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Citation style: Zbigniew Andrzej Caputa. (2016). The impact of solar radiation on the temperature of the exposed rocks of the karst canyon (the Kraków-Częstochowa Upland, Poland). "Bulletin of Geography. Physical Geography Series" (No. 10 (2016), s. 19-30), doi 10.1515/bgeo-2016-0002

Bulletin of Geography. Physical Geography Series, No. 10 (2016): 19–30
http://dx.doi.org/10.1515/bgeo-2016-0002

ISSN 2080-7686

The impact of solar radiation on the temperature of the exposed rocks of the karst canyon (the Kraków-Częstochowa Upland, Poland)

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Abstract. The paper presents results of the research on the impact of solar radiation on the formation of the thermal conditions of the exposed rock surfaces of the Kraków-Częstochowa Upland. The research comprised the structure of the radiation balance of the active surface of the bottom of the canyon, the temperature of the surface and the layer at the depth of –5 cm in limestone rock on the southern wall of the canyon. The tests were performed in various types of weather. The strongest mesoclimate contrasts were observed in the radiation type of weather: differences in insolation and in the balance of radiation, thermal differences and variations within the heat flux in the rock. The longwave stream of radiation which was emitted by the heated rocks exerted an impact on the microclimate conditions and on the radiation balance at the bottom of the canyon during the night. A diverse relief of the terrain constituted a local factor differentiating the radiation balance and the distribution of the rock temperature. The quantitatively determined structure of the radiation balance and the thermal contrasts of the canyon, particularly of the rock surfaces, point to the importance of the relief in shaping the mesoclimate of even small karst areas. These characteristics determine the heat flux in the rock, weathering processes and others. The mesoclimate and microclimate of the rocks affect the biodiversity of the rock surfaces of the Kraków-Częstochowa Upland. In addition, they shape the ecotopy of the karst canyon, among others – the vegetation on the limestone rocks.

Key words:
radiation balance,
rock temperature,
microclimate,
karst canyon,
the Kraków-Częstochowa Upland

Introduction

In karst areas, the relief of the terrain strongly influences the amount of solar radiation and the temperature distribution (Whiteman et al. 2004a). In addition, these elements are modified by the vegetation cover of the terrain (Klasa and Partyka 2008; Bárány-Kevei 2011; Bátori et al. 2012). In valleys and canyons, exposed and insolated bare rocks heat up during the day, and thus become a “specific heat emitter” during the night (Gunzburger and Merrien-Soukatchoff 2011). The radiation is strongly absorbed by the rocks of the southern exposure, which are partly covered with vegetation. Therefore, the modelling of these elements is difficult and requires experimental studies. Bare limestone rocks in the Kraków-Częstochowa Upland are an ideal material for investigating the relationships between the intensity of solar radiation and the temperature of the active surface in the upland karst areas.

The processes of the exchange of radiation and heat between the atmosphere and the substratum (e.g. bedrock) occur in the atmospheric active surface (Paszyński et al. 1999). Therefore, the analysis of the structure of radiation balance and measurements of the temperature on the surface of the rock and inside the rock enable determining the thermal field, the direction of the heat flux dependent on the intensity and pace of heating up of rocks (Gómez-Heras et al. 2006), stone degradation (Weiss et al. 2004), weathering processes (Smith et al. 2008) in the context of the ongoing global warming.

Impacts of climate change on the hydrologic cycle, water resources, carbon cycle, and eco–environment in the karst region have been observed (Bokwa et al. 2008; Lian et al. 2015). The authors examine how the terrain texture and topography influence the heat flux (Smith and Skyllingstad 2011), temperature distribution (Medeiros and Fitzjarrald 2015), wind fields (Sheridan et al. 2010), longwave radiation (Hoch et al. 2011), surface–air temperature (Bryś 2008), effects of elevation (McCutchan and Fox 1986), the temperature regime of the soil and air in deeper karst depressions (Bárány-Kevei 1999, 2011) on a regional scale. On a global scale, extensive karst limestone bedrock plays an important role in the preservation of rare, endangered, or specialized species (e.g. Wołowski et al. 2004). Karst landforms, such as canyons, wells and sinkholes, determine the geomorphologic, microclimatic (Whiteman et al. 2004a; Bokwa et al. 2008; Sheridan et al. 2014), pollution (Caputa and Leśniok 2002a,b; Caputa and Doroz 2015) and vegetation features of karst surfaces, and influence the karst aquifer system (Caputa and Partyka 2009).

Previous studies in the Kraków-Częstochowa Upland point to high radiative (Klein 1992; Caputa 2001; Caputa 2016a,b), thermal and moisture (Wojkowski 2004; Brzeźniak and Partyka 2008; Caputa 2009) contrasts or frequent inversion phenomena (Niedźwiedź 2009a,b). These contrasts indicate a diverse structure of the radiation balance of the active surface in varied karst relief, which is well recognized both in the profile of the plateau–bottom of the canyon (Caputa and Wojkowski 2013) and spatially distribution of insolation (Wojkowski and Caputa 2009, 2016).

Less numerous studies are focused on microclimatic measurements carried out directly on limestone rocks. Such studies allow determination of the role of the terrain relief in the formation of the microclimate of the boundary surface of rocks (Brzeźniak 1994a), humidity (Brzeźniak 1994b; Litschmann et al. 2012), air movement in karst craters (Whiteman et al. 2004b; Zängl 2005), and comparison of temperature inversions in sinkholes of different sizes and shapes (Whiteman et al. 2004b, c). Sparse studies take into account solar radiation or the radiation balance of the active surface (Whiteman et al. 1989; Whiteman et al. 1996; Iijima and Shinoda 2000; Sun et al. 2003; Clements et al. 2003). These studies indicate that solar radiation exerts a fundamental impact on the boundary surface of karst depression (valley, canyon, sinkhole), including the bedrock. Morphological formations of karst determine the distribution of the near–surface temperature, local air movements, the inflow of the total solar radiation, and thus affect the final radiation balance. Steinacker et al. (2007) emphasise that the temporal change of the vertical temperature profile is strongly dependent on the shading and sky view factor (SVF) in accordance with the geometry of the basin. Moreover, that even a few clouds passing over the sinkhole during an otherwise clear night result nearly instantaneously in a significant temperature signal at the bottom; it reacts like an infrared thermometer (Steinacker et al. 2007). Therefore, the formation of the microclimate of the canyon may be significantly influenced by exposed rock surfaces. These surfaces heat up faster and then alter the microclimate, for example, night time cooling is reduced by back radiation from the sidewalls in the canyon. Despite the fact that the exposed rocks cover a smaller area, their contribution to heating may be substantial.

The aim of the study was to determine what portion of the radiation is absorbed by the sidewalls of the canyon and transformed into the heat flux, and then accumulated or emitted by the limestone rock. This allowed determination of the influence of the exposed rock surfaces on the formation of the microclimate of the canyon.

Methods and study area

The research utilises the results of recording solar radiation and air temperature at two meteorological stations. The first was installed at the bottom of the canyon in the Prądnik Valley at Ojców (geographical coordinates 50°12’35” N, 19°49’44” E, altitude 322 m a.s.l.) (Fig. 1). The surroundings of the station are characterized by steep slopes of eastern and western exposure and a deep (over 100 m), narrow

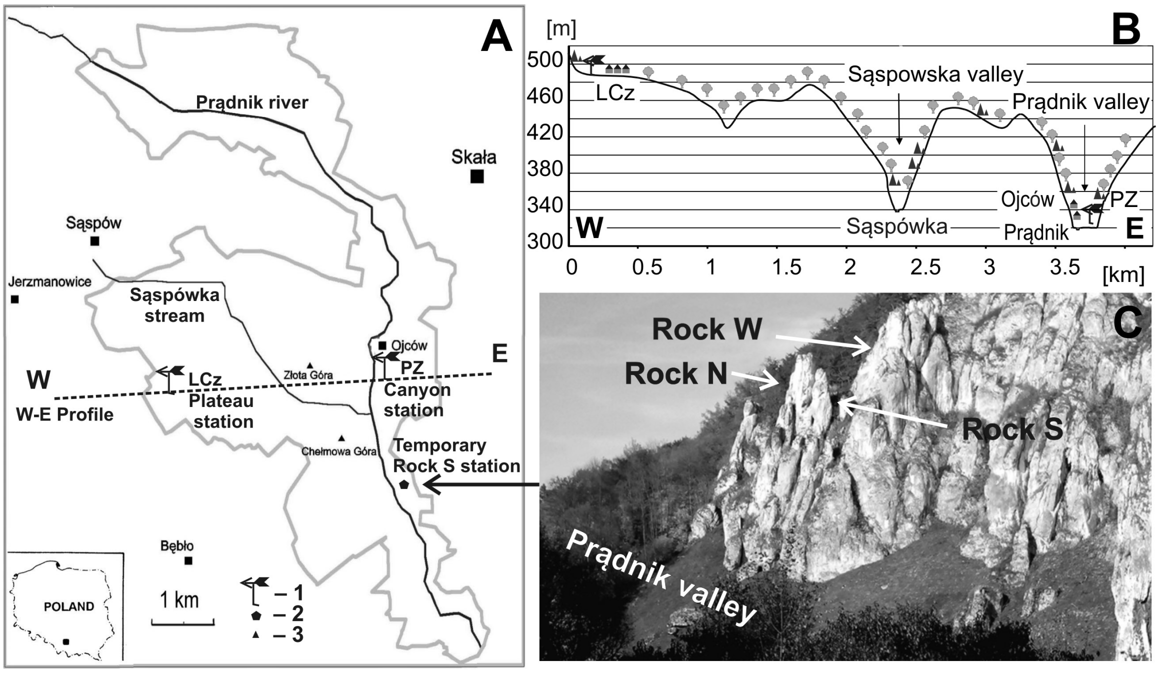

Fig. 1. Location of the measurement points in the Kraków-Częstochowa Upland: (A) the Ojców National Park 1 – meteorological station; 2 – temporary station; 3 – hill–tops; (B) profiles W–E, LCz – plateau meteorological station, PZ – bottom of the canyon – meteorological station; (C) the places of temporary measurements taken by HoboProTerm

(50–150 m), flat bottom of the canyon of the S–N course. N slopes are covered by the forest whereas S slopes and sidewalls – by the xerothermic grassy surface (Klasa and Partyka 2008). Such a location of the station accurately reflects the specificity of the deep valleys of the Kraków-Czstochowa Upland, which have the character of canyons (Gradziński et al. 2008). The obstruction of the horizon at the station is substantial and varies within the range of 10° to 35°.

The other temporary measuring site was located on the eastern slope of the Prądnik valley, on the hillside of the Góra Koronna, on the rock complex of the Rękawica in the period of 2012–2014. The site was equipped in four Hobo ProTerm recorders. The operational and laboratory tests for these data loggers were described by Whiteman et al. (2000) and Gruber et al. (2003). They were installed on the characteristic surfaces of bare limestone rock of a great inclination of 70–90° and the exposure to the south (rock S), north (Rock N) and west (rock W). The HoboProTerm sensors recorded the temperature on the rock surface as well as at the depth of −5 cm inside the rock (−5 cm rock S, −5 cm rock N, −5 cm rock W). Additionally, in the immediate vicinity of the rock complex of the Rękawica, the temperature of the air at the height of 150 cm was recorded in the radiation shield. The whole area is characterized by a great diversity of the rock relief (Fig. 1C, photo).

The radiation balance comprises elements of shortwave radiation, whose source is the sun, and longwave radiation, which represents the radiation of the Earth's surface and the atmosphere (Oke 1999; Paszyński et al. 1999):

$$Q^* = K^* + L^* = (K\downarrow - K\uparrow) + (L\downarrow - L\uparrow)$$

where:

Q^* – net radiation – net short- and longwave radiation flux density,
K^* – absorbed solar radiation – net shortwave radiation,
L^* – net longwave radiation,
$K\downarrow$ – global solar radiation – the incoming shortwave radiation,
$K\uparrow$ – reflected solar radiation,
$L\downarrow$ – atmospheric counter radiation – the incoming longwave radiation,
$L\uparrow$ – outgoing longwave radiation.

Results

The incoming of shortwave solar radiation to the bottom of the canyon

Tropical air inflowing over Poland was the reason for the radiation weather and a sweltering day of

29.08.2013. The great irradiation and high temperature in the Kraków-Częstochowa Upland during this cloudless day perfectly illustrates the phenomenon of heating-up of the active layer in the bottom of the canyon and the limestone rocks during a sunny day with high insolation.

The flux K↓ reached the bottom of the canyon strongly reduced owing to the obstruction of the horizon by the slopes and the sidewalls both in the morning from sunrise to 6:00 UTC (solar time = UTC–78 min.) and before sunset (designation SS and SR, Fig. 2A). The difference of $\Delta K{\downarrow}_{\mathrm{Plateau-Canyon}} = K{\downarrow}_{\mathrm{Plateau}} - K{\downarrow}_{\mathrm{Canyon}}$ was calculated. The bottom of the canyon of the Kraków-Częstochowa Upland received less insolation than the plateau by 2.4 $\mathrm{MJ \cdot m^{-2}}$ in the daily total. The lowest values of $\Delta K{\downarrow}_{\mathrm{Plateau-Canyon}}$ were calculated for winter fine days – from 0.3 to 1.8 $\mathrm{MJ \cdot m^{-2}}$. The highest differences in the supply of solar radiation between the grassy surface of the plateau and the bottom of the canyon were observed on fine days in the spring and summer, which reached the values high as $\Delta K{\downarrow}P_{\mathrm{lateau-Canyon}} = 3.1\ \mathrm{MJ \cdot m^{-2}}$. Basing on the analysis of 2007–2012, it was shown that K↓ reaching the bottom of the canyon during the year was on average 15% lower than the solar energy received by the plateau (Caputa and Wojkowski 2013).

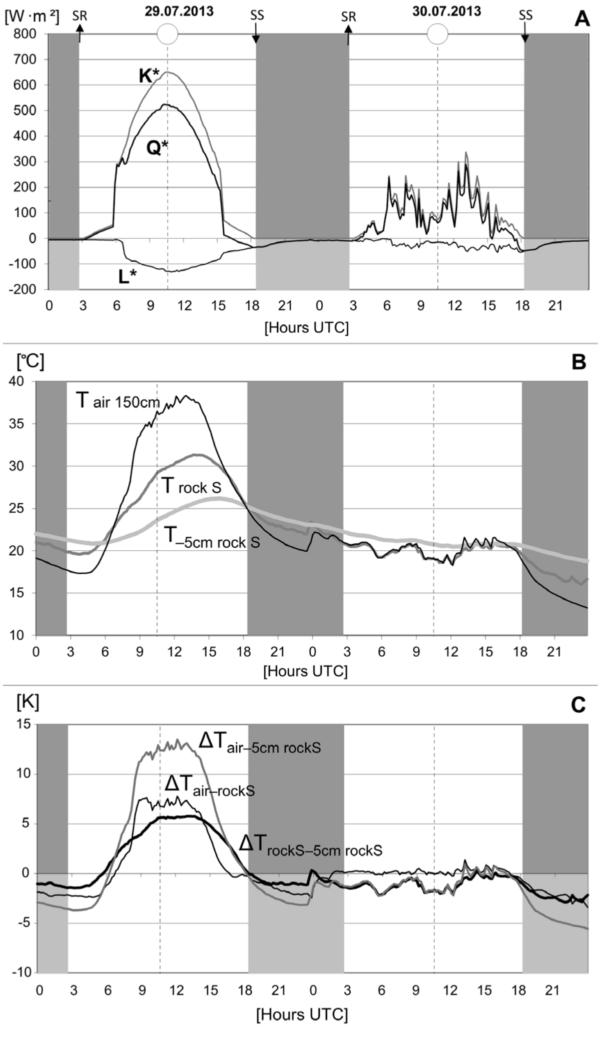

Fig. 2. Variation of: (A) the radiation balance elements; (B) the temperature of the air and rock; (C) temperature differences $T_{\mathrm{air}} - T_{\mathrm{rockS}}$ ($\Delta T_{\mathrm{air}-\mathrm{rockS}}$), $T_{\mathrm{air}} - T_{\mathrm{5cm\ rockS}}$ ($\Delta T_{\mathrm{air}-\mathrm{5cm\ rockS}}$), $T_{\mathrm{rockS}} - T_{\mathrm{5cm\ rockS}}$ ($\Delta T_{\mathrm{rock}-\mathrm{5cm\ rockS}}$) at the bottom of the canyon in Ojców on 29–30.07.2013

Figure 2A illustrating the intraday variation of net K* clearly shows a slow increase of the values for 3 hours after sunrise due to the shading by the canyon sidewalls. It reached a maximum during the ascendancy of the sun (10:42 UTC) and then decreased to the value of 70 $\mathrm{W \cdot m^{-2}}$, and very slowly went down towards zero (2 hrs and 50 min) once more obstructed by the sidewalls of the canyon. The daily total K* at the bottom of the canyon was about 3.0 $\mathrm{MJ \cdot m^{-2}}$ smaller than the total calculated for the plateau on the sunny day of 29.07.2013. Smaller radiative terms were observed during the following cloudy day of 30.07.2013 (Fig. 3). The inflow of K↓ was 15.1 $\mathrm{MJ \cdot m^{-2}}$ lower and the total K* 12.0 $\mathrm{MJ \cdot m^{-2}}$ smaller than the corresponding values on the sunny day.

Longwave radiation balance at the bottom of the canyon

The large value of the longwave radiation flux resulted from strong heating of the active surface and the air in the lower layers of the atmosphere (Figs. 2A, 3). The sunny daily net L* equal to –3.9 $\mathrm{MJ \cdot m^{-2}}$ resulted from the high emissivity of the bottom of the canyon. In contrast, at night, when only longwave radiation occurred in net Qn*, a negative value of –0.4 $\mathrm{MJ \cdot m^{-2}}$ was calculated, which means that the bottom of the canyon was cooling off during the night. Strong variations in the daily course of L* were noted. Large amplitudes in the net L* (126 $\mathrm{W \cdot m^{-2}}$) were observed in the canyon, with the minimum of –131 $\mathrm{W \cdot m^{-2}}$ at noon. The net L* was influenced by the relief of the terrain (large SVF), but also by the vegetation, which greatly hampered the heating of the soil.

The daily structure of the radiation balance at the bottom of the canyon

The course of the net Q^* during 29–30.07.2013 at the bottom of the canyon illustrates radiation contrasts on a sunny day and on an overcast day (Fig. 2A). The net Q^* reached positive values during the day, whereas almost 3 hours before sunset and during the night it decreased to negative values. On the sunny day, the arms of the parabola Q^* limited by the sidewalls of the canyon are clearly seen. The net Q^* fell rapidly at local sunset, reaching its minimum of $-36\ \mathrm{W\cdot m^{-2}}$ by astronomical sunset, and then increasing slowly to about $-10\ \mathrm{W\cdot m^{-2}}$ by sunrise. The values of the net K^* the net L^* ($Qd^*=K^*+L^*$) was designated the name of the daily net radiation of the active surface. The net Qd^* reached high values of 13.9 $\mathrm{MJ\cdot m^{-2}}$ on the sunny day, whereas by 9.4 $\mathrm{MJ\cdot m^{-2}}$ lower on the overcast day at the bottom of the canyon (Fig. 3). Slightly lower values of the daily total of the net Q^* (13.5 $\mathrm{MJ\cdot m^{-2}}$) were observed, because the net L^* in the canyon during the night is low.

On the day of 30.07.2013, polar maritime air, much cooler and of high humidity, flowed in from the west. The change of the weather resulted in reduction of solar radiation, temperature decrease and an increase in humidity and wind speed. This overcast day of 30.07 was characterised by little diversity of the values of the net Q^*. What was interesting was the negative value of the net Q^* after 18:00 UTC owing to a strong cooling of the active surface of the bottom of the canyon. There was a slow decrease of the temperature of the air and soil. The daily total of the net Q^* reached merely 3.9 $\mathrm{MJ\cdot m^{-2}}$ at the bottom of the canyon.

Daily changes in the temperature of limestone rock

The solar radiation flux reaching lower parts of the slopes and the bottom of the canyon was reduced by the sidewalls. This was reflected in the course of the temperature of the air and the limestone rock on the canyon sidewall S (Fig. 2B). The temperature of the rock surface clearly increased not earlier than a few hours after sunrise. The irradiation reached the rock surface (there was recorded a rise in the temperature until the afternoon hours). In contrast, an increase in the air temperature up to 38°C resulted from warming of the air by the grassy surface (low albedo 21%) and limestone rock of high albedo $\alpha=33\%$. The inflow of the flux $K\downarrow$ after 6:00 UTC was also the cause of the changes in the direction course of the heat flux in the rock (Fig. 2C). The negative values of $\Delta T_{\mathrm{air-rockS}}$ pointed to cooling of the limestone rock, while the positive values – to its heating (heat flux turning back to the rock). The course of $\Delta T_{\mathrm{rockS-5cm\ rocks}}$ was distinctive – the pos-

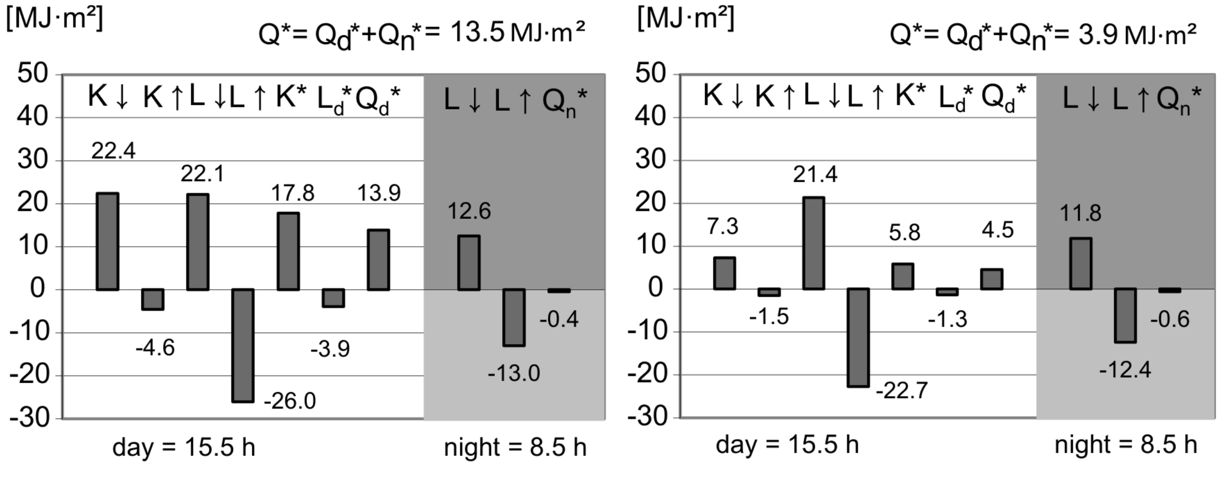

Fig. 3. The structure of the radiation balance during the day (white) and night (dark), net Q * at the bottom of the canyon on the fine day of 29.07.2013 (left) and on the cloudy day of 30.07.2013 (right). Index: d – day, n – night

itive value of this difference preceded the positive values of $\Delta T_{air-rockS}$ after sunrise, due to the fact that the surface of the rock heated up first, the air above the rock heated up after that, and the course of the direction of the heat flux changed and maintained until sunset. Then, after the solar zenith, there was a decrease in the flux K↓, which was further restricted by the slopes of the canyon in the afternoon. Because of the strong emissivity, the net Q* decreased and its course of direction changed to the negative several hours before sunset. The negative values of the net Q* pointed to cooling of the surface of the canyon, which was reflected by the drop in the temperature of the air and rock.

What was interesting was a significant inertia of the fall of the temperature at the depth of –5 cm inside the rock. Daily course of the temperature appears in the chart as $T_{-5cm\ rockS}$. After sunset, the temperature of the air decreased faster than of the rock surface due to the lower heat capacity of the air. A large heat flux inside the rock was indicated by the negative $\Delta T_{rockS-5cm\ rockS}$. The negative values of ΔT in the Figure 2C point to cooling of the rock until the arrival of the atmospheric front at night.

Inertia of the temperature and heat flux in limestone rock

The walls of limestone rocks act as a climate active layer between the atmosphere and the bedrock, within which the processes of the exchange of radiation and heat take place. They constitute another vertically arranged active surface, along with the horizontal grassy one. This surface heated up with a delay in relation to sunrise, and with a substantial inertia of the temperature despite the supply of the flux K↓ to the sidewalls of the canyon (due to the bright surface of the limestone rock). About two hours before the temperature of the rock surface had reached its highest value, there was also noted an increase in the air temperature and its maximum value (Fig. 2B). The high albedo of limestone rocks (33%) decreased the value of the net K* owing to the reflection of shortwave radiation.

High negative values of the heat flux in the rock ($\Delta T_{rockS-5cm\ rockS}$), which show strong radiation from the rock into the atmosphere, were observed at night and morning hours even on the cloudy day (Fig. 2C). However, during the sunny day, the surface heated up to a maximum, the highest value of $\Delta T_{air-rockS}$=7.8K occurred two hours after the solar zenith. Although the differences were examined at a similar level from 9:00 to approx. 14:00 UTC. The maximum $\Delta T_{rockS-5cm\ rockS}$=5.8K associated with a flow of the heat flux between the rock surface and the depth of –5 cm inside the rock occurred even later. Then, the described differences decreased until sunset, at which point the vector of the heat flux changed its course of direction, and thus the rock began to cool off. At this time, the minimum values of the net Q* were observed to be increasing until sunrise, also during other days (Fig. 5).

Extremely significant was an extended period of the cooling of the rock even during the following day, by the afternoon hours, when the intensity of K↓ was higher in the second half of the day. Even the value of 200–300 W·m^{-2} K↓ was not sufficient for the heat flux to penetrate the rock. The daily course of the difference between the temperature of the surface and the inside of the rock $\Delta T_{rockS-5cm\ rockS}$ illustrates the change in the temperature of the rock on the south wall of the canyon also during other days (Fig. 4). The high value 12.8K of the difference between the air temperature and at the depth of –5 cm inside the rock point to the heating of the rock (high heat flux) during the day.

The negative net Q*, particularly after sunset, was the reason for the cooling of the active surface of the canyon bottom. Due to the aforementioned

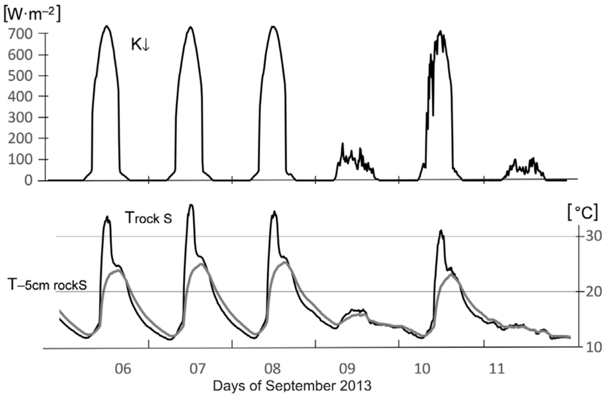

Fig. 4. Daily course of the global radiation (K↓), temperature of the rock S: on the surface (T_{rockS}) and at the depth of –5cm in the rock ($T_{-5cm\ rockS}$) at Rękawica complex in the period of 5–11.09.2013

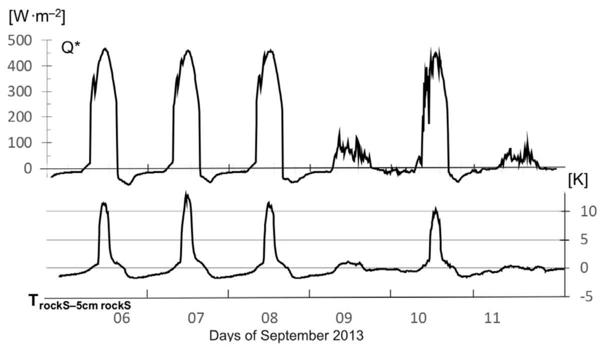

Fig. 5. Daily course of the net radiation (Q*) at the bottom of the canyon and the temperature differences $\Delta T_{rockS-5cm\ rockS} = T_{rockS\ -\ T-5cm\ rockS}$ at Rękawica complex in the period of 5–11.09.2013

inertia of the temperature in the rock, the minimum value $\Delta T_{rockS-5cm\ rockS}=-1.8$K occurred 2.5 hours later on the sunny day of 6.09.2013. The days with high or variable cloudiness were characterized by much lower values of the net Q*, and still lower diversity of the temperature in the limestone rock.

Discussion

Overcast sky was an essential factor in weather and climate processes during the studied period. It affected directly the inflow of solar energy during the day and the loss of the radiation during the clear night Qn*=–0 .4 MJ·m^{-2} and more in cloudy night Qn*=–0.6 MJ·m^{-2}. This might have been the effect of the heating up of the canyon walls. The type and size of the clouds decreased the net Q* by 9.6 MJ·m^{-2} during the analysed overcast day in comparison to the sunny day. Similar correlation was observed over a longer research period, when overcast skies reduced the net radiation Q* by 30% in comparison to the days with a clear sky (Caputa 2001). There was observed the impact of karst relief on the diversity of insolation conditions and mesoclimate variation (Wojkowski and Caputa 2016). Large temperature amplitudes were characteristic only the exposed surfaces of monadnocks, rocks and sidewalls of the canyon. The temperature of the sidewalls and rocks covered with trees were not much different, despite the exposure (S–N) and height (30–60 m) above the bottom of the canyon because of the insulating nature of the vegetation (Caputa 2009). The net Q* determined the heat balance and the heat flux inside the rock, as well as the microclimate of the near-surface layer of the air in the Kraków-Częstochowa Upland (Bokwa et al. 2008). On the other hand, since the rocks were low heat conductive, there are important temperature gradients from the surface into the rock (Fig. 5), which give rise to important expansions and contractions leading to exfoliation or weathering (Eppes et al. 2010). The importance of this was mentioned by, for example, Gómez-Heras et al. (2006), who argued that this was the zone wherein many stone decay processes (particularly weathering) operate. These processes invariably respond to temperature and moisture fluctuations, and short-term interruptions to insolation could, for example, trigger these fluctuations on numerous occasions over a day. Because of the fact that the diurnal patterns of heating and cooling were overlapped by more rapid, short-term changes in insolation (clouds), it was possible for surface and subsurface temperature regimes to develop as well (Smith et al. 2008).

The second important factor differentiating the structure of the radiation balance and the thermics of limestone rocks was the terrain relief owing to its modifying influence on the size of irradiation (Caputa 2009). The inflow of the flux K↓ was dependent on the degree to which the physical horizon was obscured, the exposure and the angle of the inclination of the surface. The flux K↓ amounted to 3955 MJ·m^{-2} on open flat areas, while at the bottom of the canyon it was lower by 19% (Caputa 2015b). The net Q* was 2120 MJ·m^{-2} on the plateau, whereas at the bottom of the canyon it was smaller by 20% for the multiyear of 2007–2012 (Caputa and Wojkowski 2013). The annual totals K↓ modelled for the slopes S of an inclination of 20% amounted to 4198 MJ·m^{-2}, and even higher values (more than 4300 MJ·m^{-2}) were calculated for non tree-covered slopes and rocks S (Wojkowski and Caputa 2009). The absolute values of the ingredients of the radiation balance of the active surface (K*, L*) were greater on the plateau surface than on the grassy surface of the bottom of the canyon by 19% and 20% respectively (Caputa and Wojkowski 2013), which pointed to a great diversity of the active surface of the karst areas. Bare rocks, rock walls and monadnocks heat up during the day and constitute a specific emitter of heat at night (Molaro et al. 2005). The topographic parameter seems to affect the correlation between the air temperature development and the amount of the sky visible from the bottom of the canyon (Steinacker et al. 2007). In the bottom zone of the canyon and the lower parts of the sidewalls, the period of the diurnal heating shortened, however K* increased because of a lower albedo, reflections of the beams from the sidewalls of the canyon, especially from white rocks, etc. At the bottom of the canyon, high temperatures of the surface and air (Caputa and Wojkowski 2013) were recorded during the day, while during the night – a longwave emission. A stable stratigraphy of the air dominated in the canyon owing to the stillness and low wind speed. This was due to the temperature inversion phenomena, during the high pressure weather characterised by cloudlessness or a small cloud cover mostly in the spring and autumn (Niedźwiedź 2009a).

The high albedo of limestone rocks (24–38%) was the cause of the strengthening of the scattered radiation in the canyon during the sunny day. It was more then 15–80% at the plateau on grass surface. The albedo has been recognised as a major factor that influences surface temperatures (Gómez-Heras et al. 2006; Bryś 2008, 2009). The albedo determines how much of the heat that reaches a surface in the form of radiation will remain available (Geiger et al. 1995; Hall et al. 2005). An average albedo modelled for the study area was 20%, the lowest in the autumn – up to 12%, and the highest for long-lying snow – more than 60%. The highest albedo recorded in the satellite photo was characteristic of limestone rock – 24% in spring, slightly lower in summer (23%) and 18% in autumn (Wojkowski and Caputa 2009). Maximum was for snow (86%) and much low for grass (21%) and at bare soil even 12% (Bryś 2013). The presented elements sharpened the microclimate contrasts in the canyon. The other surfaces on the sidewall S in the canyon heated up to the maximum temperature during the year as follows: xerothermic grassy surface – 54.1°C, rocks – 42.9°C, undergrowth – 33.7°C, and the bottom of the canyon – 52.6°C (Caputa 2009). The contrasts, karst relief and microclimatic differences have brought about the resulting ecological conditions (Wołowski et al. 2004) and very important changes of vegetation in the karst ecosystem (Bárány-Kevei 2011).

Previous investigators found somewhat weaker nighttime net outgoing radiation in other lower elevation basins and valleys under similar synoptic conditions (Whiteman et al. 1996; Iijima and Shinoda 2000). The slow nighttime increase in net radiation is caused by the changing balance between the outgoing flux, which decreases as the ground surface cools, and the downward radiative flux, which comes from the warm sidewalls and the sky and which decreases at a slower rate during the night (Clements et al. 2003). Bárány–Kevein (2011) introduced the concept of influence of the slope orientation and, in particular, the time of the day on the formation of vertical stratification of temperatures in the karst terrain depression.

The strongest thermal contrasts were recorded in this terrain in the near ground–level parts of rocks (0–10 cm above ground level) of a thermal gradient equal to 3.6K/10 cm. The same studies identified differences in vertical gradients, whose maximum values were 4.9K/10 cm in the upper parts of the slope (Brzeźniak 1994a). Other research concerning thermal differences of deep karst craters points to their origin, e.g. the inflow of cold air, a limited or lack of provision of K↓ to some parts of the bottom and sidewalls (Whiteman et al. 2004c). These causes resulted in, for example, long lying of snow cover in shady parts of a narrow canyon (Wojkowski 2009), temperature inversions up to 12K plateau–bottom of the canyon (Niedźwiedź 2009a), thermal contrasts between its south and north sides, and between day and night (Caputa 2009). Litschmann et al. (2012) described the climatic conditions of karst narrow canyons. As opposed to sinkholes, there was limited occurrence of cold air at night and the subsequent inversion in narrow canyons, which may be illustrated by the temperature differences between the bottom of the abyss and its upper edge (138.4 m) reaching up to about 10°C (Litschmann et al. 2012). In topographic depressions, night time cooling was reduced by back radiation from the sidewalls (especially in narrow canyons). Early night time (19:00 UTC) radiative cooling, for example, was reduced to 44%–58% of the value seen over a flat terrain (assuming no inversion layers on the slopes) (Hoch et al. 2011). Other studies point out that the contribution to the downward radiative flux at the basin floor from the relatively warm sidewalls and warm air mass at the top of the basin cold pool was much greater than the contribution that would be received from a less obstructed sky (Clemens et al. 2003). This might have been the effect of the heating up of the canyon walls.

Changes of microclimate may be important in several cases, especially in karst areas where the strongest influence comes from topography (Caputa and Wojkowski 2015). As a rule, the interiors of karst depressions were colder than the higher ground surrounding them. Besides, lower absolute minimum temperatures, greater numbers of cold days, and greater amounts of snow cover, fog and frost were also characteristic of enclosed karst depressions. And finally, areas with soil and vegetation cover usually promote solution processes, due to the presence of carbon dioxide in the soil (Ritter et al. 1995).

Summary and conclusions

In the diverse relief of the karst area of the Kraków-Częstochowa Upland, meso- and microclimate diversity was observed. The conclusions drawn from the earlier analyses dealing with this issue (among others, Klein 1992; Niedźwiedź 2009a,b; Caputa 2015a,b) have been enriched with the following statements: this diversification has been influenced by: a limited inflow of solar radiation (15%), thermal and moisture contrasts, frequent temperature inversions (above 12K), light winds and stillness in the valleys, etc. A sunny day (high–pressure weather: high insolation, light wind, etc.) exerted a strong mesoscale impact on the evolution of the canyon boundary layer (strong heating of the surface during the day, chilling and temperature inversion during the night).

Owing to the relief of the terrain, a limitation in the inflow of the flux K↓ to the bottom of the canyon in the morning and in the evening was observed. This limitation amounted to $\Delta K\downarrow_{\text{Plateau–Canyon}}$=2.1 MJ·m^{-2}d^{-1} on a sunny summer day. This difference constituted 15% of K↓ and 19% of net K* and 20% of net Q* for the whole year in the period of 2007–2012 in the Kraków-Częstochowa Upland. The analysis of the structure of the radiation balance provided an explanation of the impact of the radiation balance components on the rock temperature and the heat flux inside the rock. The daily total of K↓ at the bottom of the canyon reached 22.4 MJ·m^{-2}, while the maximum temperature of the rock was 31.3°C, and at the depth of –5 cm inside the rock –26.2°C on a sunny summer day.

What was also found out was a few hours' inertia of cooling of the limestone rock in comparison to the change of the net Q* into negative in the afternoon hours. The lowest value of the net Q* was equal to 63 W·m^{-2}, which corresponded to the difference $\Delta T_{\text{rockS–5cm rockS}}$=–1.5K, whereas the minimum value occurred 2.5 hours later (–1.8K). This phenomenon is of great importance for the formation of temperature inversion, air movements, net Q* in narrow karst formations (valleys, canyons, etc.).

The results will allow assessing the role of the exposed rock surfaces in shaping the heat balance of the canyon and forming its microclimate. In the future, it will be compared with the results of the currently carried out studies on the influence of solar radiation on the temperature of other selected morphological elements of the canyon.

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Received 13 November 2015
Accepted 15 April 2016