HORIZONTAL PRECIPITATION GRADIENTS IN ALPINE VALLEYS OF NORTHWESTERN SLOVENIA

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Original scientific article
COBISS 1.01
DOI: 10.4312/dela.49.5-36

Abstract
Of all mountainous regions in the world, the network of precipitation stations is the densest in the Alps. Nevertheless, the precipitation regime at the micro level continues to be poorly known at many a place. Most of the precipitation stations in mountain landscapes are located at lower elevations and in settled areas, while they are rather few at higher elevations. Moreover, the accuracy of measurements in the mountains is problematic and therefore the information on precipitation regime is deficient exactly in the wettest areas. The water balance estimation is incorrect, and it is difficult to forecast precipitation-related hazards, such as torrential floods, landslides, avalanches, and the like. The paper discusses the horizontal precipitation gradients in the Alpine valleys of Planica, Krnica and Beli Potok which are all situated in the north-western part of the Julian Alps in Slovenia. At the annual level of the studied period the following values were reached: 162 mm/km at Krnica, 192 mm/km at Beli Potok and 216 mm/km at Planica, and these belong to the highest gradients in Slovenia. In comparison with the lowest points of the researched valleys, the precipitation amount in their uppermost parts increases by the factor of 1.36 at Beli Potok, 1.55 at Krnica and as much as 1.86 at Planica.

Key words: mountain climate, horizontal precipitation gradients, precipitation measurements, orographic precipitation, Julian Alps, Alpine valleys

1 INTRODUCTION
Already in the 17th century the Slovenian polymath Johann Weichard Valvasor (1641–1693) in his own specific way wrote about the orographic effect on the precipitation amount: “Carniola has no thirst for rain […] Sometimes, there is no cloud to be seen, yet
all of a sudden a mist rises in the mountains, especially among the high snow-covered peaks, and it immediately turns into a shower [...] And it often rains twice, three times or even four times a day, particularly under the snowy peaks of Upper Carniola [...]” (Valvasor, 1978, pp. 93, 94). The fragment indicates greater precipitation amount in the mountainous world. Probably the first to tackle a more detailed study of precipitation regime in Slovenia, more precisely in the then Province of Carniola, was Ferdinand Seidl in his work *Das Klima von Krain* (Climate in Carniola) of 1891. He quoted the data from the precipitation station of Kranjska Gora (*Kronau*) with the annual precipitation amount of 1599 mm (Seidl, 1891, p. 265). He, too, recognized the significance of the vicinity of mountains for more intense precipitation; he also states that the distance of a certain place from the mountains has a greater effect on the precipitation amount than the elevation (Seidl, 1891, p. 318). This shows his knowledge about the origin of precipitation and the direct influence of mountains on its amount. In recent years Slovenian meteorologists have dealt with the method of how to establish true amounts of precipitation. Relevant for the Slovenian mountainous world is the climate study *Klima Triglavskega narodnega parka* (Climate of the Triglav National Park) of 1998 (Pristov, Pristov, Zupančič, 1998) which states that the precipitation usually – but not necessarily – increases with higher elevations.

The research done hitherto has established that in the direction towards the mountain ridges and in side valleys the differences in the winter precipitation amounts at short distances can be fairly great. The area of the Western Karavanke above Martuljek and in the cirque Pod Špikom partly reaches into the area of the present research, and Ogrin (2005) established in the winter of 2003/2004 that as much as 1.5 times more precipitation fell at Pod Špikom and 1.3 times more on the alpine pasture of Grajščica than at the precipitation station of Rateče. In the winter of 2005/2006, Ogrin and Ortar (2007) continued their research into the distribution of precipitation in the Lower Bohinj Mountains (Peči). The result of the measurements in a single winter season showed that on the highest parts of the Bohinj ridge the precipitation amount was about 200% of the measured amount on the northern edge of the ridge. As to the corrected precipitation amount on Mt. Vogel the calculated amount on the ridge was still larger by 56%.

There are no similar studies available for the summer season or even for a multiannual period. More recent Slovenian studies also include topoclimate maps of certain mountainous areas, for example of Jezersko and the Kamniška Bistrica valley (Ogrin, Vysoudil, Ogrin, 2013; Ogrin, Koželj, Vysoudil, 2016). It is true that the two said studies are not based on precise measurements, but both of them indicate higher precipitation amounts on the ridges and at the uppermost parts of Alpine valleys, which figures as an important topoclimate factor. The most recent precipitation map of Slovenia (Povprečna letna ..., 2018) states 1800–3200 mm of annual precipitation for our area of research.

Numerous researches into orographic processes have also been going on in other Alpine countries and elsewhere in the world (e.g. Bonacina, 1945; Sharon 1970; Barros, Lettenmaier, 1994; Blumer, 1994; Sevruk, 1997). Bach and Pryce (2013) give examples from the Indian subcontinent, where the precipitation amount on the Western Ghats exceeds 5000 mm and then quickly decreases to 380 mm on the lee side. The windward
areas of the Scottish Highlands receive about 4300 mm, the mouth of the River Moray on the lee side, approximately 200 km away, receives only about 600 mm. The differences in the mountains in lower latitudes are even greater. The Blue Mountains in the northeast of Jamaica receive about 5600 mm of precipitation, the capital, Kingston, which is 56 km away, receives only 780 mm, which results in an average precipitation gradient of –86 mm/km in the leeward direction. Very high horizontal precipitation gradients also occur on the Hawaiian Islands. In the leeward direction from the top of Mt. Waialeale the precipitation amount decreases on a four-kilometre section with the gradient of 1875 mm/km (Blumenstock, Price, 1967); in the leeward direction of the Olympic Mountains (Washington, USA) the precipitation amount decreases by 5900 mm at the distance of 48 km, which signifies the precipitation gradient of –120 mm/km in the direction away from the mountains (Mass, 2008).

The main reason for more abundant precipitation in mountain areas appears to be the orographic effect, which means the raising of air and the resultant condensation when masses of air move over the mountains. Precipitation in the mountains is more abundant, more frequent and usually lasts for longer spells. There is another effect that contributes to a greater precipitation amount: precipitation from fog which is in fact a cloud. It falls in the form of rime or fog drip. On numerous cloudy days in the colder half of the year enormous amount of rime occurs on the windward sides, which significantly contributes to the overall annual precipitation amount (Bach, Pryce 2013). According to Vysoudil (2009), local climatic effects of these processes are linked to the relief, distinctly convex relief forms.

The present paper deals with horizontal precipitation gradients at short distances in Alpine valleys. The precipitation gradient is defined as a change in the precipitation amount at a certain distance. We discern between the vertical gradient (d RR/dh), which means the change in precipitation amount according to the elevation, and horizontal gradient (d RR/dx), which means the change in precipitation in a horizontal direction. The present study is dedicated to horizontal precipitation gradients, in which case the precipitation gradient in a horizontal direction means the direction along a valley. In the direction towards the ridges the gradient is positive, whereas it is negative in the opposite direction. Precipitation amount increases in the direction towards the ridges, which results from the rise of the slopes. It is not reasonable to expect the same amount of precipitation at a certain elevation in a lowland area and at the same elevation in the vicinity of mountains.

2 THE STUDIED AREA

The research is focused on the Upper Sava Valley and three side valleys which branch off southwards from this valley and lie in the central part of the Julian Alps. These valleys are: Krnica, Planica and Beli Potok.

Beli Potok is a typical example of the so-called hanging valley. It is approximately two kilometres long, but its vertical course and morphology are very diverse. The valley widens in its uppermost part and turns south-westwards and westwards in its end, while one leg turns south-eastwards. The uppermost part is closed from all sides...
Figure 1: The studied area with measurement locations.
by the peaks of the Martuljek chain: Sleme above Vrtaška Planina (2051 m), Kukova Špica (2453 m), and Vršič above Beli Potok (1696 m). A rain gauge was stationed on the final slope at 2.9 km distance from the beginning of the valley, at the elevation of 1400 m.

Krnica is a continuation of the Velika Pišnica valley that starts at Kranjska Gora and mainly runs southwards. In its upper part the valley heads for the south-east, where it ends in the form of a cirque under the crags of mountains Prisojnik (2547 m), Kriška Stena (2375 m) and Razor (2501 m). The elevation at Kranjska Gora is 810 m, but Krnica evenly ascends to the elevation of about 1150 m, after which it passes into its uppermost part where it rises all to 2000 m. The length of the entire valley from Kranjska Gora to the crag of Kriška Stena is 8.4 km. Measurements at Krnica were taken in its upper part, approximately 2.5 km from the Kriška Stena crag, at the elevation of 1250 m. The rain gauge at Krnica was 5.9 km away from the precipitation station at Kranjska Gora.

Planica is the best known valley in this section of the Julian Alps. It begins at Ledine on Rateško Polje at the elevation of about 820 m and runs southwards. It ascends relatively evenly to about 1200 m where the final slope takes the uppermost part of the valley under the crag of Mt. Jalovec (2645 m). The valley is closed by the crags of Mts. Macesnovc, Rateške Ponce (2274 m), across Vevnica (2342 m) to Jalovec (2645 m) in the west, and from Mts. Ciprnik (1745 m) across Slemenova Špica (1911 m), Travnik (2379 m) to Jalovec in the east. The length of Planica from Rateško Polje to the crags in the uppermost part is about 8.8 km. The number of measurement sites was the greatest in this valley. We set up two rain gauges and we also included the meteorological station of the Slovenian Environment Agency (ARSO) at Rateče, which represents the contact point of Planica and the Upper Sava Valley, and the ARSO totalizer next to the mountain hut at Tamar. Rain gauges were placed at two locations between the measuring site of Mokri Potok and that of the Črne Vode waterfall at Tamar. The rain gauge at Mokri Potok (1060 m) was 3.6 km away from the meteorological station as measured along the length of the valley, the totalizer at Tamar (1110 m) about 5.4 km, and the rain gauge at the Črne Vode (1260 m) about 6.6 km.

3 RESEARCH METHODOLOGY

Precipitation measurements were made in the summer seasons between 2012 and 2015, which means from mid-May, or the end of May, to the second half of November. The rain gauges were adapted only to measuring rain or small quantities of snow (up to 20 cm), since they did not melt the precipitation. Precipitation water from the catching vessel flew through a funnel and a narrow tube into 50-litre to 100-litre containers, and at the end of the measurements the accumulated rainwater was measured. Because measuring lasted until November, kitchen salt was also added into the container to prevent freezing of rainwater from the catching vessel. Evaporation of water from the container was negligible, since the container was linked to the rain gauge by means of an almost a metre long narrow tube of 2 cm in diameter. To establish the precipitation regime, we also used
the data from the nearby ARSO precipitation stations, namely from the totalizer next to the Planinski dom Tamar alpine hut at Planica, from the meteorological station of Rateče and from the precipitation station of Kranjska Gora. The dates of the measurements are given in Table 1.

Figure 2: Specimen of a rain gauge: catching vessel with a funnel (a) connected to container (c) by means of a narrow tube (b) (photo: E. Kozamernik).

The catching vessel had the surface of 200 cm\(^2\) and was fastened so as to keep horizontal position about 1.8 m above the ground. When the measuring period was over we weighed the solution of rainwater and salt in the container and deducted from this mass the mass of salt that had been added to water.

Table 1: Measurement periods by individual seasons.

| Season | Start       | End          |
|--------|-------------|--------------|
| 2012   | 27 April 2012 | 24 Nov. 2012 |
| 2013   | 25 May 2013  | 16 Nov. 2013 |
| 2014   | 6 June 2014  | 23 Nov. 2014 |
| 2015   | 2 May 2015   | 12 Nov. 2015 |
3.1 Measurement errors

Errors in precipitation measurements in mountains are greater than those that occur in lowlands. Strong windiness and a greater share of snowfall are the two main causes of errors, but responsible are also the wetness of the rain gauge and evaporation (Sevruk, 1997; Pristov et al., 1998). Measurement errors can be great especially with snowfall. Yang et al. (1986) state that rain gauges catch only 22% to 87% of the precipitation during snowing, and Sevruk (1972) indicates that errors can even be as high as 80% or 90% in the case of snow storms on steep exposed slopes. Pristov, Pristov and Zupančič (1988) established the influence of precipitation measurement errors in the area of the present study and calculated correction factors. The estimated errors are rather lower than those stated by Sevruk (1972) or Yang et al. (1986). The correction factors are relatively small for the lowland stations: at Rateče, Kranjska Gora and Mojstrana, where the precipitation stations are situated at the bottom of the Upper Sava Valley (650–850 m), the correction factor amounts to 1.04. At the elevation of about 1000–1100 m, the calculated correction factors are slightly higher: Planina pod Golico (970 m) 1.06, Javorniški Rovt (940 m) 1.03, Predel (1156 m) 1.09, and Gorjuše (980 m) 1.06. At the elevation of about 1500 m the factor, for example, on Mt. Vogel (1510 m) is 1.09 and on Mt. Komna (1515 m) 1.16 (Table 2).

The rain gauges in our research were placed at the elevation from 750 m to about 1400 m, at the bottom of the valleys or in their uppermost parts, where the wind is considerably lesser than on the peaks and ridges. Besides, we only took measurements in the summer season (almost exclusively rain precipitation). When snow did fall, it was less than 20 cm high, which means that the snow cover remained in the rain gauge, melted and drained in the form of snow-water into the container. We estimate that the errors in our case were no more than 10%.

Table 2: Correction factors for precipitation measurements on selected stations close to research area (Pristov, Pristov, Zupančič, 1998).

| Station (elevation) | Correction factor |
|--------------------|-------------------|
| Rateče (864 m)     | 1.04              |
| Planina pod Golico (970 m) | 1.06      |
| Javorniški Rovt (940 m) | 1.03      |
| Predel (1156 m)    | 1.09              |
| Gorjuše (980 m)    | 1.06              |
| Vogel (1510 m)     | 1.09              |
| Komna (1515 m)     | 1.16              |

4 RESULTS

In the following pages we present the results of precipitation measurements in summer seasons in individual valleys.
Table 3: Precipitation amount (mm) in the uppermost part of Beli Potok and at Gozd Martuljek, and the ratio of the precipitation amounts of the two stations in the summer seasons of 2013, 2014 and 2015.

| Season | Precipitation Beli Potok (mm) | Precipitation Gozd Martuljek (mm) | Beli Potok/Gozd Martuljek |
|--------|-------------------------------|----------------------------------|--------------------------|
| 2013   | 967                           | 687                              | 1.41                     |
| 2014   | 1302                          | 988                              | 1.32                     |
| 2015   | 1283                          | 945                              | 1.36                     |

Table 3 demonstrates a considerable difference between the precipitation amount in the uppermost part of Beli Potok and the amount at Gozd Martuljek which lies in the Upper Sava Valley at the contact of the two valleys. In the three summer seasons the ratio never dropped below 1.32; the arithmetic mean of ratios amounts to 1.36. So in the uppermost part of the valley, only 1.8 km more to the south, 36% more precipitation fell than at its entry at the elevation of 750 m.

Table 4: Precipitation amount (mm) in the uppermost part of Krnica and at Kranjska Gora, and the ratio of the precipitation amounts of the two stations in the seasons of 2013, 2014 and 2015.

| Season | Precipitation Krnica (mm) | Precipitation Kranjska Gora (mm) | Krnica/Kranjska Gora |
|--------|---------------------------|----------------------------------|----------------------|
| 2013   | 1350                      | 835                              | 1.62                 |
| 2014   | 1664                      | 1140                             | 1.46                 |
| 2015   | 1572                      | 1004                             | 1.57                 |

The rain gauge at Krnica was about 7.4 km away from the meteorological station of Kranjska Gora. The increase of precipitation as related to Kranjska Gora was in no season lower than factor 1.46, while the arithmetic mean was as much as 1.55. On the basis of three-year measurements in summer seasons we can conclude that the uppermost part of Krnica receives a good half more precipitation in summertime than Kranjska Gora.

Table 5: Precipitation amounts (mm) and ratios of the specified measurement locations at Planica in the summer seasons of 2012, 2013, 2014 and 2015.

| Season | Precipitation Črne vode (mm) | Precipitation Tamar (mm) | Precipitation Mokri potok (mm) | Precipitation Rateče (mm) |
|--------|-----------------------------|--------------------------|-------------------------------|--------------------------|
| 2012   | 2325                        | 2162                     | 1858                          | 1282                     |
| 2013   | 1607                        | 1374                     | 1190                          | 728                      |
| 2014   | 1864                        | 1586                     | 1521                          | 1011                     |
| 2015   | 1581                        | 1389                     | 1299                          | 995                      |
| Arithmetic mean | 1844                        | 1627                     | 1467                          | 1004                     |

| | Črne vode/Rateče | Tamar/Rateče | Mokri potok/Rateče |
|----------------|----------------|-------------------|---------------------|
| 2012           | 1.81           | 1.69              | 1.45                |
| 2013           | 2.21           | 1.89              | 1.63                |
| 2014           | 1.84           | 1.57              | 1.50                |
| 2015           | 1.59           | 1.40              | 1.31                |
| Arithmetic mean | 1.86           | 1.64              | 1.47                |
The most numerous measurements were made at Planica. They show an almost linear increase along the valley, within the distance from the ARSO station at Rateče to the station at Črne Vode. The arithmetic mean of increases is 1.47 at Mokri Potok, 1.64 at the alpine hut of Tamar, and 1.86 at the Črne Vode fall.

Figure 3: Arithmetic mean of precipitation increase from the lowest point of the valley to its end (in %) at Planica as related to Rateče in the summer period of 2012–2015.

5 CALCULATION OF HORIZONTAL PRECIPITATION GRADIENTS

Horizontal precipitation gradients indicate the change in the precipitation amount at a certain distance. Gradients at short distances most often result from the difference in elevation of a certain area, which exerts influence on the rise or descent of air masses that move over this area. Positive gradients, therefore, most often result from intense rise of the area and consequently of the air, and negative ones result from the descent of the air. The greatest amount of precipitation per year occurs in the surroundings of mountain ridges or the highest mountain sections, provided these do not exceed the elevation of the wettest zone. Precipitation amount increases parallel to the increase of the elevation only to the height of the cloud base, after which it decreases (Lauer 1975) because the content of air moisture decreases from this point upwards (Miniscloux, Creutin, Anquetin, 2001). This height differs in different latitudes (McGinnis, 2000; Barry, 2008). It is lower in tropical areas than in moderate latitudes.
Table 6: Horizontal precipitation gradients (HPG) for the summer seasons 2012–2015 at Planica, and for the summer seasons 2013–2015 at Krnica and Beli Potok.

| Year | Summer HPG Beli Potok (mm/km) | Summer HPG Krnica (mm/km) | Summer HPG Planica (mm/km) |
|------|-------------------------------|---------------------------|---------------------------|
| 2012 | …                             | …                         | 158                       |
| 2013 | 97                            | 87                        | 133                       |
| 2014 | 108                           | 89                        | 129                       |
| 2015 | 117                           | 96                        | 89                        |
| Arithmetic mean | 107                         | 91                        | 127                       |

We calculated rather similar horizontal precipitation gradients for the measurement periods. The arithmetic mean of the gradients is 127 mm/km at Planica, 91 mm/km at Krnica, and 107 mm/km at Beli Potok. In the case of Beli Potok and Krnica the three-year period’s standard deviation was 8.2 mm/km and 3.9 mm/km, respectively, and at Planica it was 24.8 mm/km in the four-year period, while in the same period as in the case of the other two valleys it was 13 mm/km. Low standard deviations in the period indicate rather similar summer precipitation gradients in individual years.

Table 7 presents horizontal precipitation gradients calculated at a yearly level. They were calculated with the help of the data on annual precipitation at Rateče and Kranjska Gora, whereas for Gozd Martuljek we made an estimate of the annual precipitation with regard to the precipitation at Kranjska Gora.

The annual precipitation amounts in the discussed valleys were obtained in such a way that the annual precipitation measured at the ARSO stations of Rateče and Kranjska Gora and the estimated precipitation at Gozd Martuljek were multiplied with the summer factor of increase between these stations and the stations in the valleys.

\[
RR_{\text{Tamar year } i} = RR_{\text{Rateče year } i} \times \frac{\text{summer } RR_{\text{Tamar year } i}}{\text{summer } RR_{\text{Rateče year } i}}
\]

\[
RR_{\text{Krnica year } i} = RR_{\text{Kranjska Gora year } i} \times \frac{\text{summer } RR_{\text{Krnica year } i}}{\text{summer } RR_{\text{Kranjska Gora year } i}}
\]

\[
RR_{\text{Beli Potok year } i} = RR_{\text{Gozd Martuljek year } i} \times \frac{\text{summer } RR_{\text{Beli Potok year } i}}{\text{summer } RR_{\text{Martuljek year } i}}
\]

\[
RR_{\text{Martuljek year } i} = RR_{\text{Kranjska Gora year } i} \times \frac{\text{summer } RR_{\text{Gozd Martuljek year } i}}{\text{summer } RR_{\text{Kranjska Gora year } i}}
\]

– where RR denotes precipitation amount.
Table 7: Horizontal precipitation gradients (HPG) at annual level for the 2012–2015 period at Planica and for the 2013–2015 period at Krnica and Beli Potok.

|                      | Rateče          | Črne Vode       | RR difference (mm) | Distance (km) | Annual HPG (mm/km) |
|----------------------|-----------------|-----------------|--------------------|---------------|-------------------|
| **Annual precipitation (RR) (mm)** |                 |                 |                    |               |                   |
| 2012                 | 1700            | 3163            | 1462               | 6.6           | 222               |
| 2013                 | 1600            | 2977            | 1376               | 6.6           | 208               |
| 2014                 | 2084            | 3876            | 1792               | 6.6           | 272               |
| 2015                 | 1233            | 2293            | 1060               | 6.6           | 161               |
| **Arithmetic mean**  | **1654**        | **3077**        | **1423**           | **6.6**       | **216**           |
|                      |                 |                 |                    |               |                   |
| **Kranjska Gora**    | **1757**        | **2724**        | **966**            | **5.9**       | **164**           |
|                      |                 |                 |                    |               |                   |
| **Krnica**           |                 |                 |                    |               |                   |
| 2013                 | 1757            | 2724            | 966                | 5.9           | 164               |
| 2014                 | 2315            | 3587            | 1273               | 5.9           | 216               |
| 2015                 | 1255            | 1944            | 690                | 5.9           | 117               |
| **Arithmetic mean**  | **1776**        | **2752**        | **976**            | **5.9**       | **165**           |
|                      |                 |                 |                    |               |                   |
| **Gozd Martuljek**   |                 |                 |                    |               |                   |
| 2013                 | 1541            | 2170            | 628                | 2.9           | 217               |
| 2014                 | 2030            | 2676            | 645                | 2.9           | 222               |
| 2015                 | 1100            | 1494            | 394                | 2.9           | 136               |
| **Arithmetic mean**  | **1557**        | **2113**        | **556**            | **2.9**       | **192**           |

Figure 4: Comparison between the interpolated precipitation data based on field measurements in the 2012–2015 period (a) and the official precipitation map of corrected precipitation for the 1971–2000 period (b) (ARSO, 2015).
Horizontal precipitation gradients at a yearly level show rather high values. The greatest gradient occurs at Planica. Arithmetic mean of four years is as much as 216 mm/km with the standard deviation of 40 mm/km. At Beli Potok the horizontal precipitation gradient is 192 mm/km with the standard deviation of 39 mm/km, and at Krnica 165 mm/km with the standard deviation of 40 mm/km. In our opinion, the reasons for the differences between horizontal precipitation gradients are to be found in the direction and inclination of the valleys.

6 DISCUSSION

The Planica valley runs perpendicular to the main ridge of the western Julian Alps and is surrounded by high mountains at its end. It rapidly descends towards the exit and widens and opens near Rateče. The Beli Potok valley is rather shorter than the other two valleys, but its inclination is expressly greater as it drops by around 700 metres along the distance of 2.9 km. The great inclination of the valley’s bottom causes a fast decrease in precipitation amount. According to the measured precipitation, the Krnica valley has a lower gradient, partly because of the higher precipitation amount at its entry at Kranjska Gora, and partly because of the lower precipitation amount in its uppermost part. The former fact results from a smaller openness of Kranjska Gora in comparison to Rateče, situated on the Karavanke side of the Upper Sava Valley, and the descent of air driven by south winds that is more expressed there than at Kranjska Gora. This is also corroborated by the foehn window that occurs in southern meteorological situations, which is more frequent and more strongly expressed at Rateče than at Kranjska Gora. On the other hand, in the end part of Planica a greater precipitation amount was measured than at Krnica, which results from a different position of the valley. Krnica lies in a lee position of the central massif of the Julian Alps, partly in the lee position of the Triglav mountains, whereas Planica reaches the wall of Mt. Jalovec, where it is already under the precipitation influence of the Upper Soča Region which is the wettest area in Slovenia.

Horizontal precipitation gradients in Alpine valleys are more easily estimated if we compare them to some other selected horizontal precipitation gradients in Slovenia which we calculated from the data of the precipitation stations of the ARSO network. The distances between individual precipitation stations in this network are longer than the distances between the measurement posts within the framework of our research project. The gradients are heavily influenced by the forms of the surface. The highest gradients are to be expected in the areas where massifs continue into lowlands. Among the selected profiles in Table 8, the case of Mrzla Rupa is such a gradient. The location lies in the rear of the plateau Trnovski gozd, in the direction towards Zalošče in the Vipava Valley. Within the distance of 17 km the precipitation gradient is as much as –70 mm/km. A similar profile can be found in the area from Kamniška Bistrica towards the plains of the northern part of the Ljubljana Basin, where we used the data of the meteorological station at the Jože Pučnik Airport Ljubljana. Although Kamniška Bistrica is a lowland station, it is situated close to the central part of the Kamnik-Savinja Alps and already functions as an indicator of precipitation amount in the central part of this
mountain chain. There is no other station on the south side that would lie higher and belong to the central part of the Kamnik-Savinja Alps. There is a higher lying station on Mt. Krvavec, but due to its position the quality of its data is questionable. Within the 15 km distance of this profile the precipitation gradient is −47 mm/km. The profile across the mountain barrier, i.e. from Kamniška Bistrica to the valley Logarska Dolina, also seems to be interesting. Within the distance of 9.5 km the horizontal precipitation gradient is −30 mm/km. It should be noted that no data are available for a better presentation of precipitation amounts near the ridge of the central part of the Kamnik-Savinja Alps (i.e. the Grintovci mountains). We can presume that the area closer to the ridges is even wetter and, accordingly, the gradient is higher. The rest of the cases of horizontal precipitation gradients in Table 8 are profiles from the Upper Soča Region towards the Adriatic Sea. Because those distances are greater, the values of the gradients, logically, approach zero. If horizontal precipitation gradients in Table 7 are compared to those in Table 8, it is obvious that the absolute values of the gradients in the selected valleys are considerably higher. The reasons are as follows:

- intense wetness of the uppermost parts of the valleys which reach into the Central and West Julian Alps;
- the direction of the valleys from the central part towards the north where quick foehnisation occurs;
- the valleys do not run parallel to the ridges but are more or less perpendicular to the direction of the massif, which contributes to higher horizontal precipitation gradients;
- the areas that flank the valleys likewise slope steeply, which enhances foehnisation in the direction away from the mountains.

Table 8: Horizontal precipitation gradients within certain selected distances in Slovenia.

| Direction                                      | Distance (km) | Horizontal precipitation gradient (mm/km) | Period                   |
|------------------------------------------------|---------------|------------------------------------------|--------------------------|
| Mrzla Rupa (930 m)–Zalošče (75 m)              | 17            | -70                                      | 2000–2015                |
| Kamniška Bistrica (650 m)–Jože Pučnik Airport (364 m) | 15            | -47                                      | 2000–2006 and 2008–2015 |
| Kamniška Bistrica (650 m)–Logarska Dolina (740m) | 9.5           | -30                                      | 2000–2005 and 2007–2009 |
| Soča (487 m)–Bilje (55 m)                      | 49            | -25                                      | 2000–2015                |
| Soča (487 m)–Trst (67 m)                       | 78            | -22                                      | 2000–2009                |
| Podljubelj (679 m)–Naklo (403 m)               | 15            | -17                                      | 2000–2015                |
| Soča (487 m)–Portorož (2 m)                    | 96            | -17                                      | 2000–2015                |

Data source: ARSO, 2018; HISTALP, 2018; Weather online, 2018.
Valleys can also be found on the southern side of the Julian Alps, where the elevation of the surface is more richly varied. The valleys there do not run in a straight direction perpendicular to the central ridge (e.g. Trenta, Koritnica), and some of them are surrounded by high mountains from all sides (Zadnjica, Zadnja Trenta, Bavšica), so foehnisation is less distinct there. In addition, precipitation is expressly orographically enhanced already in the foothills of the Julian Alps, so that higher gradients already occur in the area from the Vipava Valley towards the plateau Trnovski Gozd.

7 CONCLUSION
The present study shows that horizontal precipitation gradients in Alpine valleys can differ greatly. They are influenced by the direction of the valleys, their inclination, and also the morphology of the surroundings. In the valleys of Planica, Krnica and Beli Potok, which are situated in the Julian Alps in the north-west of Slovenia, horizontal precipitation gradients at the annual level in the studied period reached the values of 162 mm/km at Krnica, 192 mm/km at Beli Potok, and 216 mm/km at Planica. They belong to the highest gradients known in Slovenia; however, it should be noted that local precipitation characteristics of other valleys remain rather unknown. In relation to the lowest point of each researched valley, precipitation amount in their uppermost parts increases by the factor of 1.36 at Beli Potok, 1.55 at Krnica and as much as 1.86 at Planica. This corroborates the findings of previous researches on the precipitation increase in mountainous areas. It also calls attention to the fact that these findings should be integrated into the practical knowledge of estimating the consequences of precipitation increase in the direction towards the highest parts of the mountains. What we have in mind is protection against avalanches, the estimation of unpredictable precipitation events and related natural disasters, and the like. We can also conclude that precipitation variety, and the ensuing climatic variety, in the mountainous world points to a new domain of geodiversity as the diversity of the inanimate world, which is manifest in the mountainous areas at the level of both landforms and climate phenomena.

(Translated into English by Branka Klemenc)

Acknowledgements
The authors warmly thank Filip Štucin, Peter Stele, Gregor Vertačnik, Ajda Kafol Stojanović, Tilen Sirše, Gašper Petretič, Marko Podlesnik, Jaka Ortar and Mojca Ošep for their help in the measurements.

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