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Increasing Frequency of Sultry Conditions in Poland Based on 60 Years of Meteorological Observations

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Abstract

Sultry conditions, resulting from the combined effect of high air temperature and humidity, represent an important component of human thermal discomfort and may intensify under ongoing climate warming. This study evaluates the occurrence and long-term variability of sultry conditions in Poland during the period 1966–2025 using meteorological observations from three synoptic stations representing contrasting geographical settings: the coastal station of Łeba, the lowland station of Sulejów, and the foothill station of Lesko. Four widely used indices (Scharlau criterion, Humidex, equivalent temperature, and apparent temperature) were compared, and long-term trends in the annual number of sultry days and the duration of sultry episodes were assessed using the modified Mann–Kendall test and the Sen's slope estimator. All indices consistently indicated significant increases in the frequency of sultry conditions, although the estimated number of sultry days differed substantially among methods. Sultry conditions occurred most frequently in Sulejów and least frequently in Łeba, reflecting the moderating influence of the Baltic Sea. Inland stations also exhibited significant increases in the duration of persistent sultry episodes. Among the evaluated approaches, Humidex provided the most balanced representation of regional variability while remaining simple and readily interpretable. The results demonstrate a clear intensification of humid heat stress in Poland over recent decades and highlight the importance of considering both temperature and humidity when assessing climate change impacts on human thermal comfort.

Keywords: sultry conditions; thermal discomfort; biometeorology; climate change; long-term variability; Poland

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1. Introduction

Climate change observed over recent decades has led not only to a systematic increase in air temperature but also to changes in atmospheric water vapor content, which constitutes one of the key components of the global water cycle [1,2]. An increase in specific humidity has been observed over both oceans and land areas across most regions of the world [1]. According to the Clausius–Clapeyron relationship, the water-holding capacity of the atmosphere increases by approximately 7% for every 1 °C rise in air temperature [3], resulting in higher water vapor pressure and specific humidity [4].

These changes affect not only hydrological processes, such as evaporation, condensation, and the occurrence of extreme precipitation events [3], but also biometeorological conditions and human thermal stress [5–7]. High air temperature combined with elevated atmospheric moisture imposes substantially greater physiological stress than high

temperature alone [8,9]. Consequently, the concurrent increase in both temperature and humidity has led to more frequent and more severe hot and humid conditions [10]. These changes therefore have hydrological, climatic, and societal implications, influencing both the intensity of processes within the global water cycle and human living conditions.

Sultriness is a phenomenon resulting from the simultaneous occurrence of high air temperature and elevated atmospheric moisture [11]. It is defined as a subjective sensation of physiological discomfort caused by excessive atmospheric humidity. In Polish climatological studies, sultry conditions are most commonly identified using the Scharlau criterion, which defines sultriness as water vapor pressure equal to or exceeding 18.8 hPa combined with air temperature above 16.6 °C [1,9,12]. Under such conditions, the efficiency of body cooling through sweat evaporation is substantially reduced, resulting in enhanced thermal discomfort [12,13]. Consequently, the assessment of heat stress is based not only on air temperature but also on variables describing atmospheric moisture, while more advanced thermal indices additionally incorporate wind speed and solar radiation [14]. As demonstrated by Falarz [1], indices combining both temperature and humidity exhibit stronger long-term trends than air temperature alone, particularly during heat waves.

The analysis of long-term changes in air temperature and atmospheric moisture has become an important research topic at the intersection of climatology, atmospheric hydrology, and biometeorology, as it enables simultaneous assessment of changes in the atmospheric branch of the water cycle and their implications for the environment and human health [15]. Increasing atmospheric moisture reduces the efficiency of human thermoregulation, thereby intensifying heat stress. Consequently, monitoring changes in thermal and moisture conditions is essential for assessing the impacts of climate change and supporting the development of adaptation strategies [2,7,15]. The increasing frequency of sultry days adversely affects health resort conditions, tourism, and outdoor recreation, while also increasing energy demand for building cooling [5,14,16]. As emphasized by Sherwood and Huber [17], heat stress represents the physiological limit of human adaptation to ongoing climate warming.

Because atmospheric moisture is the fundamental component of all sultriness indices, different measures of atmospheric humidity, including water vapor pressure, specific humidity, mixing ratio, and absolute humidity, are strongly correlated and may be used interchangeably to characterize atmospheric moisture conditions [8]. However, individual sultriness indices differ in their mathematical formulation, threshold values, and intended applications, which may result in different assessments of thermal stress under identical meteorological conditions. Humidex has been widely used in heat-wave studies in Europe and North America [18,19]. The Scharlau criterion is among the most frequently applied methods for assessing sultriness in Poland [1,5,6,9,11,12] and has also been employed in studies conducted outside Europe [20]. Apparent Temperature (AT) has been applied in biometeorological studies in Poland [21], whereas equivalent temperature (Tek) has been used, among others, by Mahmoudi et al. [20].

Despite the widespread use of different sultriness indices, relatively few studies have compared their long-term performance using the same observational dataset. Consequently, it remains unclear to what extent the choice of index influences the assessment of long-term changes in sultry conditions.

The literature also reveals a clear research gap regarding Poland. Previous studies have generally focused on individual indices, selected regions or cities, or were based on observations from a single synoptic observation time [1,6,12]. Furthermore, several long-term analyses ended in 2000 [1], thus excluding the period of the most rapid climate warming observed during recent decades. Comprehensive studies simultaneously comparing different methods of sultriness identification, assessing long-term changes in the

frequency of sultry days, and analyzing the duration of sultry episodes across different climatic regions of Poland are still lacking.

The specific objectives of this study were:

(i) To assess long-term changes in the frequency and seasonality of sultry conditions in Poland during 1966–2025;
(ii) To compare the frequency and persistence of sultry conditions identified using four different indices;
(iii) To examine long-term trends in the annual number of sultry days and the duration of sultry episodes;
(iv) To assess whether the observed changes differ among three stations representing contrasting climatic regions of Poland.

2. Materials and Methods

2.1. Study Area and Data

Poland is located in the temperate transitional climate zone and is influenced by both maritime air masses originating over the North Atlantic and continental air masses advected from eastern Europe and Asia [22,23]. As a result, meteorological conditions exhibit considerable temporal and spatial variability [24]. The climate of Poland is further shaped by the Baltic Sea, topography, and elevation, leading to pronounced regional differences in air temperature, atmospheric humidity, precipitation, and biometeorological conditions [22].

Meteorological data used in this study were obtained from the publicly available database of the Institute of Meteorology and Water Management—National Research Institute (IMGW-PIB; https://dane.imgw.pl, accessed on 8 July 2026). The analysis covered the period 1966–2025, providing a continuous 60-year observational record. Standard synoptic observations performed every 3 h (00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, and 21:00 UTC) were used. Consequently, each station contributed 175,320 observation terms over the entire study period. Air temperature, dew-point temperature, and water vapor pressure were used to calculate the analyzed sultriness indices.

The analysis was performed for three synoptic stations representing contrasting climatic regions and physiographic conditions of Poland. To minimize the influence of the urban heat island effect and local anthropogenic modifications of the thermal environment, stations located outside large urban agglomerations were selected. The study included the coastal station Łeba (2 m a.s.l.), the lowland station Sulejów (189 m a.s.l.) situated in central Poland, and the foothill station Lesko (420 m a.s.l.) located in the south-eastern part of the country. According to the high-resolution Köppen–Geiger climate classification of Beck et al. [25], Łeba is classified as Cfb (temperate, no dry season, warm summer), whereas Sulejów and Lesko are classified as Dfb (cold, no dry season, warm summer) (Table 1).

To complement the Köppen–Geiger classification, the stations were also characterized according to the Worldwide Bioclimatic Classification System (WBCS) of Rivas-Martínez, following the methodology described by Pesaresi et al. [26]. The classification was based on monthly temperature and precipitation data for 1966–2025. All three stations were assigned to the Temperate macrobioclimate and Temperate oceanic bioclimate. Łeba was classified as weak semicontinental (I_c = 17.41), whereas Lesko (Ic = 19.82) and Sulejów (Ic = 20.40) were strong semicontinental (Table 1). The station-based classification differs partly from the European bioclimatic map of Rivas-Martínez et al. [27], where parts of Poland are classified as Temperate continental. This difference may result from the climatic data and reference periods used: our classification is based on observations from 1966 to 2025, whereas the 2011 map necessarily represents an earlier climatic period. Moreover, the Ic values for

Sulejów and Lesko are relatively close to the threshold of 21 separating the Temperate oceanic and Temperate continental bioclimates.

Table 1. Geographical characteristics and climatic and bioclimatic classification of the analyzed synoptic stations.

Synoptic Station	Geographic Coordinates	Elevation [m a.s.l.]	Characteristics	Köppen–Geiger Climate Class	I_c [°C]	I_o	Rivas-Martínez Bioclimate	Continentality Subtype
Łeba	54°45′13″ N 17°32′05″ E	2	Coastal station	Cfb	17.41	6.29	Temperate oceanic	Weak semicontinental
Sulejów	51°21′10″ N 19°51′52″ E	189	Lowland station	Dfb	20.40	4.70	Temperate oceanic	Strong semicontinental
Lesko	49°27′59″ N 22°20′30″ E	420	Foothill station	Dfb	19.82	7.10	Temperate oceanic	Strong semicontinental

Note: Ic is the simple continentality index, calculated as the difference between the mean temperatures of the warmest T_{max} and coldest T_{min} months: $I_c = T_{max} - T_{min}$. I_o is the annual ombrothermic index, calculated as $I_o = (Pp/Tp) \times 10$, where P_p is the annual positive precipitation (the total mean precipitation of months with a mean air temperature above 0 °C) and T_p is the annual positive temperature (the sum of the monthly mean temperatures above 0 °C, expressed in tenths of °C). The Rivas-Martínez classification was calculated from IMGW-PIB monthly meteorological data for 1966–2025 following the methodology described by Pesaresi et al. [26].

The spatial distribution of the analyzed stations is presented in Figure 1, while their main geographical characteristics are summarized in Table 1. The meteorological variables used in subsequent analyses, namely air temperature, dew-point temperature, and water vapor pressure, constituted the basis for calculating the four biometeorological indices used to identify sultry conditions.

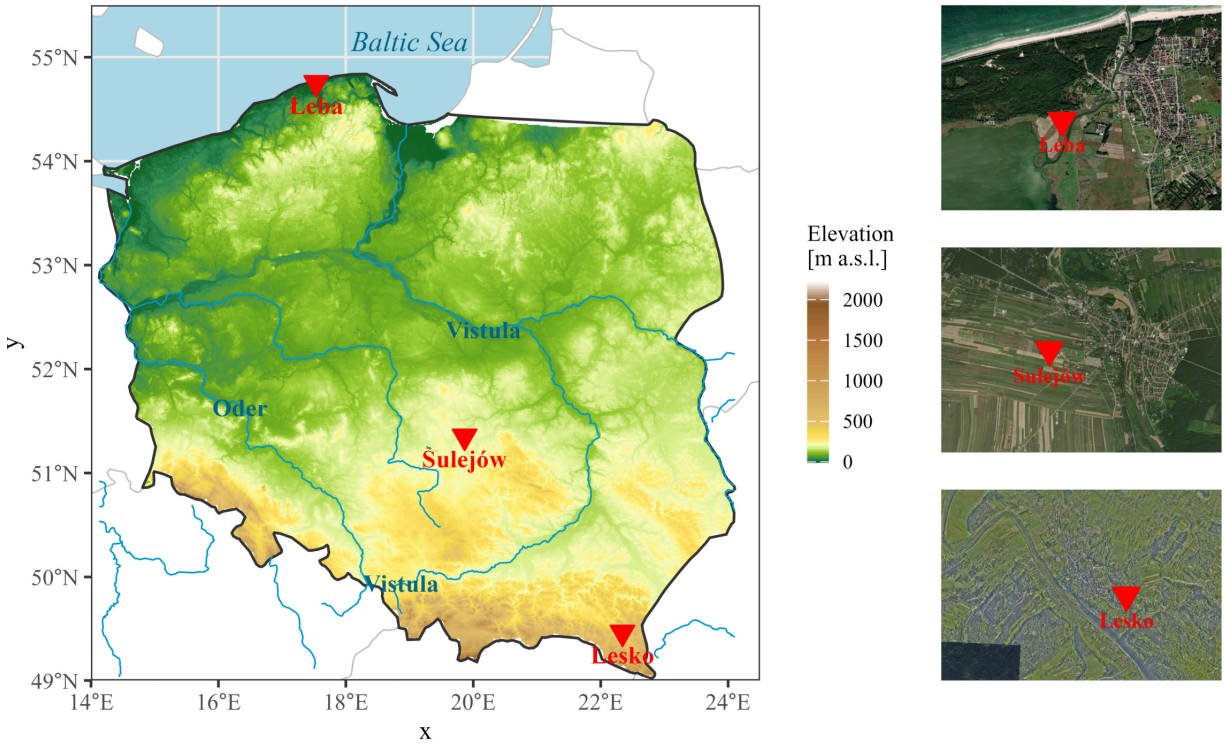


Figure 1. Spatial distribution of the analyzed synoptic stations in Poland. The locations of the Łeba, Sulejów, and Lesko stations are shown on a digital elevation model of Poland. Insets present satellite imagery of the surroundings of each station. Elevation data were derived from the Shuttle Radar Topography Mission (SRTM) digital elevation model [28]. Administrative boundaries and river network were obtained from Natural Earth [29]. Satellite imagery was provided by Esri [30].

2.2. Sultry Conditions Indices

Four established biometeorological indices representing different approaches to the identification of sultry and thermally stressful conditions were selected: the Scharlau criterion, Humidex, equivalent temperature (Tek), and Apparent Temperature (AT). The selection was based on their complementary conceptual foundations: the Scharlau criterion provides a specific threshold for sultriness based on atmospheric moisture and temperature, whereas Humidex, Tek, and AT represent composite approaches in which thermal and moisture conditions are combined into a single measure of perceived or equivalent thermal conditions. Together, these indices enable assessment of both the absolute frequency of sultry conditions and the sensitivity of the results to the choice of index.

1. **The Scharlau criterion** [31] is the most widely used method for identifying sultry conditions in Poland. According to this criterion, air is classified as sultry when the water vapor pressure (e) is equal to or greater than 18.8 hPa and the air temperature (T) exceeds 16.6 °C.
2. **Humidex** was developed by Masterton and Richardson [32] for the Canadian Meteorological Service to describe the combined effect of air temperature and atmospheric humidity on human thermal comfort. It is calculated as:

$$\text{Humidex} = \text{T} + \frac{5}{9}(\text{e} - 10) \quad (1)$$

where T is the air temperature (°C) and e is the water vapor pressure (hPa). The following classification was adopted: Humidex < 30 indicates comfortable conditions; 30 ≤ Humidex < 39 indicates noticeable sultriness; 39 ≤ Humidex < 45 corresponds to very sultry conditions; and Humidex ≥ 45 represents dangerous thermal conditions.

3. **Equivalent temperature (Tek)** represents the temperature that air would attain at constant pressure if all the water vapor it contains condensed and the released latent heat were entirely used to warm the dry air. Following Mahmoudi et al. [20], the simplified formulation based on air temperature and water vapor pressure was used:

$$\text{Tek} = \text{T} + 1.5 \cdot \text{e} \quad (2)$$

where T is the air temperature (°C) and e is the water vapor pressure (hPa).

A day was classified as sultry when Tek exceeded 56 °C [20].

4. **Apparent Temperature (AT)** is a biometeorological index proposed by [33] to quantify perceived thermal conditions resulting from the combined effects of air temperature and atmospheric humidity. In studies of heat waves and thermal stress, a simplified formulation based on air temperature and dew-point temperature is commonly applied [8]:

$$\text{AT} = -2.653 + 0.994 \cdot \text{T} + 0.0153 \cdot \text{T}_\text{d}^2 \quad (3)$$

where T is the air temperature (°C) and T_d is the dew-point temperature (°C).

According to Steadman [33], AT values exceeding 25.3 °C indicate thermal discomfort, whereas Kalkstein and Valimont [34] suggested that values above 40 °C correspond to severe heat stress.

2.3. Research Framework

The study was conducted according to the following workflow:

1. **Calculation of sultriness indices:** The Scharlau criterion, Humidex, equivalent temperature (Tek), and Apparent Temperature (AT) were calculated for all standard synoptic

observation times (00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, and 21:00 UTC) during the period 1966–2025 using meteorological data from the Łeba, Sulejów, and Lesko stations.

2. **Identification of sultry days:** A sultry day was defined as a day on which at least one of the eight synoptic observations (00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, or 21:00 UTC) met the threshold criterion for sultriness according to the respective index. Daily mean values were not used for this classification. Subsequently, the annual number of sultry days was determined separately for each station and each sultriness index.
3. **Analysis of diurnal variability of sultry conditions:** The within-day variability of sultry conditions was assessed separately for each station and each sultriness index. For each of the eight synoptic observation times (00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, and 21:00 UTC), the frequency of observations meeting the respective sultriness criterion was calculated over the entire study period. The frequency was expressed as the percentage of observations classified as sultry at each observation time.
4. **Comparison of stations and indices:** Differences in the annual number of sultry days among the analyzed stations and sultriness indices were evaluated using a linear mixed-effects model (LMM).
5. **Analysis of meteorological conditions:** Long-term variability in annual mean air temperature and annual maximum water vapor pressure, representing the principal meteorological variables controlling the occurrence of sultry conditions, was analyzed.
6. **Trend analysis of sultry days:** Long-term trends in the annual number of sultry days were assessed separately for each station and each sultriness index.
7. **Analysis of sultry episodes:** Sultry episodes were defined as sequences of consecutive sultry days. For each station and each sultriness index separately, the maximum duration of a sultry episode was determined for each year. This resulted in a separate annual time series of maximum episode duration for each station–index combination, which was subsequently analyzed for long-term trends over the period 1966–2025.

2.4. Linear Mixed-Effects Model

Differences in the annual number of sultry days among the analyzed stations and sultriness indices were evaluated using a linear mixed-effects model (LMM). The response variable was the annual number of sultry days, whereas station (Łeba, Sulejów, and Lesko) and sultriness index (Scharlau criterion, Humidex, Tek, and AT) were included as fixed effects. Year was incorporated as a random effect to account for interannual variability.

The use of an LMM was justified by the hierarchical structure of the dataset. For each year, the annual number of sultry days was determined using four different identification methods at three meteorological stations, resulting in multiple observations sharing the same meteorological background. Treating year as a random effect accounted for the correlation among observations from the same year and allowed unbiased estimation of the effects of station, sultriness index, and their interaction [35].

The fitted model was expressed as follows:

$$\text{annual number of sultry days} \sim \text{sultriness index} \times \text{station} + (1|\text{year}) \quad (4)$$

where "sultriness index" and "station" were specified as fixed effects, and "year" was included as a random intercept. This model enabled the simultaneous assessment of the effects of station, sultriness index, and their interaction on the annual number of sultry days.

The significance of the fixed effects was assessed using Type III analysis of variance (ANOVA) with Satterthwaite's approximation of degrees of freedom implemented in the lmerTest R-package [36]. Whenever significant differences were detected, post hoc pairwise

comparisons were performed using estimated marginal means (EMMs). To control the family-wise error rate associated with multiple comparisons, p-values were adjusted using Holm's correction [37].

2.5. Trend Analysis

Long-term changes in annual mean air temperature, annual maximum water vapor pressure, annual number of sultry days, and the maximum annual duration of sultry episodes during the period 1966–2025 were analyzed for the Łeba, Sulejów, and Lesko stations using non-parametric statistical methods commonly applied in climatological and hydrological studies.

The significance of monotonic trends was evaluated using the Mann–Kendall test [38,39], which is robust to outliers and does not require the assumption of normally distributed data. Because climatological time series often exhibit serial autocorrelation, the modified Mann–Kendall test proposed by Hamed and Rao [40] was applied. This modification adjusts the variance of the test statistic, providing a more reliable assessment of trend significance in autocorrelated time series.

The magnitude of long-term trends was estimated using the Theil–Sen slope estimator [41,42], which calculates the median of slopes computed for all possible pairs of observations. Owing to its robustness to outliers and non-normal data distributions, this estimator is widely used in the analysis of long-term hydroclimatic time series. Positive slope values indicate increasing trends, whereas negative values indicate decreasing trends.

All statistical analyses were performed using GNU R version 4.5.1 [43]. Statistical significance was assessed at the $\alpha = 0.05$ level.

3. Results

3.1. Number of Sultry Conditions at Synoptic Observation Times

Sultriness indices were calculated for all standard synoptic observation times (00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, and 21:00 UTC) during the period 1966–2025 at the Łeba, Sulejów, and Lesko stations using four methods: the Scharlau criterion, Humidex, equivalent temperature (Tek), and Apparent Temperature (AT).

The frequency of sultry conditions depended on both the identification method and station location (Table 2). At all analyzed stations, the Scharlau criterion classified the highest proportion of synoptic observations as sultry, ranging from 2.53% to 2.70%. Humidex and Tek yielded comparable frequencies of sultry conditions, although Humidex consistently identified slightly more sultry observation times than Tek. The AT index showed intermediate values; however, at the Sulejów and Lesko stations it classified a higher proportion of sultry observations than Humidex.

Table 2. Percentage of synoptic observation times (00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, and 21:00 UTC) classified as sultry according to the selected biometeorological indices at the analyzed synoptic stations during the period 1966–2025.

Station	Scharlau	Humidex	Tek	AT
Łeba	2.7	0.7	0.48	1.07
Sulejów	2.53	1.8	0.82	2.75
Lesko	2.58	1.4	0.68	2.14

The highest proportion of sultry observation times was recorded at Sulejów using the AT index (2.75%), whereas the lowest was observed at Łeba according to the Tek index (0.48%). The Scharlau criterion produced remarkably similar percentages across all three

stations, while the remaining indices indicated a substantially higher frequency of sultry conditions at the inland stations than at the Baltic coastal station.

3.2. Diurnal Variability of Sultry Conditions

The diurnal distribution of sultry conditions showed clear differences among observation times, stations, and sultriness indices (Figure 2). For Humidex, equivalent temperature (Tek), and Apparent Temperature (AT), sultry conditions occurred predominantly during the daytime, with very low frequencies during the night and early morning. At all three stations, the frequency increased markedly between 06:00 and 09:00 UTC and generally reached its maximum at 12:00 UTC. The highest values were recorded for AT, reaching 2.75% in Łeba, 7.17% in Sulejów, and 6.08% in Lesko at 12:00 UTC. Humidex showed a similar diurnal pattern, with maxima of 1.77%, 4.70%, and 4.08%, respectively. Tek produced the lowest frequencies among these three indices, with corresponding maxima of 1.03%, 1.89%, and 1.69%.

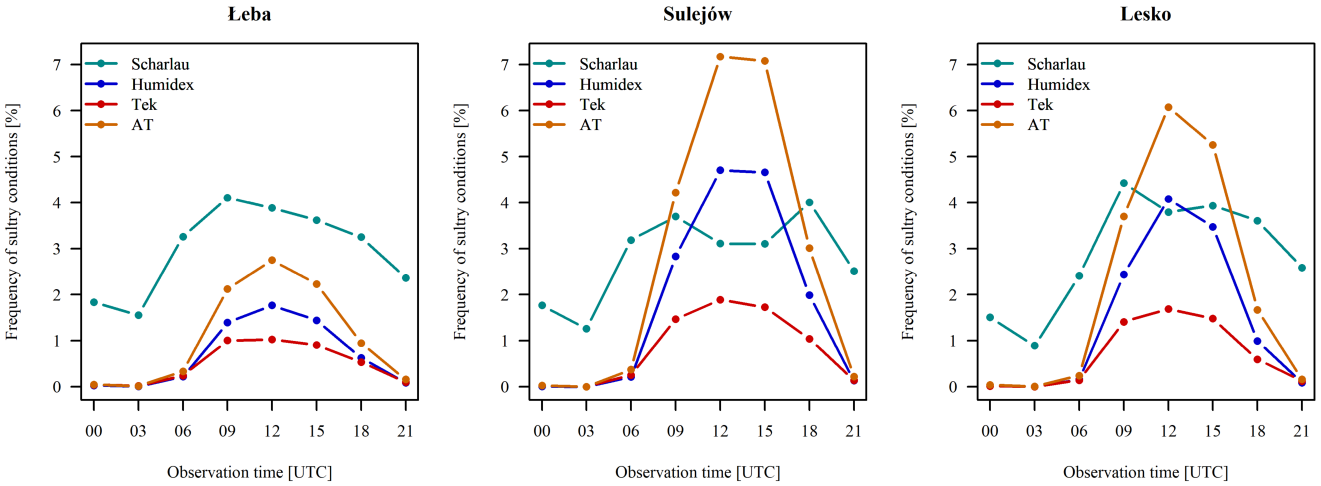


Figure 2. Diurnal variation in the frequency of sultry conditions at Łeba, Sulejów, and Lesko during 1966–2025 according to the Scharlau criterion, Humidex, equivalent temperature (Tek), and Apparent Temperature (AT). Frequencies represent the percentage of observations classified as sultry at each synoptic observation time (UTC).

The Scharlau criterion exhibited a distinctly different diurnal pattern. Sultry conditions identified using this criterion occurred more evenly throughout the day and remained relatively frequent during evening and nighttime observations. The maximum frequency occurred at different observation times depending on the station: at 09:00 UTC in Łeba (4.11%) and Lesko (4.43%), and at 18:00 UTC in Sulejów (4.01%). Even at 00:00 UTC, the frequency of sultry conditions according to the Scharlau criterion reached 1.83% in Łeba, 1.76% in Sulejów, and 1.51% in Lesko, whereas the other indices indicated almost no sultry conditions at that observation time.

The strongest diurnal variability was therefore observed for AT and Humidex, particularly at Sulejów and Lesko, where frequencies increased sharply during the daytime and declined after 15:00 UTC. In contrast, the Scharlau criterion indicated a broader period of sultry conditions extending into the evening and nighttime. These results demonstrate that both the frequency and timing of sultry conditions within the day depend substantially on the index applied (Figure 2).

3.3. Number of Sultry Days

Based on the sultry conditions identified at individual synoptic observation times, sultry days were defined as days on which at least one observation met the criterion

for sultriness. During the study period (1966–2025), the number of sultry days varied considerably depending on both the identification method and station location (Table 3).

Table 3. Number and percentage of sultry days identified at the analyzed synoptic stations during the period 1966–2025.

Station	Scharlau	Humidex	Tek	AT
Łeba	1523 (6.9%)	518 (2.4%)	359 (1.6%)	768 (3.5%)
Sulejów	1550 (7.1%)	1231 (5.6%)	586 (2.7%)	1836 (8.4%)
Lesko	1596 (7.3%)	1057 (4.8%)	546 (2.5%)	1543 (7.0%)

The highest numbers of sultry days were identified using the Scharlau criterion and the AT index. According to the Scharlau criterion, the number of sultry days ranged from 1523 in Łeba to 1596 in Lesko, corresponding to 6.9–7.3% of all days during the study period. Similarly high values were obtained using the AT index, which identified between 768 sultry days in Łeba and 1836 in Sulejów, representing 3.5–8.4% of all analyzed days.

Considerably lower values were obtained using the Humidex and Tek indices. Humidex identified between 518 sultry days in Łeba and 1231 in Sulejów, corresponding to 2.4–5.6% of the study period. The Tek index yielded the lowest numbers of sultry days, ranging from 359 in Łeba to 586 in Sulejów, representing only 1.6–2.7% of all analyzed days.

With the exception of the Scharlau criterion, all methods indicated a substantially higher frequency of sultry days at the inland stations than at the Baltic coastal station. The highest frequency of sultry days was recorded at Sulejów, particularly according to the AT index (1836 days; 8.4%) and Humidex (1231 days; 5.6%). In contrast, Łeba consistently exhibited the lowest number of sultry days regardless of the applied method. The Scharlau criterion, however, produced remarkably similar numbers of sultry days across all three stations (1523–1596 days), suggesting relatively low sensitivity of this method to regional differences in thermal and moisture conditions.

The largest discrepancies among the evaluated methods were observed at Sulejów, where the number of sultry days ranged from 586 according to the Tek index to 1836 according to the AT index. Thus, the estimated frequency of sultry days differed by more than a factor of three solely as a consequence of the selected sultriness index.

3.4. Annual Number of Sultry Days

The annual number of sultry days was calculated for each station and sultriness index based on the identified sultry days.

As shown in Table 4 and Figure 3, the annual number of sultry days depended strongly on both the applied sultriness index and station location. The Scharlau criterion produced the most consistent results among the analyzed stations. The median annual number of sultry days amounted to 24.5 days in Łeba, 25.0 days in Sulejów, and 25.5 days in Lesko. The very small differences among stations indicate that the Scharlau criterion is relatively insensitive to regional variations in thermal and moisture conditions.

The Humidex index revealed substantially greater spatial variability. The median annual number of sultry days increased from 7.5 days in Łeba to 16.0 days in Lesko and reached 21.0 days in Sulejów, indicating a clear inland increase in the frequency of sultry conditions.

The Tek index produced considerably lower values than both the Scharlau criterion and Humidex. Median values ranged from 5.0 days in Łeba to 7.0 days in Lesko and 9.0 days in Sulejów. Spatial differences identified by this index were less pronounced than those obtained using Humidex and AT.

Table 4. Median (Q1–Q3) annual number of sultry days determined using different indices at the analyzed meteorological stations. Different letters indicate significant differences between methods within the same station according to post hoc comparisons of estimated marginal means (Holm-adjusted $p < 0.05$).

Station	Method	Min	Q1	Median	Mean	Q3	Max
Łeba	Scharlau	8	17	24.5 (a)	25.4	31.3	59
Łeba	Humidex	2	5	7.5 (b)	8.6	11	22
Łeba	Tek	0	2	5 (c)	6.0	7.25	19
Łeba	AT	4	8.75	11.5 (d)	12.8	15.25	27
Sulejów	Scharlau	8	18	25 (a)	25.8	35	43
Sulejów	Humidex	4	13	21 (b)	20.5	27.5	38
Sulejów	Tek	0	4.75	9 (c)	9.8	13	26
Sulejów	AT	6	22	29.5 (d)	30.6	40	59
Lesko	Scharlau	2	20	25.5 (a)	26.6	33.5	50
Lesko	Humidex	1	11	16 (a)	17.6	24	40
Lesko	Tek	0	5	7 (b)	9.1	12	25
Lesko	AT	6	18	25.5 (c)	25.7	33.3	49

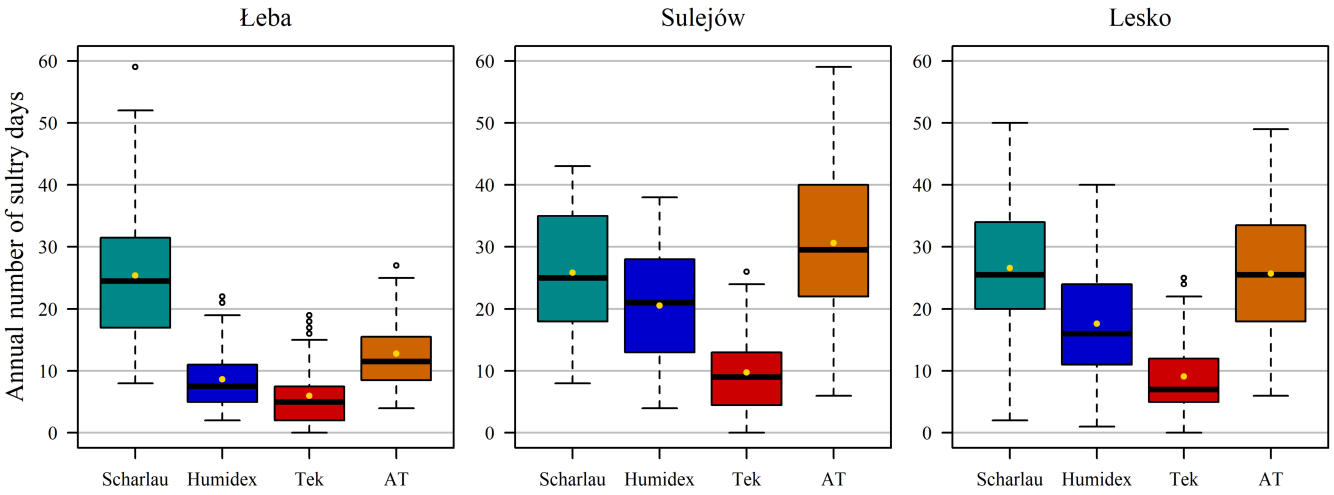


Figure 3. Annual number of sultry days at the analyzed stations according to the four sultriness indices. Yellow dots indicate means.

The greatest spatial variability was observed for Apparent Temperature (AT). The median annual number of sultry days was 11.5 days in Łeba, 25.5 days in Lesko, and 29.5 days in Sulejów. Consequently, the difference between the coastal and lowland stations reached 18 days per year, indicating that the AT index was the most sensitive to regional differences in the occurrence of sultry days.

Regardless of the applied method, the lowest annual numbers of sultry days were consistently recorded at Łeba, whereas the highest values generally occurred at Sulejów. The only exception was the Scharlau criterion, which produced nearly identical annual frequencies of sultry days at all three stations.

3.5. Comparison of the Annual Number of Sultry Days Determined Using Different Indices

The linear mixed-effects model revealed significant effects of both the sultriness index and station location on the annual number of sultry days. The strongest effect was observed for the sultriness index (Table 5; $F = 489.25$, $p < 0.001$), indicating substantial differences among the analyzed indices. Station location also had a significant effect ($F = 137.91$, $p < 0.001$), reflecting differences in the frequency of sultry days among Łeba, Sulejów, and Lesko. In addition, a significant interaction between sultriness index and station was

detected (F = 24.70, $p < 0.001$), indicating that differences among the indices depended on station location.

Table 5. Results of the Type III analysis of variance for the linear mixed-effects model evaluating the effects of sultriness index, meteorological station, and their interaction on the annual number of sultry days during the period 1966–2025.

Source of Variation	F Statistic	*p*-Value
Sultriness index	489.25	<0.001
Station	137.91	<0.001
Index × Station	24.70	<0.001

The results of the post hoc comparisons are presented in Table 4. Different letters (a–d) denote statistically significant differences among the sultriness indices within the same station. At Łeba and Sulejów, all four indices formed distinct homogeneous groups, indicating significant differences between every pair of indices. At Lesko, only the Scharlau criterion and the AT index belonged to the same homogeneous group, indicating no significant difference between these two methods, whereas all remaining pairwise comparisons were statistically significant.

Overall, the results demonstrate that the choice of sultriness index had a greater influence on the estimated annual number of sultry days than station location. The largest discrepancies among the indices were observed at Sulejów, where the median annual number of sultry days ranged from 9.0 according to the Tek index to 29.5 according to the AT index.

The significant interaction between sultriness index and station indicates that the evaluated indices differed in their sensitivity to regional climatic conditions. The Scharlau criterion deserves particular attention, as it produced very similar numbers of sultry days across all three stations, whereas the Humidex and AT indices exhibited pronounced spatial differences. These findings suggest that the Scharlau criterion is less sensitive to regional variability in thermal and moisture conditions than the other analyzed indices.

3.6. Long-Term Changes in the Annual Number of Sultry Days and Thermal–Moisture Conditions

Positive trends in the annual number of sultry days were identified at all analyzed stations regardless of the applied sultriness index (Figure 4), indicating a systematic increase in the frequency of sultry conditions throughout the study period (1966–2025).

The strongest increasing trends were observed for the Scharlau criterion and the AT index. For the Scharlau criterion, the Theil–Sen slope estimates were 0.38 days year^{-1} in Łeba, 0.33 days year^{-1} in Sulejów, and 0.25 days year^{-1} in Lesko. Corresponding values for the AT index were 0.17, 0.45, and 0.34 days year^{-1}, respectively.

The most pronounced increases were recorded at Sulejów, where the Theil–Sen slope estimates ranged from 0.22 days year^{-1} for the Tek index to 0.45 days year^{-1} for the AT index. These values correspond to an increase of approximately 13–27 sultry days over the 60-year study period.

The Humidex and Tek indices also exhibited significant positive trends at all analyzed stations, although the estimated rates of change were generally lower than those obtained using the Scharlau criterion and AT. The weakest trends were observed for Humidex in Łeba (0.11 days year^{-1}) and for Tek in Łeba (0.11 days year^{-1}) and Lesko (0.13 days year^{-1}). All analyzed trends were statistically significant ($p_{MK} \leq 0.01$), indicating a systematic increase in the frequency of sultry days throughout the study period. The coefficients of determination (R^2 = 0.14–0.47) indicate that the long-term trend explained approximately

14–47% of the interannual variability in the annual number of sultry days, with the best fit obtained for the Humidex and AT indices at Sulejów (R^2 = 0.47).

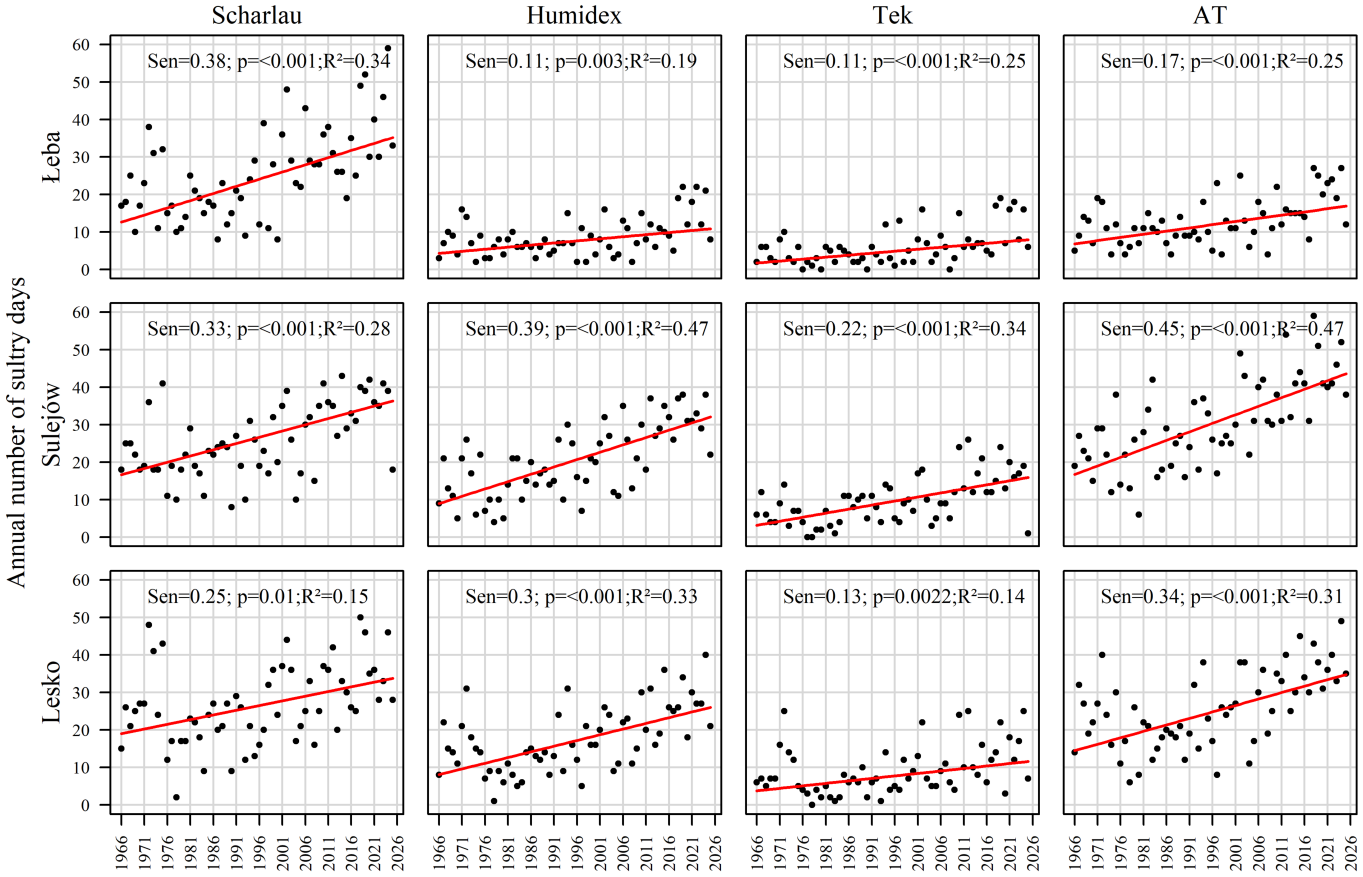


Figure 4. Temporal variability and long-term trends in the annual number of sultry days at the Łeba, Sulejów, and Lesko stations during the period 1966–2025 according to four sultriness indices.

Among the evaluated indices, Humidex was selected for further analysis of long-term changes. This index yielded intermediate estimates of the number of sultry days while clearly reflecting the spatial differences among the analyzed stations. Moreover, it simultaneously incorporates the effects of air temperature and atmospheric moisture, the two principal factors governing the perception of sultriness. To facilitate interpretation of the observed changes in the number of sultry days, the Humidex time series was compared with changes in mean annual air temperature and annual maximum water vapor pressure, the latter representing atmospheric moisture availability (Figure 5).

During the period 1966–2025, the number of sultry days identified using Humidex increased at all analyzed stations (Figure 5). A total of 518 sultry days were recorded at Łeba, 1231 at Sulejów, and 1057 at Lesko, demonstrating pronounced spatial differences in the frequency of sultry conditions. The highest number of sultry days occurred at Sulejów, whereas the lowest was recorded at Łeba.

The weakest increase was observed at Łeba, where the Theil–Sen slope reached 0.11 days year^{-1}, corresponding to an increase of approximately 1.1 sultry days per decade. This trend was statistically significant (p_{MK} = 0.003). Łeba also exhibited the lowest mean annual air temperature and relatively small changes in annual maximum water vapor pressure.

The strongest increase was recorded at Sulejów, where the Theil–Sen slope reached 0.39 days year^{-1} (p_{MK} < 0.001), corresponding to an increase of nearly four sultry days per decade. This station also showed a significant increase in mean annual air temperature

(0.041 °C year^{-1}; $p_{MK} = 3.4 \times 10^{-9}$) together with a significant increase in annual maximum water vapor pressure ($p_{MK} = 6.7 \times 10^{-3}$).

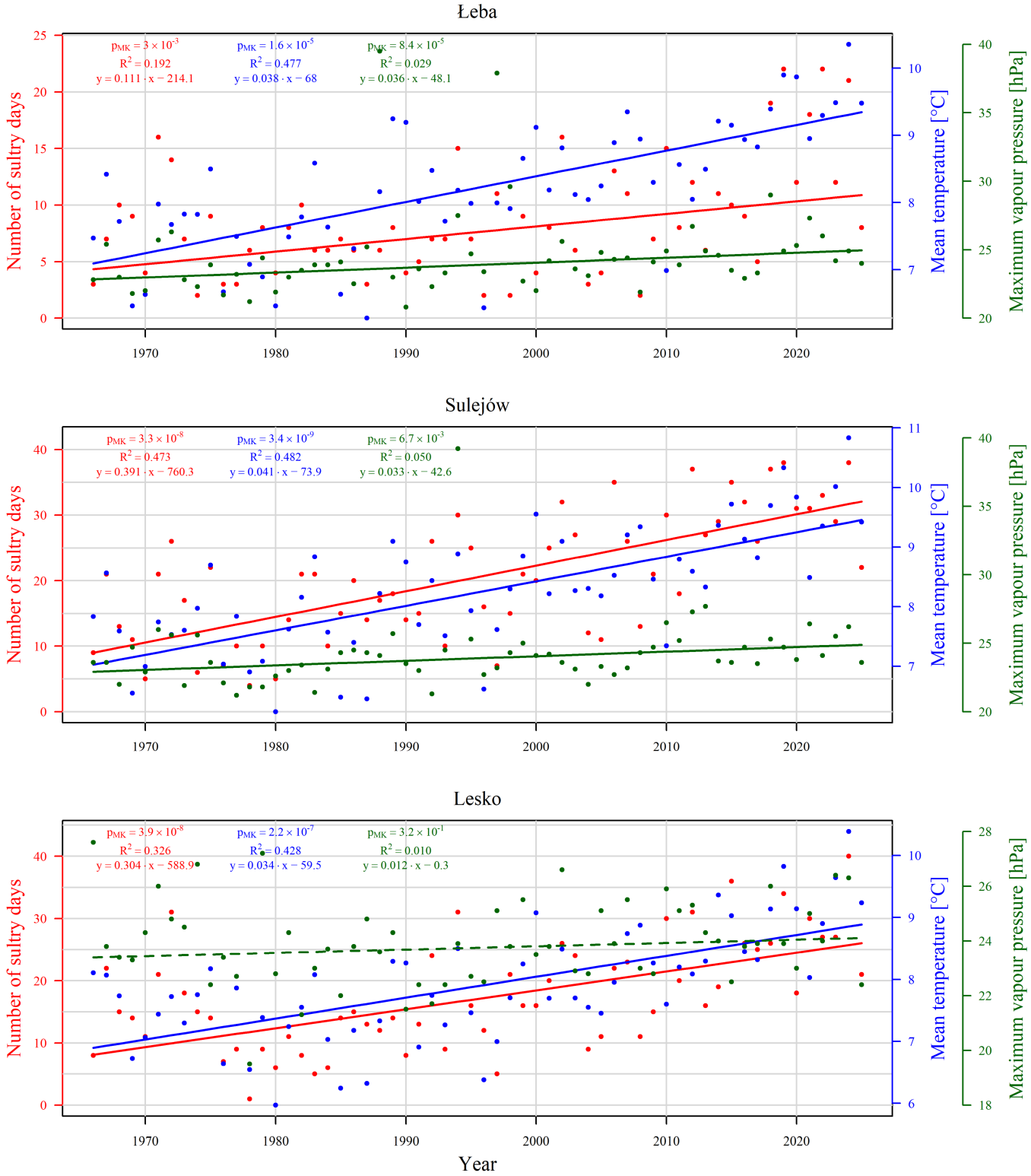


Figure 5. Long-term changes in the annual number of sultry days determined using the Humidex index at the Łeba, Sulejów, and Lesko stations during the period 1966–2025. A sultry day was defined as a day on which at least one synoptic observation met the criterion of Humidex ≥ 30. Solid colored lines represent Theil–Sen trend lines, whereas p_{MK} values correspond to the modified Mann–Kendall test. Dashed colored lines indicate non-significant trends ($p_{MK} > 0.05$).

Lesko also exhibited a significant increase in the annual number of sultry days (0.30 days year^{-1}; $p_{MK} < 0.001$), corresponding to approximately three additional sultry days per decade. Although the rate of increase was lower than at Sulejów, it was substantially greater than at Łeba.

All analyzed stations exhibited significant increases in mean annual air temperature, whereas changes in annual maximum water vapor pressure were generally weaker and did not always reach statistical significance. Nevertheless, the number of sultry days identified using Humidex increased significantly at all stations, with the strongest trends observed at Sulejów and the weakest at Łeba.

3.7. Long-Term Variability in the Maximum Duration of Sultry Periods

The analysis of sultry periods, defined as sequences of consecutive sultry days, made it possible to determine the maximum duration of a sultry period in each year and to assess its long-term variability during the period 1966–2025 (Figure 6).

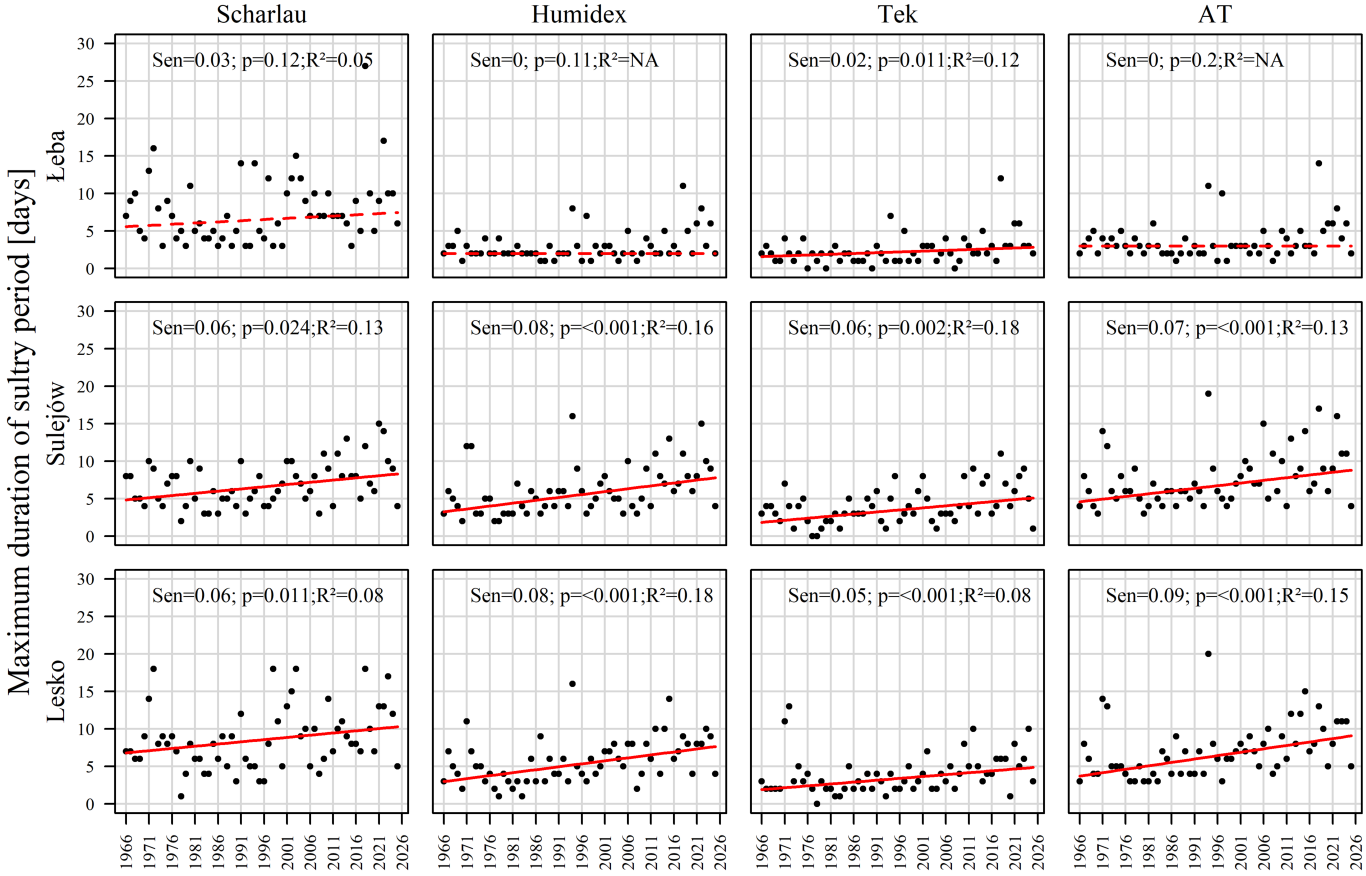


Figure 6. Long-term variability in the annual maximum duration of sultry periods determined using the Scharlau, Humidex, Tek and AT methods at the Łeba, Sulejów and Lesko meteorological stations during 1966–2025. A sultry period was defined as a sequence of consecutive days in which at least one observation time met the criterion of the respective method. Red lines show Theil–Sen trends. Solid lines indicate statistically significant trends according to the modified Mann–Kendall test ($p_{MK} < 0.05$), whereas dashed lines indicate non-significant trends ($p_{MK} \geq 0.05$).

The maximum duration of sultry periods generally exhibited increasing trends for most stations and sultriness indices. This indicates that, together with the increasing number of sultry days, the longest uninterrupted episodes of sultry conditions also became progressively longer.

The weakest changes were observed at Łeba. The Scharlau criterion and the Tek index showed only slight increases in the maximum duration of sultry periods, with Theil–Sen slopes of 0.03 and 0.02 days year^{-1}, respectively. However, only the trend for Tek was statistically significant (p_{MK} = 0.011). No significant trends were detected for Humidex or AT (p_{MK} > 0.05), and the maximum duration of sultry periods generally remained limited to only a few consecutive days.

Much stronger changes were observed at Sulejów. All analyzed indices showed statistically significant positive trends, with Theil–Sen slopes ranging from 0.06 days year^{-1} for Tek to 0.08 days year^{-1} for Humidex. These values correspond to an extension of the longest sultry periods by approximately 4–5 days over the 60-year study period. The longest sultry episodes locally reached 15–19 consecutive days.

Lesko also exhibited statistically significant positive trends for all analyzed indices. The rates of increase were comparable to those observed at Sulejów, ranging from 0.05 days year^{-1} for Tek to 0.09 days year^{-1} for AT. The longest sultry periods reached approximately 20 consecutive days, while the strongest trends were recorded for Humidex and AT (p_{MK} < 0.001).

A comparison of the evaluated indices indicates that Humidex and AT generally showed the greatest increase in the duration of sultry periods. In contrast, Tek identified the shortest sultry periods, although positive trends were also observed for this index at all stations. Łeba exhibited the greatest temporal stability, with no significant long-term changes detected for either Humidex or AT.

The coefficients of determination were relatively low (R^2 = 0.05–0.18), indicating substantial interannual variability in the maximum duration of sultry periods. Nevertheless, most of the identified trends were statistically significant, demonstrating a gradual lengthening of the longest sultry episodes, particularly at the inland stations.

4. Discussion

This study demonstrates a substantial increase in both the frequency and persistence of sultry conditions in Poland during the period 1966–2025. However, the magnitude of these long-term changes varied depending on the sultriness index applied. The observed trends are consistent with ongoing climate warming and increasing atmospheric water vapor content, which together intensify human heat stress.

The results show that both the annual number of sultry days and the rate of their long-term increase depend strongly on the selected sultriness index. This indicates that assessments of changes in biometeorological conditions are sensitive to the method used to identify sultriness and that comparisons among studies employing different indices should be made with caution. The present study extends previous research conducted in Poland, which also demonstrated that the choice of index influences estimates of sultry day frequency. Bartoszek and Węgrzyn [6] and Wereski [9] reported differences between the Scharlau criterion, equivalent temperature, and other indices, although their analyses were limited to shorter observation periods or individual locations. By applying four sultriness indices to a 60-year observational record, the present study shows that, although all indices indicate increasing numbers of sultry days, they differ considerably in both the absolute number of identified days and the estimated rates of long-term change.

The different responses of the analyzed indices to identical meteorological conditions result from their distinct formulations and varying sensitivities to changes in air temperature and atmospheric moisture. Although variables describing the actual atmospheric water vapor content, such as water vapor pressure, specific humidity, and mixing ratio, are strongly correlated [8], complex heat stress indices may respond differently to the same atmospheric conditions. Simpson et al. [44] demonstrated that, within specific temperature

ranges, an increase in water vapor pressure may produce substantially larger changes in one heat stress index than in another, a finding also confirmed in comparisons between Humidex and Apparent Temperature. Similar conclusions were reported by Cvijanovic et al. [45], who showed that the choice of heat stress index affects the assessment of thermal stress. Havenith et al. [46] further emphasized that among the currently available indices, only the Universal Thermal Climate Index (UTCI), which incorporates air temperature, humidity, wind speed, and solar radiation, provides a comprehensive assessment of human thermal stress across a wide range of climatic conditions. At the same time, Simpson et al. [44] argued that, despite the high diagnostic value of UTCI, climate studies should apply several heat stress indices simultaneously and report the underlying meteorological variables to evaluate whether the conclusions are independent of the selected index. The results of the present study support this recommendation by demonstrating that the choice of sultriness index can substantially influence estimates of both the magnitude and rate of change in the annual number of sultry days.

The analysis of diurnal variability further demonstrates that the choice of index affects not only the frequency of sultry conditions but also their distribution throughout the day. Humidex, Tek, and AT showed a pronounced diurnal cycle, with the highest frequencies generally occurring at 12:00 UTC, whereas the Scharlau criterion showed a broader diurnal distribution extending into the evening and nighttime. These differences reflect the varying sensitivities of the indices to changes in air temperature and atmospheric moisture and should be considered when assessing the timing of thermal discomfort.

All analyzed stations exhibited increasing numbers of sultry days regardless of the applied sultriness criterion. This increase occurred concurrently with rising mean annual air temperature and increasing maximum water vapor pressure, indicating progressively more frequent meteorological conditions favorable for exceeding sultriness thresholds and intensifying combined thermal and moisture stress. These findings are consistent with previous studies conducted in Poland, which also reported increasing numbers of sultry days and a growing risk of heat-related physiological stress [1,6,12,15]. Compared with the study by Falarz [1], which covered the period 1966–2000, the maximum annual number of sultry days increased from 35 to 50 in Lesko and from 30 to 59 in Łeba, indicating a further intensification of sultry conditions during the twenty-first century. Similar trends have also been reported outside Poland. For example, Muthers et al. [18] projected a marked increase in the frequency of extreme heat waves in neighboring Germany as a consequence of climate change. Studies from other regions of the world likewise indicate that the intensification of hot and humid conditions is a global phenomenon [2,20,47,48].

The observed changes also reveal clear regional differences in both the number of sultry days and the duration of uninterrupted sultry periods. The highest frequency of sultry days was recorded at Sulejów, representing the lowland region of central Poland, intermediate values occurred at the foothill station in Lesko, whereas the lowest frequency was observed at the coastal station in Łeba. These differences reflect the contrasting climatic and physiographic conditions of the analyzed regions. Because all three stations are located outside densely urbanized areas, the results are not substantially affected by the urban heat island effect. Dense urban surfaces, such as concrete and asphalt, promote the occurrence of sultry conditions, whereas well-ventilated areas with abundant vegetation generally experience lower thermal and moisture stress [12]. The relatively low number of sultry days at Łeba can be attributed to the moderating influence of the Baltic Sea, which limits summer air temperatures [1,16]. In contrast, the higher elevation of Lesko favors lower air temperatures [49] and better ventilation conditions [9,11]. This interpretation is supported by the present results, which show that the increase in sultry days at Lesko occurred despite the absence of a significant trend in maximum water vapor pressure, suggesting

that rising air temperature was the primary driver of increasing sultriness. In Sulejów, the lack of maritime influence and its relatively low elevation promote high air temperatures while maintaining relatively high atmospheric moisture, thereby favoring the occurrence of sultry conditions.

The results further demonstrate that not only the number of sultry days but also the duration of uninterrupted sultry periods increased during the study period. From a biometeorological perspective, this finding is particularly important because prolonged periods of sultry conditions reduce opportunities for physiological recovery. Similar increases in the duration of sultry periods have also been reported in previous studies conducted in Poland [6,11,12]. Prolonged accumulation of heat within the human body and reduced opportunities for physiological recovery, particularly during nighttime, increase cardiovascular strain and elevate the risk of cardiovascular events [50,51]. Consequently, the duration of sultry episodes may be of greater importance for public health than the total number of sultry days, highlighting the value of analyzing consecutive sultry days when assessing both climate change impacts and associated health risks.

From a practical perspective, the observed increase in both the frequency and persistence of sultry conditions may have important implications for everyday activities in Poland [1,12]. Hot and humid conditions increase thermal discomfort by reducing the efficiency of evaporative cooling and may consequently enhance physiological heat strain [7,10,17]. This is particularly relevant to prolonged physical activity and outdoor work, as thermal stress may adversely affect thermal perception, physiological strain, and work capacity [2,7,43].

More frequent and persistent sultry conditions may also reduce the thermal suitability of weather conditions for outdoor recreation and tourism, for which biometeorological conditions constitute an important environmental factor [2,13,14]. The regional differences identified in the present study are particularly relevant because the stronger increase in the frequency and persistence of sultry conditions at the inland stations indicates greater exposure to persistent hot and humid weather in these regions [1,12,15].

Increasing exposure to prolonged hot and humid conditions is also relevant to public health, as severe heat stress may increase the risk of adverse health outcomes, including cardiovascular strain [47–49,52]. These findings may therefore support the planning of outdoor activities, occupational heat-protection measures, and the management of tourism and recreational activities during periods of persistent hot and humid weather [2,7].

The observed increase in both the frequency and duration of sultry episodes indicates that biometeorological conditions in Poland will increasingly require adaptation measures. Matthews et al. [52] demonstrated, using examples from South Asia, that the relationship between air temperature, atmospheric humidity, and heat stress is highly nonlinear. Consequently, future warming comparable to that already observed may lead to disproportionately larger increases in health risks and societal impacts. Similarly, Russo et al. [53] showed that the probability of extreme heat waves in Europe is expected to increase substantially during the coming decades, even if the average increase in air temperature appears relatively modest. In light of the present findings, further development of Heat Health Warning Systems (HHWS) and effective heat adaptation strategies becomes increasingly important. Achieving this goal requires consistent methods for assessing thermal stress and an international consensus on integrating meteorological observations with models describing human physiological responses to atmospheric conditions [2,18]. The ability to quantify thermal discomfort under different climatic conditions is essential for both climate change research and practical applications in public health and civil protection [54,55]. The increasing duration of sultry periods observed in this study confirms

that unfavorable biometeorological conditions are becoming progressively more persistent, thereby increasing long-term thermal and moisture stress on the human body [5,15].

Although the specific climatic results obtained in this study refer to the three analyzed stations in Poland, the methodological framework can be applied to other regions with long-term meteorological observations. In particular, the comparison of multiple sultriness indices, together with the analysis of their diurnal variability, episode duration, seasonality, and long-term trends, provides a general approach for assessing sultriness conditions across different climatic settings. Such an approach also allows the influence of the choice of index on the detected frequency, persistence, and long-term changes in sultry conditions to be evaluated. Therefore, when applying the methodology to other regions, the climatic context and the characteristics of the selected index should be taken into account when interpreting and comparing the results.

5. Conclusions

Overall, the results provide consistent evidence of a long-term increase in sultry conditions across the three contrasting climatic regions of Poland, while also demonstrating that their estimated frequency and magnitude depend strongly on the index used for their identification. The comparison of four biometeorological approaches highlights the importance of the methodological choice when assessing long-term changes in sultriness.

1. **Influence of the sultriness index**: The frequency of sultry conditions in Poland depends strongly on the selected sultriness index. The estimated annual number of sultry days differed by more than a factor of three among the evaluated methods, highlighting the need for caution when comparing results obtained using different indices.
2. **Differences among sultriness indices**: The Scharlau criterion and the Apparent Temperature (AT) index identified the greatest numbers of sultry days, whereas the Tek index consistently identified the fewest. The Humidex index produced intermediate estimates between these methods.
3. **Humidex as the preferred index**: Among the evaluated methods, Humidex proved to be the most suitable index for assessing long-term changes in sultry conditions. It simultaneously accounts for the effects of air temperature and atmospheric moisture while effectively capturing the regional variability in the frequency of sultry days.
4. **Spatial variability**: The occurrence of sultry days exhibited pronounced spatial variability. The highest frequency was recorded at Sulejów, an intermediate frequency at Lesko, and the lowest frequency at Łeba. The only exception was the Scharlau criterion, which yielded very similar numbers of sultry days at all analyzed stations.
5. **Effects of method and location:** The linear mixed-effects model confirmed that both the selected sultriness index and station location had significant effects on the annual number of sultry days. The significant interaction between these factors indicates that the evaluated indices differ in their sensitivity to regional variations in thermal–moisture conditions.
6. **Diurnal variability of sultry conditions:** The timing of sultry conditions varied among the indices, with Humidex, Tek, and AT showing the highest frequencies generally at 12:00 UTC, while the Scharlau criterion indicated a more extended occurrence throughout the day.
7. **Increasing frequency of sultry days**: All analyzed stations exhibited significant increases in the annual number of sultry days during the period 1966–2025. Positive trends were detected irrespective of the sultriness index applied, indicating a systematic intensification of meteorological conditions conducive to thermal discomfort.
8. **Regional differences in trends:** The strongest increase in the annual number of sultry days was observed at Sulejów, whereas the weakest increase occurred at Łeba,

suggesting that thermal–moisture conditions have changed more rapidly in inland Poland than along the Baltic coast.

9. **Role of temperature and atmospheric moisture:** The increase in the number of sultry days was primarily driven by rising air temperature. All analyzed stations exhibited significant positive trends in mean annual air temperature, whereas changes in annual maximum water vapor pressure were weaker and showed less spatial consistency.
10. **Longer sultry periods:** In addition to the increasing number of sultry days, the maximum duration of sultry periods also increased over the study period. This tendency was particularly evident at Sulejów and Lesko, where significant positive trends were identified for all analyzed indices.
11. **Implications of climate warming**: The results indicate that ongoing climate warming is associated not only with an increasing frequency of sultry days but also with progressively longer-lasting sultry episodes. These changes are likely to increase thermal stress on the population and exacerbate the adverse health and environmental impacts of hot and humid weather conditions.
12. **Need for multiple indices**: The observed differences among the evaluated indices demonstrate that no single index is sufficient to comprehensively characterize sultry conditions. The indices differed not only in the estimated frequency and long-term trends of sultry days but also in their diurnal patterns. Because thermal stress is determined by both air temperature and atmospheric moisture, and individual indices assign different weights to these variables, the combined application of several indices provides a more comprehensive assessment of sultry day occurrence and a more robust evaluation of the potential impacts of climate change on thermal comfort and human health.

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Conflicts of Interest: The authors declare no conflicts of interest.

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