through of low pressure (Bc, > 70%) and unclassified situation or pressure col (x).

During the data analysis, only ten occurrences of sultriness ( $D < 45$  hPa) were found at 12:00 UTC during the 50-year period at the summit of Kasprowy Wierch. This represents 0.05% of the total number of observations. All these cases, together with the indication of the air mass and type of circulation with which they occurred, are summarised in Table 3. The earliest case occurred on 17th August 1974. All other cases occurred in or

**Table 3.** Cases of perceived sultriness based on the physiological air humidity deficit index at 12 UTC during the period 1971-2020 at Kasprowy Wierch. Each case includes the corresponding air mass type and circulation type. Abbreviations for air masses and circulation types are explained in Fig. 7.

Date	Physiological air humidity index D [hPa]	Air mass	Circulation type
17.08.1974	44.5	PZ	Ca
21.07.2007	44.8	PZ	Bc
17.07.2010	44.6	PZ	Bc
23.08.2011	42.6	PPms	Ea
25.08.2011	44.2	PZ	SEa
02.07.2012	44.7	PPms, PZ	x
20.06.2013	44.7	PZ	Sa
09.08.2013	44.7	PZ, PPm	Bc
11.07.2016	44.7	PZ	SWc
26.06.2019	44.6	PZ	SWa

after 2007 (the latest one on 26th June 2019). Such cases only occurred in the summer months (June to August). The vast majority of cases of sultriness (9 out of 10) occurred when tropical air masses were flowing over southern Poland (including cases where two different air masses were recorded during a given day). One case of occurrence of a perception of sultriness occurred with a transformed polar maritime air mass. Three days with sultriness occurred when there was a trough of low pressure (Bc) over southern Poland. The remaining cases occurred with different types of circulation, most of which were anticyclonic types with advection from the directions of the southern sector (SEa, Sa, SWa).

The comparison of the basic characteristics of the D index for Kasprowy Wierch, Zakopane and Śnieżka in the years with the highest (in 1978) and the lowest (in 2018) annual average D value at Kasprowy Wierch in the period 1971-2020 shows quite large differences between the summit parts of the Tatra Mountains, their foothills and the peaks of the Karkonosze Mountains (Tab. 4). The annual average values belong to the range of perceived dryness in all cases except Zakopane, where the value in 2018 is in the humidity comfort range. The minimum values that occurred in the period from June to August indicate comfortable conditions at Kasprowy Wierch and Śnieżka, while in Zakopane they were included in the range of sultriness in both analyzed years. The maximum values that occurred between November and February in all cases indicate a feeling of dry air. In both analysed years, the highest value of the Ddry was recorded at Kasprowy Wierch, while the lowest in Zakopane. At all measuring points, the Ddry values are higher in 1978 compared to 2018, while the Dcomf values are lower in 1978. Only at the foot of the Tatra Mountains is the occurrence of sultry days in the range of D index criteria observed; in 1978 there was only one such day, and in 2018 the percentage of such days was 7%. From the above comparison, it appears that the humidity conditions were more favorable in 2018, with a decrease in the Ddry in favor of Dcomf. Only in Zakopane on summer days with the highest air humidity were the conditions in 2018 worse than in 1978 due to the occurrence of sultry weather.

**Table 4.** Main characteristics of D index for two selected years for Kasprowy Wierch, Zakopane and Śnieżka. The selected years are the years of the highest (1978) and the lowest (2018) annual mean of the D index at Kasprowy Wierch in the period 1971-2020

Year	1978			2018		
Station	Kasprowy Wierch	Zakopane	Śnieżka	Kasprowy Wierch	Zakopane	Śnieżka
mean [hPa], class of perceptibility	55.7 dry	53.4 dry	55.0 dry	54.3 dry	52.0 comfortable	53.9 dry
minimum [hPa], date, class of perceptibility	49.2 29 <sup>th</sup> Jul comfortable	44.4 8 <sup>th</sup> Jun sultry	48.3 7 <sup>th</sup> Jun comfortable	46.0 29 <sup>th</sup> , 30 <sup>th</sup> Jul comfortable	41.0 1 <sup>st</sup> Aug sultry	45.5 3 <sup>rd</sup> , 4 <sup>th</sup> Aug comfortable
maximum [hPa], date, class of perceptibility	60.8 15 <sup>th</sup> Jan dry	60.0 20 <sup>th</sup> Feb dry	59.6 20 <sup>th</sup> Feb, 19 <sup>th</sup> Dec dry	60.7 29 <sup>th</sup> Nov dry	59.8 27 <sup>th</sup> Feb dry	60.2 29 <sup>th</sup> Nov dry
Dry days [%]	84.9	56.4	77.8	63.6	49.0	59.5
Comfort days [%]	15.1	43.3	22.2	36.4	43.6	40.5
Sultry days [%]	0.0	0.3	0.0	0.0	7.4	0.0

## Discussion of results and conclusions

The paper analyses the long-term variability of the D index and the impact of atmospheric circulation thereon at the summit of Kasprowy Wierch. The main results of the study can be summarised in the following points:

- The average, maximum and minimum values of the D index in the long-term course are characterised by negative trends, both annually and for the individual months of the year. In summer, these trends show statistical significance.
- At the summit of Kasprowy Wierch, days with a comfortable perception of air humidity occur more and more frequently, especially in late spring and summer. This is conducive to the well-being of tourists. On the other hand, the proportion of days with a perception of dryness decreases during the year. Days with a perception of sultriness only make up a negligible percentage but may occasionally occur during the summer.
- The highest conditional probability of occurrence of comfortable conditions of air humidity is recorded when tropical air masses (83%) and warm polar maritime air masses (62%) travel over southern Poland. Dry air conditions occur in 91% of cases of the arrival of arctic air. This air, however, arrives over southern Poland quite rarely (on about 8% of days per year, most often in spring (11%); [Bielec-Bąkowska, 2022](#)).
- Situations with a perception of air sultriness at Kasprowy Wierch occurred in tropical air with a small share of transformed polar maritime air.

It is worth noting that the criterion of sultriness adopted for the D index is different than the better-known criterion proposed by Scharlau who considered that days with sultry weather are days on which the water vapour pressure is greater than or equal to 18.8 hPa. In the period under study, such a value of water vapour pressure did not occur at Kaspro-

wy Wierch. The highest recorded water vapour pressure was observed on 23rd August 2011 and was 18.4 hPa. The limit of water vapour pressure in a sultry weather situation for the D index is 16.1 hPa.

Kozłowska-Szczęsna et al. (1997) analysed the average D index in Poland in January and July in the years 1961-1970. The value of the index at the summit of Kasprowy Wierch in July (1961-1970) was 55 hPa while a value of 51 hPa was recorded in this study for July (1971-2020). The currently lower value is the result of a negative trend of the index.

The trends of specific humidity studied by Wypych (2021) are, like the trends of the D index shown in the present study, the largest (statistically significant) in summer, and they show the highest statistical significance in the Carpathians. Relative humidity trends across Poland are consistent with the trends of the D index analysed and are also significant in summer (Wypych, 2021).

In Lesko, at an altitude of 420 m asl, days with a perception of sultriness, calculated for the physiological air humidity deficit index criterion, occur on average more than 60 times a year and occur from the second half of May to the end of September, with the highest number of days with a perception of sultriness in July and August (Wereski & Wereski, 2012). At Kasprowy Wierch, in the whole fifty-year period 1971-2020, there were only ten instances of conditions of perception of sultriness at 12 UTC, and these only occurred in the summer months.

The values of the index in the analysis are slightly lower for Kasprowy Wierch (from 0.6 to 2.2 hPa for the annual average) than the values characterising the bioclimate of the Norwegian Arctic (Araźny, 2005; Przybylak & Araźny, 2005). The annual average values of the D index show a decreasing trend in the area of the Norwegian Arctic. Araźny (2005) recorded the largest statistically significant decrease in seasonal and annual average index values during autumn and summer, which is consistent with the results presented in this paper. There were no sultry days recorded in the Arctic between 1975 and 2000. High altitude conditions (approx. 2,000 m asl) are therefore similar to those of the Arctic in terms of the perception of air humidity.

The high parts of the Tatra Mountains represent an area where local anthropogenic influences are absent. Despite this, significant trends in biometeorological indices are observed here, not only those based on air temperature, but also the index of D index relating to the air humidity conditions. This is clearly the result of the global climate change (IPCC, 2021; 2023). The negative trends of the D index at Kasprowy Wierch are the result of increasing water vapour pressure. Under conditions of increasing air temperature across the globe (IPCC, 2023); with a positive temperature trend also found at the summit of Kasprowy Wierch: (0.3°C/10 years; Błażejczyk, 2019), intensification of evaporation takes place. Furthermore, warmer air can hold more water vapour.

The described humidity conditions in the area of Kasprowy Wierch, representing the summit parts of the Tatra Mountains, are of great importance for tourists, who visit this region in large numbers at any time of the year. Many of them use the available tourist trails for many hours of hiking along the ridge of the Tatra Mountains.

Further analyses will focus on studies of the D index in other mountain areas of Europe. The investigation will include the directions and magnitude of the physiological air humidity deficit in order to determine whether tourism and skiing conditions in the harsh climate of high mountains are improving.

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