



Evaluation of outdoor thermal comfort conditions: evidence from the Serbian major ski resort over the last 30 years

Slavica Malinović-Milićević¹ · Marko D. Petrović^{1,2} · Milan M. Radovanović^{1,2}

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Abstract

The study aims to present reliable information about thermal conditions and their impacts on visitors to ski travel destinations. Mountain tourism areas are specific since high altitudes affect the ambient weather conditions which can affect different types of human activities. In this paper, the thermal comfort and its changes in Kopaonik Mountain, the most popular ski resort in Serbia over the last 30 years, have been evaluated. Information about thermal comfort is presented by using the Universal Thermal Climate Index (UTCI), physiologically equivalent temperature (PET), and modified physiologically equivalent temperature (mPET) in 3-h resolution for the period 1991–2020. The results indicate prevailing cold stress all year round. Days with moderate, strong, and very strong heat stress were not recorded. Strong and extreme cold stress prevailed during winter, while slight and moderate cold stress prevailed during summer. Transitional seasons were very cold, but autumn was more comfortable than spring. The occurrence of days with neutral and slightly warm/cool conditions is concentrated in the summer months. However, summer is not used enough for tourism because the choice of tourists to stay at Kopaonik is not primarily based on favorable bioclimatic conditions, but on resources for winter tourism. With global warming, the annual number of thermally favorable days has been increasing, while the number of days with extreme and strong cold stress is decreasing. Continuing this trend can significantly influence tourism in the future, and therefore, new strategies in ski resorts will be required to adapt to the changing climate.

Keywords Thermal comfort · Tourism · UTCI · PET · mPET · Kopaonik Mountain

Introduction

The tourism market is a significant source of economic income for many countries around the world. Among other natural resources, meteorological resources are a very important factor that influences the individual perception of the quality of tourist destinations and plays a significant role in the tourists' decision-making process. The enjoyment of tourists at a particular location largely depends on weather conditions, and it is to a large degree based on thermal comfort (Lin and Matzarakis 2008; Perch-Nielsen et al. 2010). Thermal comfort is assessed by subjective assessment and it is defined as “that state of mind that expresses

satisfaction with the thermal environment” (ASHRAE1966; Fanger 1970). Meteorological conditions affect the ability to stay outdoors. Also, performing certain physical activities is closely related to meteorological conditions, such as temperature, precipitation, wind speed, cloud cover, and air humidity. Different values and combinations values of meteorological variables not only affect the subjective feeling of comfort in the natural environment but also affect the psychological or physiological state of people. Although there are large spatial and temporal variations in microclimatic conditions, the environment is often evaluated only in terms of air temperature. Too-hot locations reduce the time spent on outdoor activities, while those that are too cold or too humid can prevent such activities altogether. However, besides air temperature, humidity, wind speed, and solar radiation, physical activity and clothing insulation are key elements that influence the “comfort zone.” Therefore, an accurate assessment of thermal comfort implies consideration of both environmental and psychological conditions, while information about the climate of tourist destinations

✉ Slavica Malinović-Milićević
s.malinovic-milicevic@gi.sanu.ac.rs

¹ Geographical Institute “Jovan Cvijić” SASA, 9 Đure Jakšića St, 11000 Belgrade, Serbia

² Institute of Sports, Tourism and Service, South Ural State University, 76 Lenin A, 454080 Chelyabinsk, Russia

should not include only general climate characteristics, but also information about outdoor bioclimatic comfort conditions.

Numerous studies describe different thermophysiological indices for the quantification of thermal conditions (Höppe 1999; Matzarakis et al. 2010, etc.) and their use in different environments, climates, and regions (Mayer and Höppe 1987a, b; Konstantinov et al. 2020; Peñalba et al. 2021 etc.), as well as their influence on tourism (Amelung et al. 2007; Roshan et al. 2016; Kapetanakis et al. 2022; etc.). In climate–tourism research, commonly used thermophysiological indices for the quantification of thermal conditions are predicted mean vote (PMV, Fanger 1970), perceived temperature (PT, Jendritzky et al. 1990, standard effective temperature (SET*, Gagge et al. 1986), physiological equivalent temperature (PET, Höppe 1999), and Universal Thermal Climate Index (UTCI, Jendritzky et al. 2012). All these indices include meteorological and physiological parameters and are well described by Matzarakis (2001a, b). These thermophysiological indices require the input of the same meteorological parameters, but each of them has a specific thermophysiological basis and applicability. Considering physiological factors, PET and its modification mPET allow variable parameters (Chen et al. 2020), PT and UTCI use a fixed value of activity (Staiger et al. 2012), and SET* uses standardized conditions (Chen et al. 2020). When it comes to clothing adaption, PET does not use a self-adapting clothing model (Höppe 1999); PT, UTCI, and mPET have adjusted one based on temperature (Matzarakis 2021); and SET* uses clothing adjusted by metabolic rate (Charalampopoulos and Nouri 2019; Chen et al. 2020; Wu et al. 2020, etc.). PET and UTCI are more commonly used than other thermal indices because of their units (°C), which makes the results more easily interpretable (Matzarakis et al. 1999).

Mountains are popular tourist destinations that attract visitors through natural landscapes, wildlife, clean air, and specific climate. Mountain areas are suitable areas for different kinds of outdoor tourist and recreational activities (walking, hiking, skiing, etc.). Mountains are important from the point of view of bioclimatic research because they modify weather conditions: decrease atmospheric pressure, temperature, and humidity; increase insolation; and enhanced receipt of solar radiation. There are several papers presenting the biometeorological conditions of the mountain in Europe (Zaninović et al. 2006; Endler and Matzarakis 2011a, b; Błażejczyk et al. 2021a, b, etc.). In Serbia, mountains and hills occupy more than 70% of the area. Areas with altitudes above 1000 m make up about a tenth of the territory and are located in the southern part of the country. Several mountain ranges offer good conditions for outdoor recreation, while the most visited are Zlatibor and Kopaonik. Until now, there have been several papers presenting the biometeorological conditions of mountains in Serbia, mostly Zlatibor. Basarin

et al. (2018) presented bioclimatic conditions at Zlatibor by using physiologically equivalent temperature (PET) and Universal Thermal Climate Index (UTCI). Pecelj et al. (2017) investigated bioclimatic differences during the summer between the city of Belgrade and the mountain resort of Zlatibor by using heat load (HL) in man and UTCI. Błażejczyk et al. (2021b) assessed thermal conditions in nine mountains in Central and Eastern Europe, including Zlatibor, using UTCI. Błażejczyk et al. (2021a) used the weather suitability index (WSI) to assess the suitability of the climate for outdoor tourism and recreation at several European locations, including Zlatibor. When it comes to Kopaonik, if we analyze the scientific works in the field of bioclimatology, back in 1961, Vujević (1961) investigates the equivalent temperature (ET) and cooling power (CP), while the works on the topic of climate influence on the tourism sector are more numerous (Anđelković et al. 2016; Stojsavljević et al. 2016; Pecelj et al. 2018; Pavlović et al. 2020; Lukić et al. 2021, etc.). Based on the review of previous research, there is an evident lack of studies investigating the outdoor thermophysiological comfort in Kopaonik. Given that climate change will, among others, affect tourism, it is important to take a closer look at past and current thermophysiological comfort conditions, as well as investigate interactions between them and tourism. This research is to a lesser extent similar to the earlier articles of the co-authors (Malinovic-Milicevic et al. 2013; Malinović-Milićević 2013; Lukić et al. 2021; Pecelj et al. 2021), but essentially, it is a new topic that has now been explored for the first time by the co-authors and presented in the form of this manuscript. The aim of the study is to present initial research dealing with the assessment of human thermal comfort conditions outdoors in the high-altitude tourist center Kopaonik as well as their impacts on tourist flows. For that purpose, information about thermal comfort was presented by using three thermophysiological indices (UTCI, PET, and mPET). The study is based on data with a 3-h resolution for 30 years (period 1991–2020), providing the opportunity to analyze trends and assess thermal conditions not only in different parts of the year but also in different parts of the day.

Materials and methods

Research area

Kopaonik, one of the highest mountains in Serbia, is located in the southern part of central Serbia, between 43° 28' and 42° 43' north latitude and between 20° 37' and 21° 24' eastern longitudes (Mijatov et al. 2016). It stretches in a northwest-southeast direction with a length of 82 km and a width of 40 to 60 km. The total area of the mountain massif

is about 2750 km² (Bursać 1991), while 119.69 km² was declared a national park in 1981 (Fig. 1).

According to Beck et al. (2018), the Köppen-Geiger classification of the ski center Kopaonik belongs to the “Dfc” climate type, which implies a continental cold snow climate with cold summer. In this climate type, according to the Köppen-Geiger classification, the monthly mean temperature of the coldest month is $-3\text{ }^{\circ}\text{C}$ or lower, while the temperature of 1–3 months averages above $10\text{ }^{\circ}\text{C}$, but the temperature of the warmest month is less than $22\text{ }^{\circ}\text{C}$. In particular, in Kopaonik, the coldest month is February with an average monthly temperature of $-5.1\text{ }^{\circ}\text{C}$. The summer months (June to August) are above $10\text{ }^{\circ}\text{C}$, while the warmest is August. Precipitation is evenly distributed throughout the year.

Kopaonik Mountain has good facilities for both summer and winter outdoor recreation. The basis of mountain tourism in Kopaonik is winter tourism (skiing and other winter sports), while in the rest of the year, most people come for passive vacation and leisure activities, such as walking and enjoying nature (Petrovic et al. 2016). The high peaks of Kopaonik (Pančičev vrh (2017 m), Suvo Rudište (1976 m), Veliki Karaman (1936 m), and Velika Gobelja (1934 m))

enable the formation of high-quality alpine ski trails, while the vast plateau of Ravni Kopaonik (1600–1800 m) is suitable for Nordic and tour skiing (Đorđević et al. 2016). It represents the oldest and the largest ski center in Serbia (Ćurčić et al. 2019), with more than 55 km of trails and ski roads arranged for alpine disciplines and 12 km of trails for Nordic skiing, all of which are connected by a vertical ski transport system that can handle 32,000 skiers an hour (Ski Resorts of Serbia 2022). There are also conditions for night skiing from 18:00 to 22:00 local time. The alpine ski field is located at an altitude of 1057 to 2017 m above sea level. The resort is equipped with an artificial snowing system that covers 97% of the trails.

Tourist traffic in Kopaonik has significantly changed in the last 30 years. Figure 2a shows a decreasing trend in the number of overnight stays of both domestic and foreign tourists in the first two decades of the observed period when the number declined from approximately 730,000 overnight stays in 1992 to 230,000 in 2010. After that, there has been an increase in the number of overnight stays, although in 2020 there is again an evident decrease due to the COVID-19 outbreak. The trend of overnight stays of domestic tourists was similar to the trend of total tourist overnight stays,

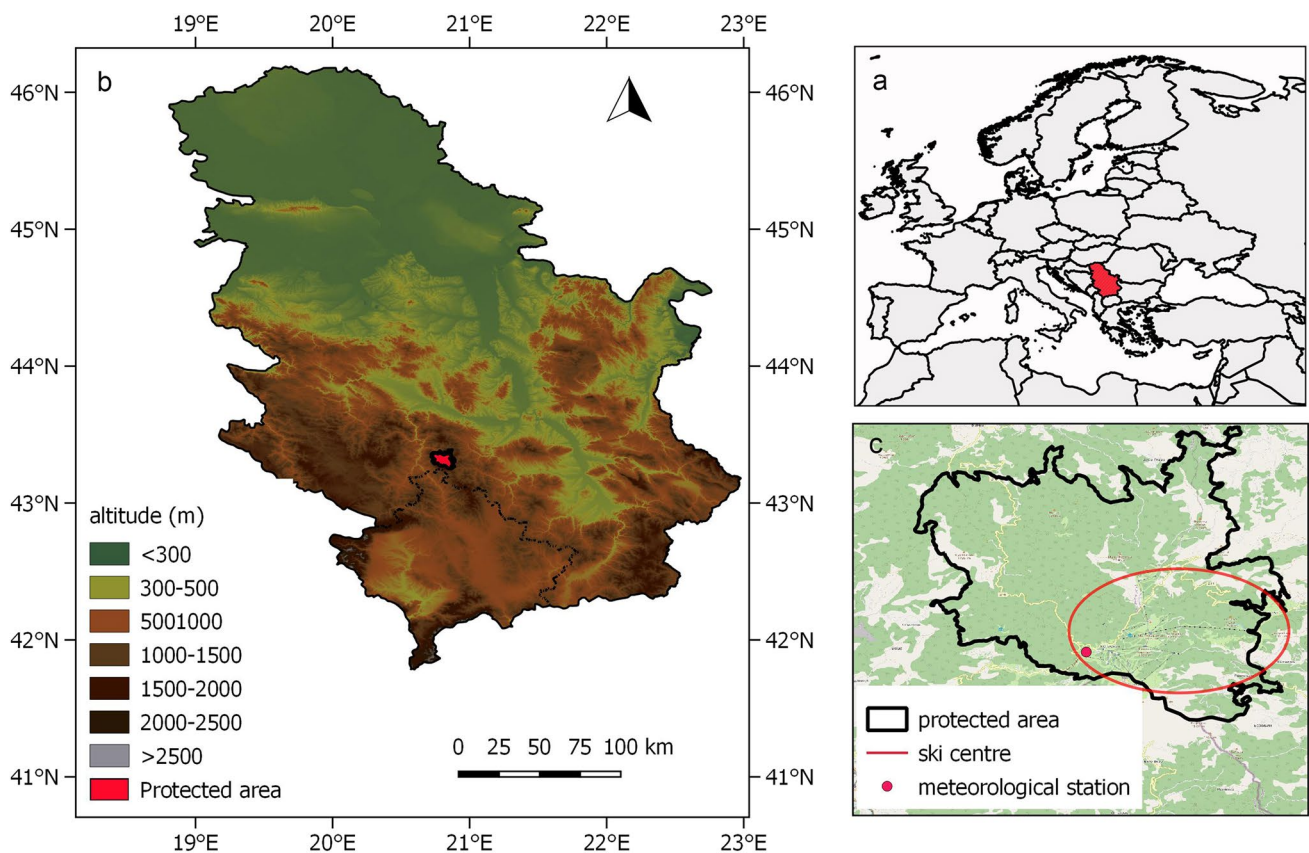


Fig. 1 The geographical position of the research area: **a** Serbia in Europe, **b** map of Serbia, and **c** National park Kopaonik (protected area), the position of the ski center and meteorological station

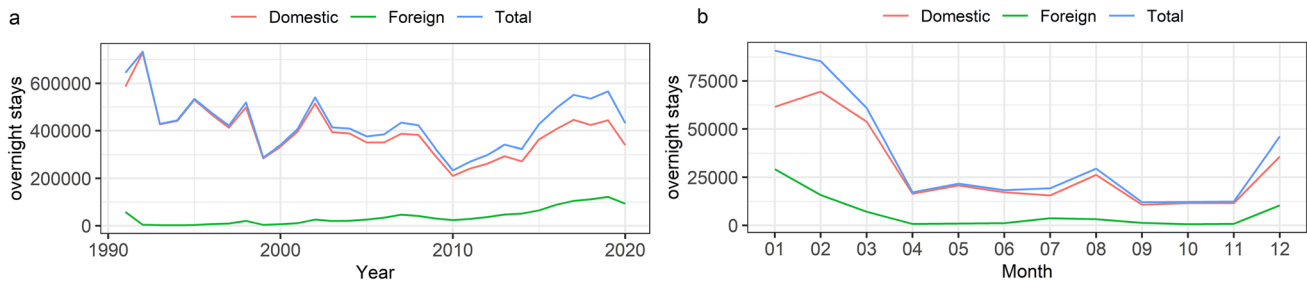


Fig. 2 Overnight stays of tourists at Kopaonik **a** by year (for the period 1991–2020) and **b** by months (for the period 2011–2020)

while the number of foreign tourists has been gradually increasing since the 2000s. The largest number of foreign tourists was recorded in 2019. Figure 2b shows a many times higher number of total overnight stays in the winter months than the rest of the year. The highest number of overnight stays was recorded in January (around 90,000), and the lowest was in September, October, and November (around 12,000). The trend of domestic tourists is almost the same with a slightly lower number of overnight stays from January to March. Foreign tourists mostly visit this mountain during winter, but their number is low.

Data description

Meteorology data including air temperature (T), wind speed (ws), and relative humidity (RH) in 3-h resolution (00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, 21:00 Universal Time Coordinated (UTC)) for the measuring station Kopaonik (43.283 N, 20.8 E, 1713 m asl) were downloaded from the Integrated Surface Database (ISD) of the National Centers for Environmental Information (NCEI) of the National Oceanic and Atmospheric Administration (NOAA) for the 30 years between 1991 and 2020. The ISD database provides access to global hourly and synoptic observations compiled from numerous sources organized into a single common ASCII format (NOAA 1901—present). Quality control in the ISD is performed by automatic software and involves checking the correct data format for each field, extreme values, and limits, consistency between parameters, and continuity between observations (Lott 2004). For the year 2005, the data for all three parameters is completely missing, so this year is excluded from the analysis. Since the cloud cover data in the ISD NOAA database is sparse, this data was taken from the Copernicus European Regional ReAnalysis (CERRA) datasets that provide spatially and temporally consistent historical reconstructions of meteorological variables in the atmosphere and at the surface in $5.5 \text{ km} \times 5.5 \text{ km}$ resolution (Schimanke et al. 2021). NOAA and Copernicus's data used here are spatially comparable since the area covered by one CERRA raster cell comprises both the meteorological station and the entire ski

center Kopaonik. Since the NOAA data are available at a 3-h resolution, while the Copernicus data are available at a 1-h resolution, we matched and used the 3-h resolution data to be fully time-aligned. Calculations of thermophysiological indices analyzed in this study were done for 78,385 measuring terms (that is, 92.82% of availability if we exclude the year 2005).

Methodology

The assessment of outdoor thermal comfort is assessed using UTCI, PET, and mPET indexes which are calculated using the RayMan Pro model (Matzarakis et al. 2007, 2010). The RayMan Pro model requires the input parameters T, RH, and ws while the mean radiant temperature can be calculated based on global radiation or cloud coverage.

The Universal Thermal Climate Index is a comprehensive thermal comfort indicator that describes how the human body experiences atmospheric conditions recommended by the World Meteorological Organization (WMO) (Kolendowicz et al. 2018). It is based on an advanced multi-node Fiala thermoregulation model (Fiala et al. 2011) and is capable to assess whole-body and local thermal effects (Błażejczyk et al. 2010). The UTCI is defined as the air temperature of the reference environment that produces the same value of strain index compared to the reference response of the person to the actual environment. Reference environment implies calm air (ws of 0.5 m/s on 10 m above the ground), RH=50%, and radiant temperature equal to air temperature (Jendritzky et al. 2012). The physiological parameters are set fixed in UTCI calculations and they accept the walking of the average person at speed of 1.11 m/s with heat production of 135 W/m^2 , while clothing is adaptable based on the actual temperature of air (Jendritzky et al. 2012). Limitations for the applicability can lead to a tendency that some results can be omitted since the calculation is limited by the range of wind speed from 0.5 to 17 m/s, air temperatures from -50 to $50 \text{ }^\circ\text{C}$, and relative humidity from 10 to 100%. To facilitate the interpretation of UTCI results, Błażejczyk et al. (2013) proposed a thermophysiological stress classification offering 10 different categories of heat and cold stress (starting with the CS5 category). However, to comprehensively delineate

thermophysiological conditions in cold mountain climates and better represent values below $-40\text{ }^{\circ}\text{C}$, we added three additional levels to the existing Błażejczyk et al. (2013) classification (CS6, CS7, CS8). Given that the possibility of cold stress in mountainous areas is increased, such an extension for additional levels was introduced to better describe the categories of cold stress when UTCI falls below $-40\text{ }^{\circ}\text{C}$. Since the initially determined category of CS5 at this location included a wide range of values (from -40 to $-57\text{ }^{\circ}\text{C}$), the introduction of additional levels aims to better identify and represent the extent and frequency of different levels of extreme cold events.

The PET index was obtained from the energy balance equation of the human body and defined as “the air temperature at which, in a typical indoor setting (without wind and solar radiation), the energy budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed” (Mayer and Höppe 1987a, b; Höppe 1999). It is based on the Munich Energy-Balance Model for Individuals (MEMI) where activity, clothing insulation, height, and weight are usually standardized. In this research, the average values of physiological characteristics are used: male age of 35 which is a height of 1.75 cm and weight of 75 kg. For the clothing insulation,

a value of 0.9 was taken, and 80 W/m^2 was intended for the amount of activity. A shortcoming of PET is its slight variation influenced by changing the humidity and clothing insulation, and therefore, it is not appropriate to be applied in highly humid conditions. Matzarakis and Mayer (1996) proposed nine categories of thermal perception for central Europe that are presented in Table 1 (starting with the CS4 category). Similar to the UTCI, to better represent values within the coldest provided category (CS4), we limited the CS4 category and added three additional levels (CS5, CS6, CS7). These levels are also proposed and applied to studies conducted by Matzarakis (2014) and Santos Nouri et al. (2021).

The mPET index is also based on MEMI principles, but with several changes in calculation parameters that have already been shown to give slightly different estimates of thermophysiological conditions, especially in extreme climates. The two main modifications of mPET in relation to PET are the thermoregulation model and the clothes model. Unlike PET which is a two-node model, mPET is based on a multiple-segment body model with a passive heat transfer system in the body and the bio-heat equation. A self-adapting multiple-layer clothing model is used in mPET that

Table 1 Thermal stress classification for UTCI and PET/mPET (Błażejczyk et al. 2013; Matzarakis and Mayer 1996)

	$^{\circ}\text{C}$	Thermal stress category	Thermal perception	Abbreviations
UTCI	< -55	Beyond extreme cold stress 3 ^a	-	CS8
	-55 to -50	Beyond extreme cold stress 2 ^a	-	CS7
	-50 to -45	Beyond extreme cold stress 1 ^a	-	CS6
	-45 to -40	Extreme cold stress	-	CS5
	-40 to -27	Very strong cold stress	-	CS4
	-27 to -13	Strong cold stress	-	CS3
	-13 to 0	Moderate cold stress	-	CS2
	0 to $+9$	Slight cold stress	-	CS1
	$+9$ to $+26$	No thermal stress	-	NS
	$+26$ to $+32$	Slight heat stress	-	HS1
	$+32$ to $+38$	Moderate heat stress	-	HS2
	$+38$ to $+46$	Strong heat stress	-	HS3
	$\geq +46$	Very strong heat stress	-	HS4
	PET/mPET	< -20	Beyond extreme cold stress 3 ^a	-
-10 to -20		Beyond extreme cold stress 2 ^a	-	CS6
0 to -10		Beyond extreme cold stress 1 ^a	-	CS5
0 to 4		Extreme cold stress	Very cold	CS4
4 to 8		Strong cold stress	Cold	CS3
8 to 13		Moderate cold stress	Cool	CS2
13 to 18		Slight cold stress	Slightly cool	CS1
18 to 23		No thermal stress	Comfortable	NS
23 to 29		Slight heat stress	Slightly warm	HS1
29 to 35		Moderate heat stress	Warm	HS2
35 to 41		Strong heat stress	Hot	HS3
> 41		Extreme heat stress	Very hot	HS4

^aAdditional level

includes simulations of water vapor resistance and provides a different energy-exchanging profile due to an inhomogeneous clothing cover (Chen and Matzarakis 2018). Numerous studies have already documented the augmented ability of mPET to make more precise thermophysiological estimations and realistic assessments of thermal perception (Chen and Matzarakis 2018; Chen et al. 2020; Pecelj et al. 2021, etc.). The mPET uses the same classification as PET.

To detect significant trends in thermophysiological indices, the non-parametric Mann–Kendall test was used. The magnitude of the trend was assessed by Sen's slope estimator (Sen 1968). If not indicated otherwise, statistical significance refers to the 0.05 level.

Results

Analysis of averaged thermophysiological indices

Diagrams in Fig. 3 reveal the frequency of appearance of categories of UTCI, PET, and mPET (averaged over the day of the year and hour of the day) through three decades of the observed period, while diagrams in Fig. 4 illustrate annual (*X*-axis—averaged for each day of the year) and diurnal (*Y*-axis—averaged for the hour of the day) changes in thermophysiological indices.

Over the last 30 years, averaged UTCI values at the Kopaonik Mountain covered five out of the thirteen categories (CS4–NS), while PET and mPET values covered eight of twelve categories (CS7–NS). In general, the share of days with extreme, very strong, and strong cold stress decreased, while those with slight cold stress and no thermal stress increased (Fig. 3). Considering UTCI, no beyond extreme cold stress and extreme cold stress categories have been observed while considering PET and mPET, a very

high share of beyond extreme cold stress and extreme cold stress categories was observed. The noticeable positive shift towards less cold stress categories and a category without thermal stress is observed at the beginning of the twenty-first century. However, this positive shift was the most pronounced during the summer, while it was the weakest during the winter (because of lack of enough space, we did not present change by season in the current paper).

Figure 4 reveals that cold stress was prevailing throughout the year. PET and mPET show that in the cold period of the year (October–March), strong and extremely stressful conditions (CS3–CS6) prevailed throughout the day, while UTCI shows that in the middle of the day, extremely cold stress conditions can be replaced by very strong and strong cold (CS4 and CS3). As the days became longer, in late spring (and early autumn), thermal conditions became less stressful in the middle of the day, while at night, early morning, and late evening, cold thermal conditions remain extreme and strong (CS4 and CS3). During the summer, averaged values of thermophysiological indices show the appearance of NS conditions between 09:00 and 15:00. The longer duration of the categories with a lower degree of cold thermal stress and without thermal stress during the year is also noticeable through the different decades.

Frequency distribution analysis

The frequency distribution diagrams depicted the resulting frequency of thermal stress categories for the nocturnal and diurnal periods. Figures 5 and 6 present the annual course of frequencies (expressed in percentages) of thermal stress categories of all three UTCI, PET, and mPET indices in Kopaonik at different times of day expressed through 10-day periods.

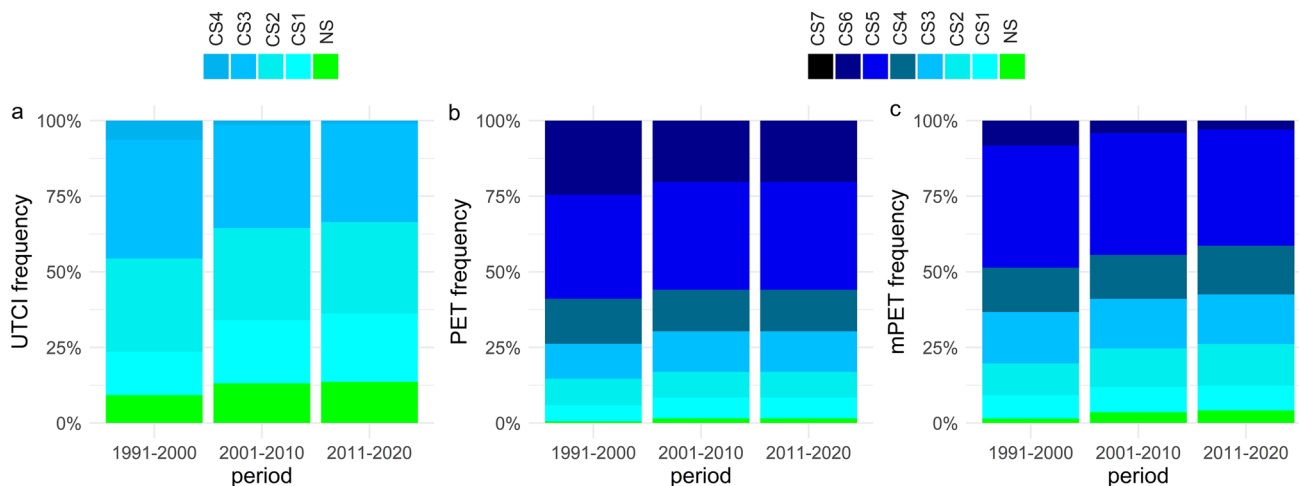


Fig. 3 Frequency diagrams of UTCI, PET, and mPET categories

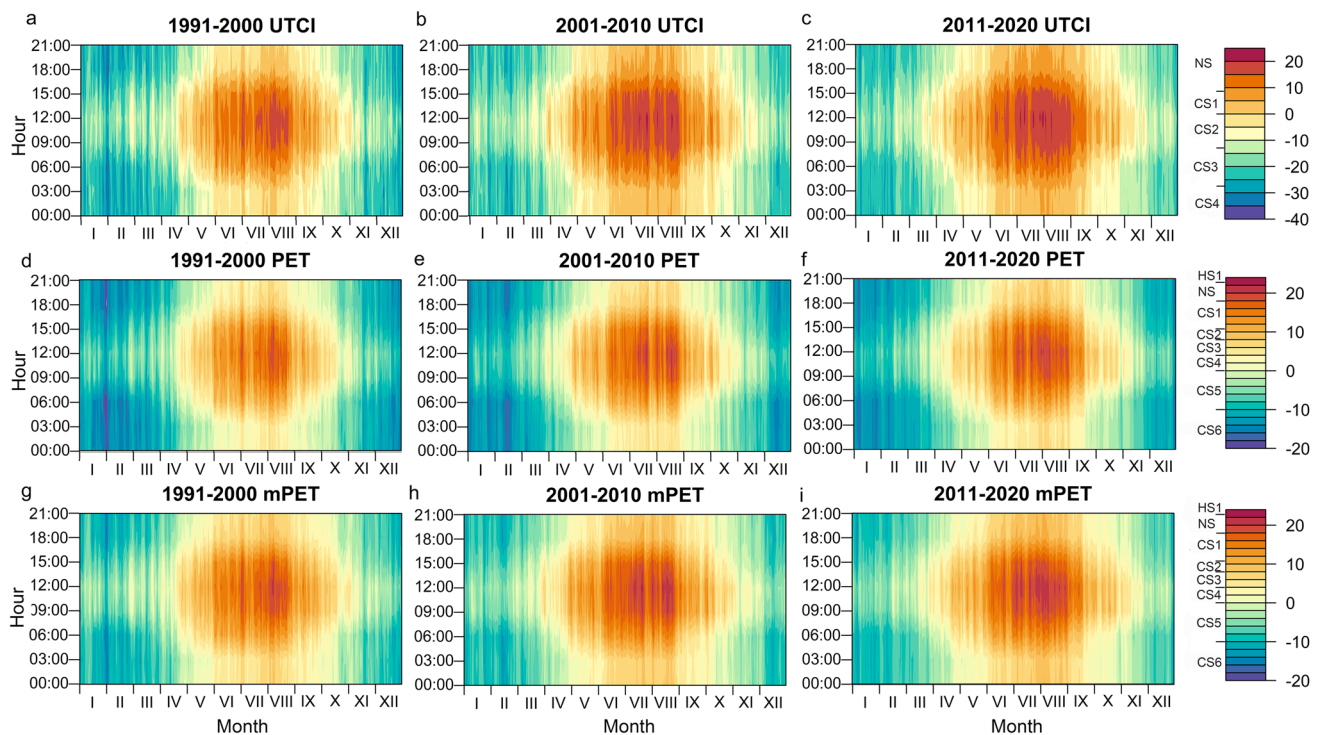


Fig. 4 Annual distribution of UTCI, PET, and mPET indices in hourly data at Kopaonik Mountain during three different decades in the period 1991–2020

Considering nocturnal exposure, heat stress levels were often below -40 (UTCI) and 4 °C (PET, mPET), so the original lower limit of cold stress would not have been able to effectively represent the more extreme climatic conditions recognized for the months between November and April. Therefore, the expanded categories of cold stress, shown in Table 1, allowed variations in thermal stress levels to be better displayed and analyzed. In the coldest measurement hour (03:00 UTC), according to PET and mPET between December and March, it was possible to identify only beyond extreme cold stress categories. The most prominent category was CS6, with a frequency of about 45%. However, according to UTCI, the frequency of beyond extreme cold stress categories was much lower, up to 10%. The beyond extreme cold stress categories were also very frequent in morning and evening hours (06:00 and 18:00). According to MEMI indices (PET and mPET), morning and evening are extremely cold in the cold period of the year, with a frequency of almost 100% between December and February, and above 50% in transitional seasons.

Considering diurnal exposure, beyond extreme cold stress categories were very frequent in the cold period of the year, having a frequency above 80% in winter and between 20 and 60% in transitional seasons. According to UTCI, the NS category was very frequent during summer months in the period between 09:00 and 15:00 UTC, with a frequency of

up to 80%, while according to PET and mPET, it had quite a lower frequency and was the most frequent between the end of the June and middle of the August. Analysis of all indices revealed that winter mornings and evenings have similar thermal conditions, while summer mornings are more pleasant than evenings. Considering transitional seasons, autumn has more favorable thermal conditions than spring. From the end of May to the beginning of September is possible slight and moderate heat stress in the period between 09:00 and 15:00 UTC, however very rare (HS2 below 5% and HS1 up to 15%).

Trend analysis

In this section, we checked whether there are general trends in the average values of minimum and maximum and seasonal averages in three periods of days (morning—06:00 UTC, noon—12:00 UTC, and evening—18:00 UTC).

The variability of absolute and mean minimum and maximum values is demonstrated in Fig. 7. Analysis revealed that minimal values increased at a higher rate (0.38 °C, 0.13 °C, and 0.08 °C per year, for UTCI, PET, and mPET respectively) than maximal. In the decade 2001–2010, there was a noticeable increase in the variability of daily values of minimal and maximal MEMI indices. As an example, the 2004 dataset in particular showed the highest variability between

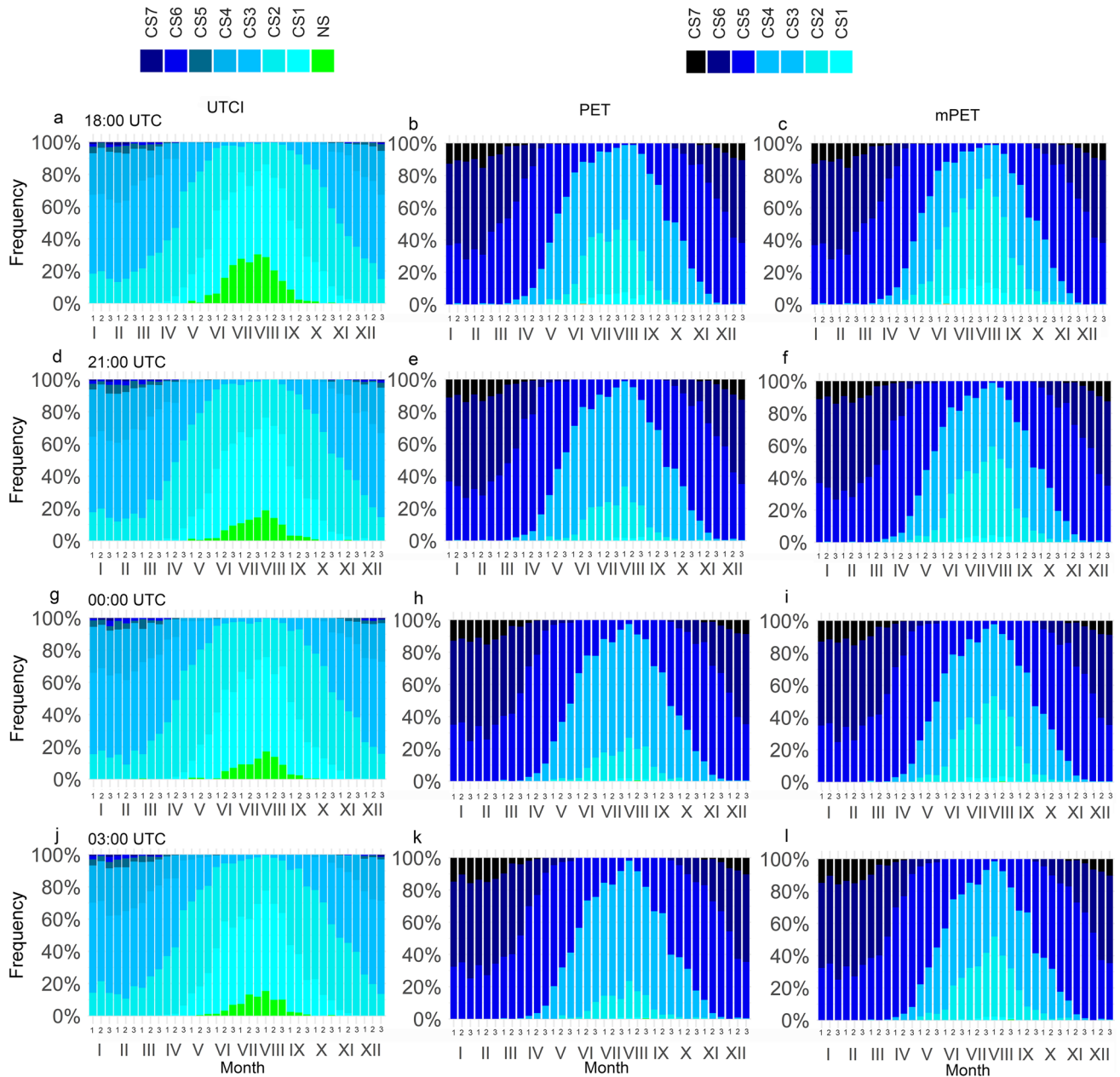


Fig. 5 The frequency of occurrence of different UTCI, PET, and mPET categories at different nocturnal periods

minimal and maximal values of MEMI indices which in numerical terms correspond to a variation of 71.9 °C and 61.7 °C for PET and mPET respectively. On a seasonal base, the year 2012 showed the highest variability between summer and winter indices, which in numerical terms correspond to a variation of 36.89 °C, 26.66 °C, and 24.67 °C for UTCI, PET, and mPET respectively. The 2003 dataset presented the second-highest variability between summer and winter averages, showing differences of 32.60 °C, 23.90 °C, and – 21.95 °C for UTCI, PET, and mPET respectively. Described enhanced variability based on average values and

the high difference between maximal and minimal values of thermophysiological indices which depict extreme conditions during the last decade are also visible in Fig. 4.

Figure 8 reveals positive trends of the morning, noon, and evening thermophysiological indices in all seasons. The trends of all three analyzed indices in almost all seasons were statistically significant ($p < 0.05$), except for MEMI indices in the winter season. UTCI shows that in all seasons, evening values increased at the highest rate, while MEMI indices show the highest rise of noon values in spring, summer, and autumn. Figure 8a–c show that, although winter mornings

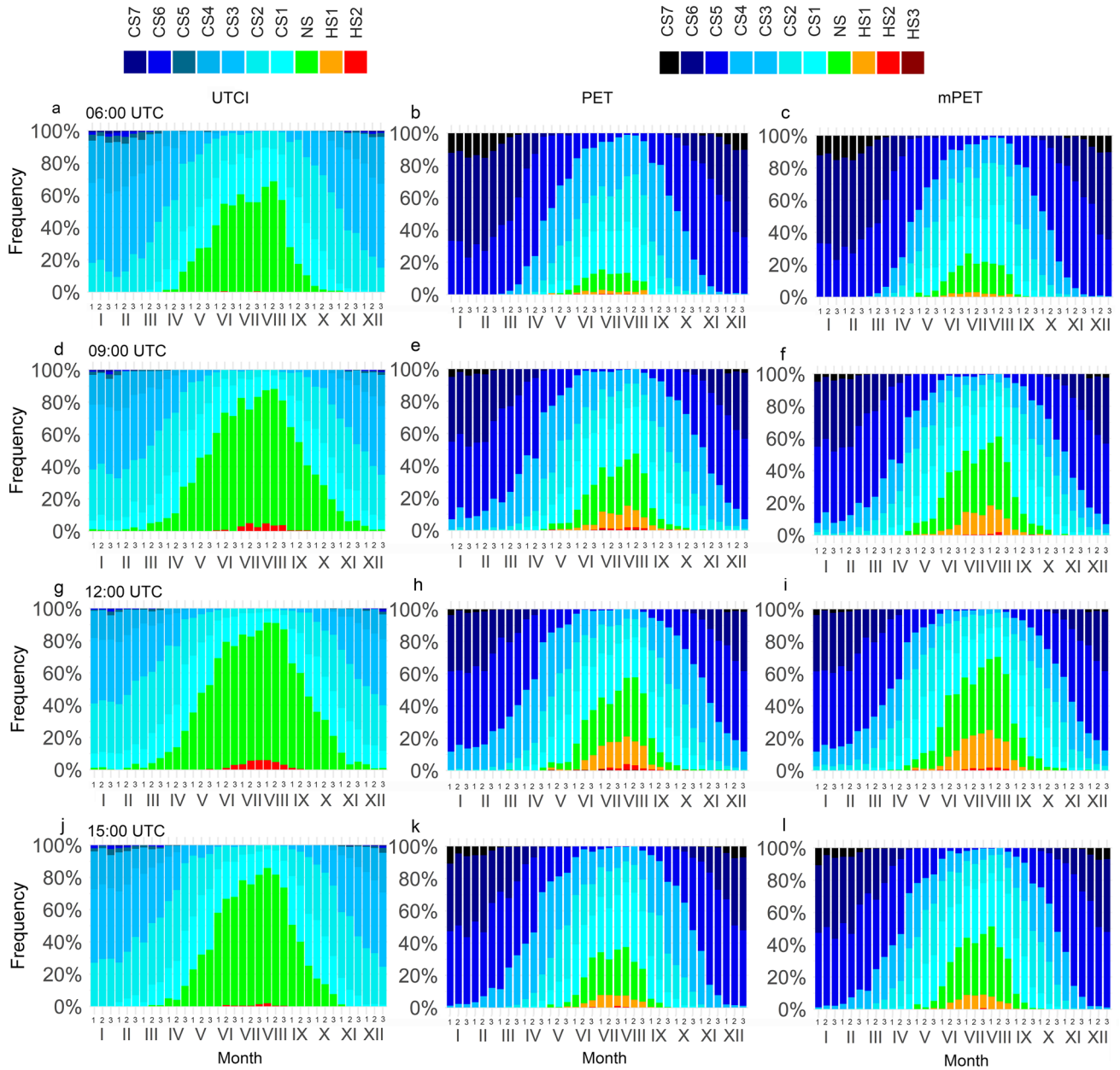


Fig. 6 The frequency of occurrence of different UTCI, PET, and mPET categories at different diurnal periods of the day

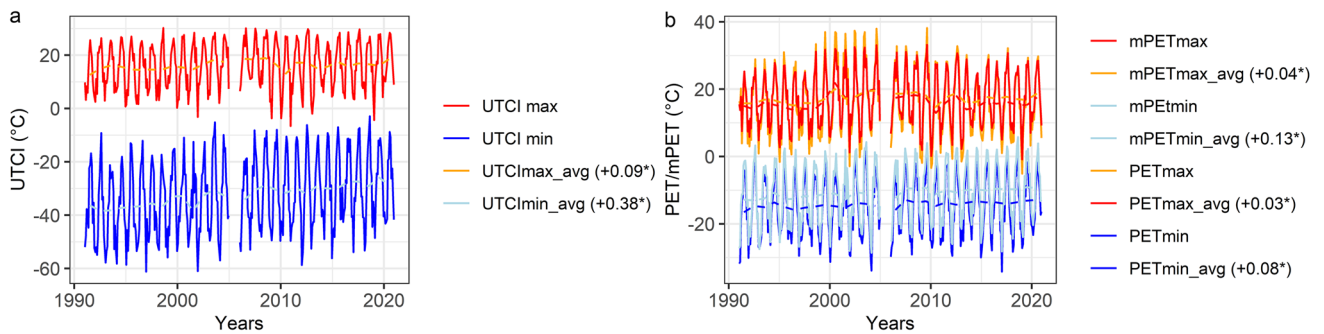


Fig. 7 Variability of absolute and mean minimum and maximum values of **a** UTCI and **b** PET and mPET in the period 1991–2020. *Indicates the significance of the trend ($p < 0.05$ level)

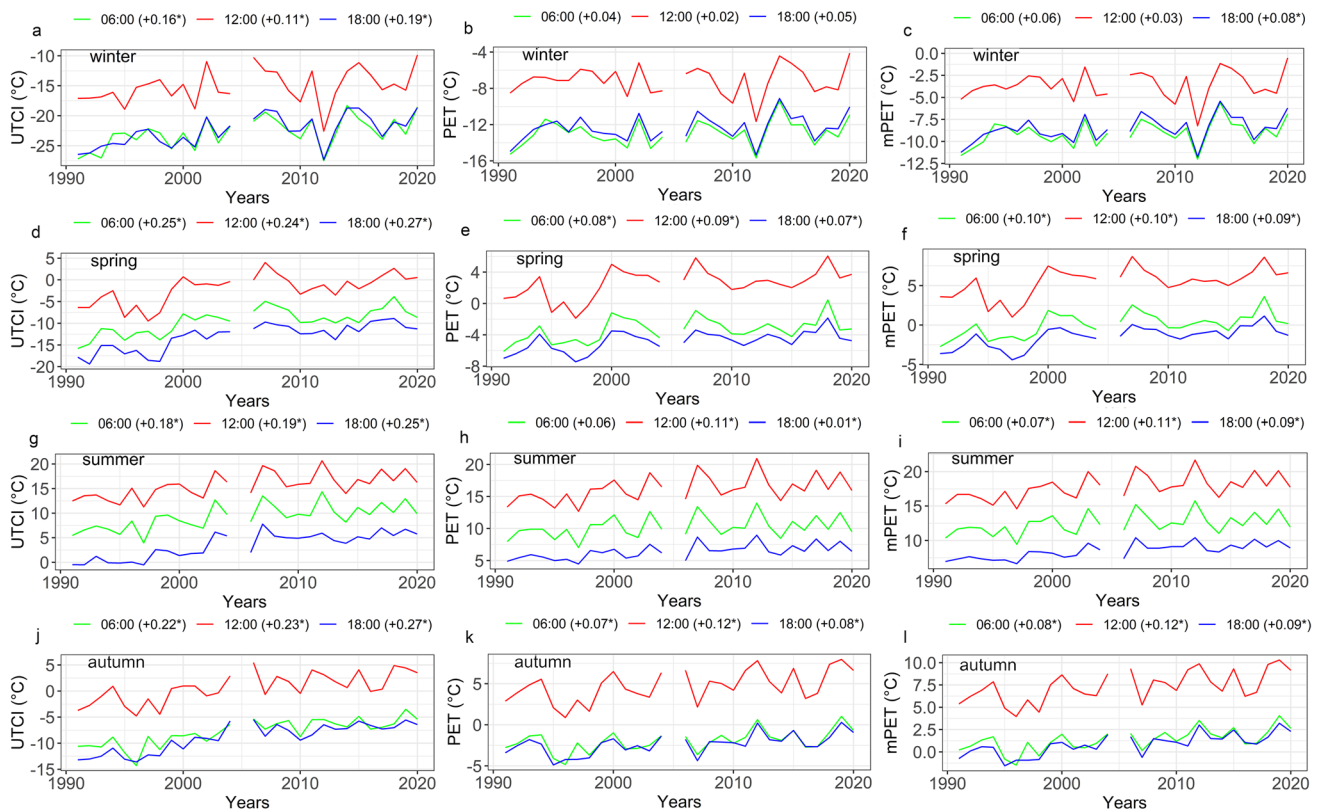


Fig. 8 Variability of seasonally averaged values of UTCI, PET, and mPET indices in the morning, noon, and evening. Trends in °C are shown in parentheses. *Indicates the significance of the trend ($p < 0.05$ level)

and evenings have similar thermal comfort conditions, winter evenings are still slightly more pleasant than mornings. Considering the different times of the day in transitional seasons, Fig. 8d–f and j–l show that spring mornings are considerably more pleasant than evenings, while autumn mornings and evenings have similar bioclimatological thermal conditions.

Discussion

Kopaonik ski resort is one of the most important tourist destinations in Serbia and the Western Balkans region. According to the Serbian Bureau of Statistics, more than 430,000 overnight stays of tourists are achieved at Kopaonik every year. Given that the number of tourists has been steadily increasing over the past decade, for the tourism economy, providing information about bioclimatic conditions is important to both decision-makers and visitors.

Comparison with other studies

Mountain climate is characterized by vertical zonation of meteorological elements. With increasing altitude, air

temperature decreases, wind speed increases, and global solar radiation and insolation gradually increase due to a decrease in optical masses of the atmosphere at elevated locations and cloud conditions where mountain tops are often above the clouds. Several authors report a gradual increase in the value of the thermal comfort index in different mountain regions, both over the years and with altitude. Therefore, we compared our results obtained by PET with results of other places at high altitudes: Qinghai–Tibet Plateau (Li and Chi 2014), Zavizan in the Croatian Dinaric Alps, and Kredarica in the Slovenian Julian Alps (Zaninović et al. 2006), and Sonnblick in the Austria Alps (Matzarakis et al. 2012). Similar to our results, cold stress prevails in all these sites. The thermal sensation varies from very cold winters to slightly cool/warm and neutral summers. Also, a positive trend in PET values was observed in all places.

Differences between thermophysiological indices

Observing the indices mutually, this study highlighted the differences in the results between the three processed indices. Compared to the MEMI indices, UTCI presented generally more attenuated cold stress levels, with a greater

frequency of NS category. UTCI is very sensitive to changes in temperature, humidity, solar radiation, and wind speed, and therefore, it well represents different weather conditions, while the others are more related to air temperature (Błazejczyk et al. 2013). However, a comparison between UTCI and PET is not recommended due to different levels of physical activity and different setups of clothing insulation (particularly in cold conditions). Discussing results between PET and mPET, it was shown that PET tends to vary more from the NS category compared to mPET, especially in extreme conditions, which is also shown by several other studies (Chen and Matzarakis 2018; Lin et al. 2018; Santos Nouri et al. 2021). This is due to modifications of the clothing insulation in the mPET model, which is the main difference in comparison to PET. According to Chen et al. (2020), PET has almost no effect on clothing insulation variation, while mPET has a significantly different performance on clothing insulation variation. Also, mPET always revealed higher probabilities of lower cold stress categories, especially in the warm period of the year.

Influence on tourist flows

In the last 30 years, the occurrence of days with neutral and slightly warm/cold conditions is concentrated in the summer months, while the highest percentage of days was recorded in August. Consequently, summer is the most favorable for most outdoor sports and recreational activities. In the winter months, days with extreme and very strong cold thermal conditions prevailed, with the highest percentage of days in January and December. Although Kopaonik is primarily a winter tourist center, it is important to point out that a very small number of tourists exploit the period with the best thermal comfort conditions (summer and autumn). Certainly, the decision on the period of stay on Kopaonik is not primarily based on favorable bioclimatic conditions, but on resources for winter tourism (ski slopes, ropeways, etc.), which results in underutilization of the tourist potential in summer and autumn, when there is less heat stress and more days with thermal comfort. Although spring has much less favorable thermal conditions than autumn, due to the extension of the skiing season by making artificial snow, the number of tourists in spring is almost three times higher than in autumn. In the future, increasing warmer thermal conditions can have both negative and positive impacts on tourism. The ski season may be shortened, which could result in the more intensive use of adaptation measures such as snowmaking but also result in an appropriate transition to other forms of recreational activities. Also, it can be expected that increasingly warmer thermal conditions will be more pronounced at lower altitudes, which could make mountain areas even more attractive for tourism, leisure, and recreational activities, especially in the warm part of the year.

Conclusions

This research is the first case study on the thermophysiological comfort conditions in the high-altitude tourist center Kopaonik based on three thermophysiological indices (UTCI, PET, and mPET). All three indices are displayed in 3-h resolution, providing the possibility to assess thermal conditions not only in different parts of the year but also in different parts of the day.

Results demonstrate that in the tourist center Kopaonik, the cold stress is prevailing all year round. Warm, hot, and very hot days were not recorded. According to the mean seasonal values, MEMI indices showed that thermal comfort varied from very cold winters to cool summers, while according to UTCI, thermal stress varied from strong cold during the winters to slightly cold during the summers. Transitional seasons were very cold, but autumn was more comfortable than spring. Slightly cold/warm and neutral conditions extend from May to September, indicating that summer is the most favorable season for outdoor recreational activities. However, summer is a period with a small number of tourists, which indicates the fact that thermal comfort is not the main decision-making factor in choosing this tourist destination. Still, as a result of climate change, the annual number of thermally favorable days is increasing, and the number of days with extreme and strong cold stress is decreasing. However, despite a considerable increase in overall thermal comfort in the last 30 years, winter values have not had a statistically significant rise and, until now, still have not influenced thermal perception in the winter tourist season. Considering climate change and increasingly warmer thermal conditions, detailed monitoring of bioclimate parameters and their variability is necessary to offer a basis to stakeholders in decision-making for the strategic planning and adaptation of tourist destinations. It is evident that the global warming scenarios present worrying projections of increasing heat stress caused by anthropogenic emissions, so we believe that the continuation of the research should be directed to quantify changes in outdoor thermal comfort conditions at Kopaonik for different climate scenarios and their possible influence on the future development of tourism.

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Data availability The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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