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Interaction of valleys and circulation patterns (CPs) on small-scale spatial precipitation distribution in the complex terrain of southern Germany

M. Liu[1], A. Bárdossy[2], and E. Zehe[3]

[1]State Key Laboratory of Earth Surface Processes and Resource Ecology,
Beijing Normal University, Beijing, China
[2]Institute for Modelling Hydraulic and Environmental Systems, University Stuttgart,
Stuttgart, Germany
[3]Institute of Water Resources and River Basin Management,
Karlsruhe Institute of Technology, Karlsruhe, Germany

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Correspondence to: M. Liu (min.liu@gmx.net)

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Abstract

Topography exerts influence on the spatial precipitation distribution over different scales, known typically at the large scale as the orographic effect, and at the small scale as the wind-drift rainfall (WDR) effect. At the intermediate scale ($\sim$ 1–10 km), which is characterized by secondary mountain valleys, topography also demonstrates some effect on the precipitation pattern. This paper investigates such intermediate-scale topographic effect on precipitation patterns, focusing on narrow-steep valleys in the complex terrain in southern Germany, based on the daily observations over a 48-yr period ($\sim$ 1960–2007) from a high-density rain-gauge network covering two sub-areas, Baden-Wuerttemberg (BW) and Bayern (BY). Precipitation data at the valley and non-valley stations are compared under consideration of the daily general circulation patterns (CPs) classified by a fuzzy-rule based algorithm. Scatter plots of precipitation against elevation demonstrate a different behavior of valley stations comparing to non-valley stations. A detailed study of the precipitation time series for selected station triplets, each consisting of a valley station, a mountain station and an open station have been investigated by statistical analysis with the Kolmogrov–Smirnov (KS) test supplemented by the one-way analysis of variance (one-way ANOVA) and a graphical comparison of the means. The results show an interaction of valley orientation and the moisture flow direction of the CPs at the intermediate-scale, i.e. when the valley is shielded from the moisture flow, the precipitation amount within the valley is comparable to that on the mountain crest; when the valley is open to the moisture flow, the precipitation within the valley is much less than that on the mountain. Such a phenomenon, whereby the precipitation is “blind” to the valleys at the intermediate scale conditioned on CPs, is defined as the “narrow-valley effect” in this work, and it cannot be captured by the widely used elevation–precipitation relationship. This implies that the traditional geostatistical interpolation schemes, e.g. ordinary kriging (OK) or external drift kriging (EDK) applying digital elevation model (DEM) as external information are not sufficient. An interpolation experiment applying EDK with orographic surrogate

elevation defined in this paper as auxiliary information to account for the valley effects shows improvement for the cross-validation.

1 Introduction

Precipitation is characterized by remarkable spatial and temporal variability at different space-time scales (Bidin and Chappell, 2003; Nezlin and Stein, 2005; Jeniffer et al., 2010; Langella et al., 2010), and the spatio-temporal variability is of critical importance for a wide range of hydro-meteorological and hydro-geological applications. For instance, the persistent precipitation pattern will shape the terrain through erosion (Anders et al., 2006), and a co-evolution of topography-precipitation can be observed (Roe, 2003; Stolar et al., 2007). Numerous studies have also shown that the spatial variability of rainfall is essential for runoff generation processes and flood forecasting (Koren et al., 1999; Arnaud et al., 2002). The spatial precipitation variability is also a major source of the uncertainty of hydrological models (Younger et al., 2009). The local and regional water balance is also determined by precipitation patterns at the corresponding scales (Fekete et al., 2004). Furthermore, detailed knowledge on precipitation patterns can be used to optimize the design of the rain-gauge network (Cheng et al., 2008) such that a limited number of stations can adequately represent the underlying rainfall field.

Topography, among many other factors, has profound effects on spatial distribution of precipitation. Thanks to the readily availability of digital elevation model (DEM) data, topographic effects have been extensively studied. Statistical analysis and numerical simulation are the two major tools for investigation of topographical precipitation. Meteorological precipitation models can generate spatial precipitation distribution, but require detailed input of environmental parameters, such as temperature, lapse rate, wind, etc., which renders the modeling practice rather location- and event-specific (Smith, 2006). Furthermore, even informed by very detailed data, current models still have a limited accuracy and capacity in resolving the small-scale precipitation. Due to the limitation of the modeling approach, statistical studies on topography-altered spatial precipitation have been very popular, which range from pure precipitation–altitude relationships (Sevruk and Nevenic, 1998) to multivariate regression models relating precipitation to multiple topographic parameters including elevation, slope, orientation and exposure (Prudhomme and Reed, 1998; Daly et al., 2002; Sun et al., 2008), and in some cases also wind parameters (Johansson and Chen, 2003).

The orographic effect at the large scale and the wind-drift rainfall effect (WDR) at the small scale are the most widely reported topographic effects on precipitation in the literature. The orographic effect refers to the forced uplifting and consequently cooling down of moist air at the windward side of the mountain to generate precipitation and the descending and warming up on the lee side of the mountain to reduce the precipitation, known as “rain-shadow”. Orographic precipitation occurs at large scales consisting of primary mountain valleys, and the associated spatial distribution of precipitation can be usually reflected by an elevation–precipitation relationship. The orographic effect has been widely studied and confirmed by theory (Houze, 1993; Haven, 2004), modeling (Jiang, 2007), and statistical analysis (Basist et al., 1994; Weisse and Bois, 2001; Marqulnez et al., 2003). In contrast, the WDR effect focuses on the precipitation trajectories affected by topography-conditioned perturbations of the local wind field at a much finer scale featured by micro topography, which is not part of the rainfall generation process. WDR has also been extensively investigated with both observation data and fluid mechanical models (Sharon and Arazi, 1997; Blocken et al., 2005; Lehning et al., 2008). In general, the orographic effect entails precipitation climatology at the scale of around or larger than 100 km, whereas the WDR effect describes the redistribution of rainfall by micro topographic features of less than around 1 km. Limited attention has been paid to precipitation patterns at the intermediate scale consisting of the secondary mountain valleys, which remains a scale gap in describing the spatial variability of precipitation. Furthermore, neglecting the interaction of topography with climatology in most studies has also left a theoretical gap in studying precipitation patterns.

Faures et al. (1995) and Merz and Bárdossy (1998) have shown that the small-scale spatial precipitation variability has a strong impact on runoff processes for very small areas. However, when the resolution of catchment models goes beyond 1 km which is normal for medium- and large-size basins, the spatial variance resulting from the WDR effect may be homogenized out, is thus not relevant for the areal precipitation of each single grid. In such cases, the spatial variance at the intermediate scale corresponding to the resolution of hydrological models becomes increasingly critical.

Studies on spatial precipitation reported in the literature are usually undermined by two problems: (i) the spatial locations of stations tend to be biased to easily accessible sites; (ii) rain-gauge networks seldom have the spatial density that is fine enough to sample the small- and intermediate-scale variability of precipitation, therefore only the large-scale precipitation structure can be resolved. One climatological study with observation data that is closer to the intermediate scale defined in this paper is presented by Frei and Schär (1998) (about 25 km), which demonstrates that a simple precipitation–height relationship does not exist in the Alpine region. As with many other studies, it investigates only the effects of topography without considering interactions with other factors, especially the atmospheric conditions. Some other studies have tried to link the precipitation patterns to circulation patterns (CPs), but only at the very large country or continental scale and neglect topographic effects (Busuioc et al., 2001; Haston and Michaelsen, 1997). To the authors' knowledge, only Wastl and Zängl (2008) have investigated the mountain–valley precipitation difference with consideration of the climatology at the intermediate scale. In this paper, the authors tried to relate the precipitation difference to MM5 simulated wind at 700 hPa level and the vertical moisture profile from 600 hPa to 850 hPa. By careful selection of mountain–valley station pairs, they excluded the precipitation difference caused by horizontal gradient to see the pure effects of local topography. The rain-gauge observations combined with the meteorological simulations showed that, in some cases the valley stations receive comparable rainfall to the mountain stations, while in other cases the precipitation exhibits a wind direction dependent difference, therefore a systematical mountain–valley precipitation relationship could not be concluded.

This paper revisits the issue of spatial precipitation variability at the intermediate scale characterized by secondary mountain valleys using a statistical approach. The high-density rain gauge network with long-term observations in southern Germany enables the investigation of mountain–valley precipitation difference and the interaction of topography with CPs at the intermediate scale to close the aforementioned scale gap in precipitation patterns. The study applies both parametric and non-parametric tests to analyze daily precipitation for all days and for days with a specific CP. One-way analysis of variance (one-way ANOVA) test is applied as a parametric method to compare the mean precipitation, whereas the non-parametric Kolmogrov–Smirnov (KS) test is applied to compare the empirical distribution. The consequence of neglecting the intermediate-scale precipitation pattern in the interpolation procedure is demonstrated with traditional OK and EDK, which shows systematic bias.

The paper is outlined as follows: Sect. 2 describes the studying area and the database. Following the introduction of the CP classification, the valley and non-valley stations identified for the study areas will be presented; Sect. 3 will first demonstrate the results of a simple statistical analysis through scatter plots of precipitation and elevation, and then the detailed analysis with statistical tests for the selected station triplets. Section 4 will illustrate the consequences of neglecting of the precipitation variability at the intermediate scale during interpolation and the possibility to consider it, by showing the bias of OK and EDK in one of the study areas and the improvement of EDK with orographic surrogate elevation as an example. The main findings are summarized in Sect. 5.

2 Study area and data

2.1 Study area

Because this study relies mainly on statistical analysis which demands detailed observational data, southern Germany consisting of two German federal states – Baden

Wuerttemberg (BW, 35 751 km^2) and Bayern (BY, 70 551 km^2) (see Fig. 1) with good precipitation data availability and rich topographic features has been taken as the study area. To consider the directions of moisture flow more accurately, the two states are investigated separately in this work. Baden-Wuerttemberg is located in south-west Germany and contains two mountain ranges, the Black Forest of medium elevation in the west and the Swabian Alps of lower elevation in the east. The Swabian Alps lie between the Danube in the southeast and the Upper Neckar in the northwest. In the southwest they approach the high-elevation part of the Black Forest. The highest peak of the region is Lemberg (1015 m). The area's profile resembles a high plateau, which rises abruptly in the northwest with a steep escarpment up to 400 m, while over the top it is flat or gently hilled. The Black Forest occupies a 200 km × 60 km bell-shaped region tilted to northeast bounded by the Rhine valley in the west and south. The highest peek in the Black Forest stretches to 1493 m at Feldberg in the southwest surrounded by a higher region, which reduces its elevation while extending to the northeast, and rises again after a few kilometers. The state Bayern contains the middle-north ranges of the Alps which defines its border with Austria. The Alps in Bayern are characterized by high mountains with a peak of 2962 m at Zugspitze. The main profile of the mountains extends from the west to east, but locally, mountain crests in different orientations can be observed. The entire study domain contains mountains ranging from low, medium to high, which offers a possibility of a comprehensive study of mountain–valley precipitation variability over different elevation. For the study area, 30 m DEM is available from the local environmental agency, and is resampled to 100 m in ArcGIS (see Fig. 1).

2.2 Precipitation data

The study areas are located in a temperate climate region with abundant precipitation, with annual precipitation ranging from 500 mm to 1800. The German Weather Service (DWD) has operated a high-density rain-gauge network in these areas – in Baden-Wuerttemberg there are in total 294 stations with a mean gauge distance of around

10 km, and in Bayern 1239 stations with a mean distance of around 7.5 km. In certain regions of the study areas, the mean gauge distance reaches 2.5 km, with a minimum distance of around 1.5 km. The station data span over 40 yr from 1961 to 2007, but the valid station observations vary over time. The average number of daily reported stations is lower than the total number of stations due to the missing records at some of the stations and in general the average number of daily stations has been decreased over time because of the deployment of Radar stations. However, the station density in the two data sets exhibits only slight variations until year 2000. In this study, only stations with precipitation records longer than 10 yr are considered for the statistical analysis. While the high-density network enables the statistical investigation of the mountain–valley precipitation variation at the intermediate scale, the long-term records guarantee the reliability of the analysis.

Some descriptive statistics in Fig. 2 show the hypsometric distribution, the altitudinal distribution of rain gauges and the corresponding mean daily precipitation of stations lying in each elevation band. In principal, the altitudinal distribution of rain gauges follows the hypsometric distribution curve, which appears to be a more or less equally representation of precipitation of different elevation. However, as shown by the mean precipitation of different elevation band in Fig. 2, there is a gap in the mean precipitation bars, which reflects missing observation at the higher elevations in both areas (∼ 1050–1450 m in BW and ∼ 1900–2900 m in BY). If such areas are neglected, the precipitation seems to demonstrate an increasing trend with increasing elevation up to a certain elevation and keeps constant at the higher elevation in both BW and BY.

2.3 Circulation patterns

Circulation pattern (CP) is the mean air pressure distribution over an area, and is defined using 500 or 700 hPa geo-potential anomalies. Any given circulation type persists for several days and during this time the main features of weather remain mostly constant across the CP covered region. Then through a rapid transition, another CP will emerge. Similar CPs will generate similar weather conditions, and can be classified by

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their characteristic pressure field as either wet or dry corresponding to a low (cyclone) or high pressure center (anti-cyclone). The direction of moisture flow can be considered to be identical to the circulation pattern.

In this work, the CPs are classified with the automated fuzzy-rule based algorithm by Bárdossy et al. (2002). Fuzzy rules specify the position of high- and low-pressure anomalies and are then optimized automatically with the simulated annealing (SA) algorithm. With the help of the optimized fuzzy rules, the pressure fields, i.e. the large-scale atmospheric CPs, can be classified into groups associated with a certain local precipitation characteristics (Bárdossy et al., 2005). The ratio of mean daily precipitation of a given CP to the climatological average, i.e. the mean daily precipitation of all days, is referred to as the wetness index (WI). In this paper, the wetness index is scaled by 10, therefore, a value higher than 1 indicates "wet", e.g. if the wetness index is equal to 20, it means it is twice as wet as the climatic average. To consider more accurately the direction of moisture flow, the CPs in the two states are classified individually. In BW, 18 CPs are obtained, with 6 of them being so-called wet CPs, whereas in BY, 8 out of 21 CPs are wet (see Table 1). Figure 3 shows geopotential anomalies and the scaled wetness index (WI multiplied by 10) of some example dry and wet CPs respectively. For BW, the CP04 is a dry CP, for which the study region is covered by a high pressure center, whereas CP10 is a wet CP associated with a low pressure center. Because the wet CPs generate the major rainfall, they are elaborated more in details in this research.

2.4 Identification of valley stations

Because the goal of this paper is to investigate the effects of narrow-steep valleys, the first step is to define and identify the target valleys, i.e. to differentiate the stations in narrow-steep valleys from the other stations. Valleys are formed by either river or glacial erosion, or sequential occupation of one after the other (Montgomery, 2002). With its erosion, transportation, and sedimentation functions, rivers will form valleys with different cross section shapes depending on the surrounding topography – rivers with steep gradients produce steep walls with a narrow bottom, and rivers with smaller slopes will result in broader and gentler valleys, with the resulted valleys being commonly V-shaped. At the lowest reach of a river, a floodplain comes into being by sedimentation. The invasion and recession of the glaciers will form the U-shaped valleys. Characteristics such as bottom width, shoulder width, ridge-crest–valley-bottom relief and cross-sectional area are used to classify the valley shapes. In this study, criteria based on elevation difference for all cross sections passing a given location are selected. Whether a given point P with elevation Z_p is located in a valley or non-valley area is evaluated by the following trial-and-error procedure:

1. a vertical plain passing point P intersects the terrain at a planar curve S. The plain will be rotated N times such that its horizontal angle (with regard to the east) changes from 0° to 360° at an interval of $\frac{360}{N}$;
2. for each rotation, search on the plain for the lowest elevation (Z_l^l and Z_r^l) on each side of the station along the curve within a horizontal distance l;
3. search for the highest elevation Z_l^h on one side of the station within a horizontal distance $L\,(L > l)$, the actual distance from the highest point to point P is recorded as L_l;
4. search for the highest elevation Z_r^h on the other side of the station within a distance of $L - L_l$;
5. for a station to be recognized as within narrow-steep valley, n out of N plain should satisfy the following conditions:

$$\max(Z_l^h, Z_r^h) - \min(Z_l^l, Z_r^l) \geq \Delta h_1 \tag{1}$$

$$\min(Z_l^h, Z_r^h) - \max(Z_l^l, Z_r^l) \geq \Delta h_2 \tag{2}$$

$$\max(Z_l^h, Z_r^h) - Z_\mathrm{p} \geq \Delta h_3. \tag{3}$$

Except N is set to 72, all the other parameters ($L, l, \Delta h_1, \Delta h_2, \Delta h_3, n$) are determined by trial-and-error procedure started from reasonable initial values and changed by visual comparison with the DEM map. The parameters of valley identification for both study areas are listed in Table 2.

After several iterations, a nearly perfect identification of valley stations is achieved, with 2 or 3 stations being manually adjusted by visual inspection. Figures 4 and 5 demonstrate the identified valley stations together with their station numbers for BW and BY, respectively. For detailed investigation with selected station triplets, the non-valley stations are further defined as mountain stations on mountain top and open stations in open low area.

3 Statistical analysis

A preliminary study of the mountain–valley station difference is demonstrated by scatter plots of station precipitation and elevation. The scatter plots are shown for general days as well as for specific CPs. Furthermore, statistical analysis with the KS test and one-way ANOVA test for selected stations triplets then gives insight into the spatial precipitation patterns.

3.1 Scatter plot of altitude vs. precipitation

Figure 6 shows the scatter plot of mean daily precipitation at both the valley and non-valley stations for BW. The valley stations are given as circles with the corresponding station number. The trend line of the valley stations lies above the trend line of the mountain stations, and most valley stations appear on the upper left part of the scattered points and above the all-station trend line except two groups of stations marked by the red and blue ovals in Fig. 6. However, closer investigation shows that most stations from the two groups are located on either side of the Swabian Alps (BW-A and BW-B in Fig. 7a), where a smaller regional mean precipitation occurs. If the two localized groups are excluded, the trend line of the valley stations will exhibit a much higher slope than the non-valley stations, which implies that the valley stations behave systematically different from the non-valley stations. If the station elevations and their precipitation of each localized group are plotted, they again show characteristics as in Fig. 6, i.e. larger intercept and higher slope (see Fig. 7b and c). Of note are four stations (CS, HE, EO, GW) enclosed in the red oval in Fig. 6 but not located in the Swabian Alps which are not shown in Fig. 7b. These 4 stations appear to behave differently with regards to the majority of the valley stations, but when comparing to its neighboring stations, they still demonstrate the typical characteristics of valley stations, which is trivial and not shown here. Another single exceptional station KO is a station in the river valley, which is not actually narrow and steep. We do not exclude that some exceptional valley station, which does not follow our assumption, such as station EC in Fig. 7c which may be caused by very specific local geographical and meteorological conditions.

Figure 8 shows the scatter plot of BY. As in the case of BW, the scatter plot shows a clear distinction of valley and non-valley stations with some localized groups. For example, the group of valley stations BY-A (L38, L45, N09, N38, Q42, T04, U01, U27, W06) in the low mountain region located in the middle of the state are mixed in the cluster of non-valley stations because of lower regional precipitation; the valley stations in the middle-east of the state (L05, M03, M10, M26, N07, N18, N19, N21, N37, N49, O13, O24, O29, O36) form another outlier group in the scatter plot. When plotted locally, the trend line of the valley stations of group BY-A is almost flat, which seems contradictory to the results obtained in BW. However, this area contains two mountain ranges in different directions. Stations in the north–south mountain ranges appear mostly on the upper edge of the scattered points, whereas four other stations (L38, L45, N09, N38) are mixed with non-valley stations exhibiting a lower amount of precipitation (Fig. 9a). This implies that the amount of precipitation at the valley stations may be related to the mountain/valley orientation. The trend line of group BY-B show again the general characteristics when plotted locally (Fig. 9b). Some stations, such as N18, N49, N07 show exceptionally low precipitation, because they are located at the fringe of the mountainous area. Individual exceptional stations including Y37, A07 and W32 may be caused by very specific local geographic conditions, which are beyond the scope of discussion of this paper.

The phenomenon that valley stations lie in the upper part of the scatter plot can be interpreted in two ways by comparing the valley station with either a station with higher elevation but similar precipitation or a station with lower precipitation but comparable elevation: for a valley station and a non-valley station located at the same elevation, the valley station receives more rainfall, which reflects higher areal precipitation in the mountainous region. For example, it can be seen that station Eberbach (DU) which is a valley station receives higher precipitation than the nearby station Spechbach (KI) on the open area (see Fig. 6). Sometimes, even an open station is located at a higher elevation than the valley station, it receives less precipitation, for example, Titisee (GZ) comparing to Zastler (EV) (see Fig. 6). Alternatively, it can be interpreted that a valley station receives comparable rainfall to a station which is located at a much higher elevation, for example, Waldbrunn (KF) with Eberbach (DU) in Fig. 6. The precipitation relationship among the station triplet such as DU/KI/KF contains very useful information of precipitation patterns and will be investigated further in detail.

3.2 Scatter plot with consideration of CPs

Further investigation of scatter plots of daily precipitation also demonstrates similar features that valley stations lie above other stations in the scatter plots, although the distribution of the valley and non-valley stations in the scatter plots varies from day to day. Figure 10 shows the scatter plots of the mean daily precipitation of all the wet CPs of BW. The locations of valley and non-valley points in the scatter plots change for different CPs. For CP10 the valley and non-valley stations are rather mixed, but for other wet CPs valley stations are on the upper edge. For CP05 the valley and non-valley stations are clearly separated, while in CP09 some of them become mixed, which may imply that valley stations receiving comparable precipitation as some non-valley stations under CP05 receive less precipitation under CP09, i.e. the precipitation amount at a station depends not only on whether it is a valley station, but also on the CP on that day. Whether the assumption is true or not should be checked through detailed comparison of the precipitation time series at neighboring valley and non-valley stations.

3.3 Statistical test of precipitation time series for selected station triplets

To confirm whether the mountain–valley precipitation difference is affected by CPs, statistical tests of selected mountain–valley-open station triplets were performed. To properly reflect the local spatial precipitation pattern, the three stations of a triplet should be geographically close. But due to the general problem of rain gauge availability on mountainous region, there are only very few such ideal station configurations available. Another problem is that for stations deep inside the mountain range, there are no open stations in the nearby neighborhood. In such cases, the closest open station is taken. Nevertheless, six station triplets, from T-1 to T-6, three for each state satisfying the requirements were selected and analyzed. The location of the station triplets are shown in Figs. 4 and 5. The name, ID number and elevation of the stations are shown in Table 3. To have a clear impression about the local topography, Google Map terrain with a very fine resolution has been used as auxiliary information.

Two different statistical tests are conducted for the precipitation time series: the non-parametric two-sample KS test of the empirical cumulative distribution (CDF) and the parametric one-way ANOVA test of the mean precipitation. Although one-way ANOVA is known to be based on the assumption of the normal distribution of underlying data, it is robust with respect to modest violation of the assumption given that the samples are mutually independent (see Matlab R7 manual). The tests are applied with the valley station being the reference station, i.e. by comparing the mountain–valley- and valley-open station pairs respectively. Both tests are conducted for daily precipitation of each CP and for all days in general. The null-hypothesis of the KS-test is that the two stations are drawn from the same continuous distribution, and for the one-way ANOVA test it is that the mean precipitation of the three stations are the same. In addition, the mean daily precipitation is plotted together with its standard error. To be mentioned, the power of the statistical tests are depending on the sample size. The power of the statistical analysis decreases, when the sample size is either too small or too large. Because for different station triplets and different CPs of the same station triplet, the sample size is different, the significance level is adjusted from case to case in this research, i.e., when the sample size is large, the significance level is taken as 0.05, and when the sample size is medium and reasonable, the significance level is taken as 0.15.

3.3.1 Statistical analysis of station triples in Baden-Wuerttemberg

The station triples selected from Baden-Wuerttemberg are T-1 in the Black Forest, which is a middle-range mountain, T-2 in Odenwald and T-3 in the Swabian Alps, both being low-range mountains. The exact configuration of the station triplets can be found in Fig. 11a,b,c. Table 4 shows that, for both T-2 and T-3 null-hypothesis, the precipitation time series of the mountain and valley stations are from the same population cannot be rejected for all CPs, neither for general days. On the contrary, the null-hypotheses are in most cases rejected for the open-valley stations pairs for the two triples. This means the valley and mountain stations receive in all cases similar precipitation, while only in very rare cases the valley stations behave similarly to the open stations. This can be also manifested by the mean precipitation plotted in Fig. 12b,c. The valley station Urbach receives in some cases, e.g. CP10, CP14, CP18, even higher amounts of precipitation than the mountain station Eningen (Fig. 12c). It seems that CP does not have any effect. However, closer investigation of the detailed topography reveals that both Eberbach and Urbach are lying in some shielded corner of a valley, therefore they are isolated from the CP flow in almost all directions. When the orographic precipitation is approaching Urbach, Urbach appears to be at a higher elevation as its surrounding areas which shield the station, prevent the moisture from sinking and thus receive more rainfall than Eningen. The apparent elevation of the valley station is defined here as the orographic surrogate elevation, which is the weighted average of the highest elevation before and after the valley station in the CP direction. The orographic surrogate elevation is changing depending on the direction of the CP.

For T-1, the null hypotheses are rejected for the mountain–valley pair with regard to the precipitation time series of all days. However, for the west moving CPs, e.g. CP10(W) and CP17(W), the null hypothesis cannot be rejected. On the contrary, the two northwest moving CPs (CP14(NW), CP18(NW)) which are parallel to the valley containing the station Zastler, lead to rejection of the null hypothesis. A possible explanation might be that in such cases, the valley provides a pathway for the moisture flow, and the moist air is not as high as on the valley shoulder, therefore less rainfall is generated at the valley station than at the mountain station. The null hypotheses for CP05 and CP09 are rejected probably because of the precipitation gradient caused by the orographic effect of these two CPs. Hofsgrund is high on the ridge of the Black Forest, whereas Zastler is on the slope. For these two CPs, the moisture flow is parallel to the orientation of the Black Forest, both in the northwest, therefore the orographic surrogate elevation of Zastler in these cases is lower than Hofsgrund.

Furthermore, in addition to the valley effects, the wind-drift effects at small-scale also influence the precipitation pattern, i.e. local enhancement of precipitation at the windward side of the valley. As for CP05 and CP09, the precipitation at Eberbach is even slightly higher than the mountain station Waldbrunn.

3.3.2 Statistical analysis of station triples in Bayern

In Bayern, T-4 in the middle-range Rhoen Mountain, in the north and T-5/T-6 in the high-range Alps in the south are taken for statistical investigation (see Fig. 11d,e,f). The mean daily precipitation plotted in Fig. 12d,e,f shows that the precipitation at the valley station is much closer to that at the mountain station and sometimes even higher. The precipitation at the open station is lowest for all three triplets. As it can be seen from Table 5, the null-hypotheses are rejected at the significance level of $\alpha = 0.05$ for all three triplets when general days are studied. However, the test statistics vary for different CPs, which are subjected to the following investigation that considers the interaction of the valley with the CPs.

As for T-4, the valley is southwest oriented. The test statistics show that the null hypothesis is rejected at the significance level of $\alpha = 0.15$ for the mountain–valley station pair (Kreuzberg-Wildflecken) in the case of CP05 which is parallel to the valley, while the null hypothesis cannot be rejected for the valley-open station pair as shown in Table 5, which confirms the above assumption of the interaction between valleys and CPs. The null hypothesis cannot be rejected neither for Wildflecken and Geroda nor for Kreuzberg and Wildflecken in the case of CP20(SW). This may show that even CPs moving in exactly opposite directions (forward and backward) interact with the valley in a different way. For CP14 which is not in the direction of the valley orientation, the valley station is supposed to be similar to the mountain station but different from the open station. Even though both tests failed to reject the null-hypothesis for the the valley-open station pair under CP14 (see Table 5), Fig. 12d shows that the mean precipitation at Kreuzberg and Wildflecken is almost identical, whereas the difference of precipitation amount between Wildflecken and Geroda are very distinct. For CP09, the null hypothesis for the mountain–valley station pair cannot be rejected at the significance level of $\alpha = 0.05$, while for the valley-open station pair it is rejected. Because CP09(W) is not in the orientation of the valley, the valley station behaves more similar to the mountain than to the open station. This can be confirmed by the mean precipitation of the three stations under CP09 shown in Fig. 12d. The precipitation amount at the valley station Wildflecken is closer to the mountain station Kreuzberg than to the open station Geroda. In this case, the precipitation at Wildflecken is even higher than Kreuzberg, probably due to the local WDR effect or observation errors.

The valley station Garmisch from T-5 is located at a bifurcation of three valleys: one west-moving, one northeast-moving and one northwest-moving. As shown in Table 5, the precipitation time series of the valley station Garmisch and the mountain station Kreuzeckhaus are very similar, except for CPs moving in any of the three valley directions, e.g. CP05(NE), CP10(E), CP17(W, NW). For each of these cases, at least one of the test hypothesis is rejected or very close to the selected significance level $\alpha = 0.15$. In contrast, the valley station Garmisch resembles more closely the open station Uffing for these three CPs than for other CPs. Figure 12e shows that, the precipitation amount at the valley station is always between the open station and the mountain station and it converges to the open station when CPs are parallel to the valley orientation and vice versa.

For T-6, the valley station Rhupolding is lying in a gap of the east-west going mountain ridge, and the valley station is open to northeast direction. For the southwest moving CP20, both tests for both pairs cannot reject the null-hypotheses, which means there is an areal even precipitation and the three stations are indifference. For most CPs (CP09, CP11, CP13, CP14, CP17) that are not parallel to the valley orientation, i.e. northeast, the null hypotheses cannot be rejected at the significance level of $\alpha = 0.15$ for the mountain–valley station pairs by either test, whereas they are rejected for the valley-open station pair by one-way ANOVA. This can also be confirmed by the mean precipitation for each CP plotted in Fig. 12f. For CP10 from the east, the valley station seems to be partially open to the moisture flow, therefore it behaves differently from both the mountain and the valley station.

From the statistical analysis of the six mountain–valley-open station triplets, it confirms the assumption that there is an interaction between the valley and the CP. When the valley is shielded from the moisture flow, the precipitation within the valley is comparable to the precipitation on the mountain crest and both are higher than the precipitation on the open area; when the valley is open to the moisture flow, the precipitation within the valley is much less than on the mountain and more closer to the open area. Such effect can only be observed for the secondary narrow and steep valleys, and is referred to as the “narrow-valley effect” in this work. It is worth to mention that topographic modification of precipitation distribution is a complex procedure involving many processes, such as orographic gradient and WDR, etc., the “narrow-valley effect” can be observed only when other effects can be properly excluded.

4 Consequence of neglecting the valley effects

The spatial precipitation patterns caused by the interaction of valley and CP are not accounted for in many hydrological applications, for example, the spatial interpolation of precipitation. Not only in the simple procedures, such as Thiessen Polygon or an inverse distance, but also in the more advanced geostatistical methods of Kriging, such as OK or EDK, such intermediate-scale patterns are neglected. Although EDK has taken the topographic effect into the consideration of the interpolation, the linear relationship can account for the orographic effect at the large scale, but it fails to include the valley effect discussed in this work. Therefore all these techniques produce unavoidable bias in the interpolation results, which are hidden when the overall error for all stations, such as mean squared error, is applied as evaluation criteria for the interpolation results. As an example, cross validation with both OK and EDK has been performed on 47 yr (~ 1960–2007) daily precipitation data. Figure 13 shows the station-wise mean bias of the valley and non-valley stations, respectively, for the data in Baden-Wuerttemberg. Figure 13a shows that the bias of OK which exhibits a systematic trend for both valley and non-valley stations, when the orographic effect is completely neglected. Consideration of the orographic effect by EDK reduces the bias, leading to more normally distributed errors if all stations are counted, but a systematic bias of valley and non-valley stations has been generated artificially. For valley stations, EDK gives a positive mean bias ($Z-\hat{Z}$) of around 0.4 mm, with a mean bias of around −0.10 mm for the non-valley stations, i.e. there is an essential underestimation for the valley stations and a slight overestimation for the non-valley stations.

By adjusting the elevation of the stations to the orographic surrogate elevation during the EDK procedure according to the CP direction, the interaction of valley and the CP will be considered, and consequently the interpolation results should be improved. A cross-validation experiment is carried out for the valley station Zastler. First, the precipitation at the station is interpolated using OK and EDK with actual station elevation as auxiliary information, assuming no observation at Zastler. Then the cross-validation is repeated by adjusting the elevation to the surrogate elevation used in the EDK according to CPs. Figure 14 shows the histogram of the bias for the three different interpolation of 5400 raining days. The underestimation by EDK and overshooting by OK can be observed again by the histogram. Although still some bias can be seen in EDK with surrogate elevation, the bias is more normally distributed than the other two cases. Furthermore, the mean absolute bias EDK with surrogate is 2.00 mm, which is the minimum, and for OK and EDK it is 2.18 mm and 2.410 mm, respectively.

5 Conclusions

The spatial precipitation pattern at the intermediate scale has been investigated in this research. Scatter plots of precipitation to elevation have confirmed the interaction between the secondary narrow and steep valleys and the CPs in complex terrain, which is referred to as the “narrow-valley effect”. Non-parametric KS test and parametric one-way ANOVA test with selected station triplets have further demonstrated the precipitation patterns in mountain ranges of different elevation from low, medium to high. Although some exceptional cases where the test statistics do not show a very clear dependence on CPs due to local complexity of micro topographic configuration and the interference of the large-scale orographic precipitation gradient, a general interaction rule can be concluded, i.e. if the valley is open to the moisture flow, it behaves more similarly to the open station and differently to the mountain station and vice versa.

Such spatial variability of the precipitation is usually neglected by widely applied interpolation techniques, even the more advanced ones, such as OK and EDK. Cross-validation using OK and EDK have demonstrated that completely neglecting topography in OK leads to a systematic drift of errors, whereas consideration of elevation with a overall linear relationship causes overestimation at the mountains and underestimation in the valleys. An experiment with EDK applying the orographic surrogate elevation shows the potential to improve the interpolation results. This work has pointed out a blind spot in the spatial statistics of precipitation and calls for future research to account for the “narrow-valley effect”.

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Table 1. CPs classified by automated fuzzy-rule based algorithm.

	CP	Direction	Type	CP	Direction	Type
BW	CP01	NE	dry	CP10	NW, W	wet
	CP02	E	dry	CP11	SW	dry
	CP03	SE	dry	CP12	SW	dry
	CP04	SE, E	dry	CP13	W	dry
	CP05	SW	wet	CP14	NW	wet
	CP06	W, SW	dry	CP15	SE	dry
	CP07	E, SE	dry	CP16	S	dry
	CP08	S	dry	CP17	W	wet
	CP09	NE, N	wet	CP18	NW	wet
BY	CP01	NW	dry	CP12	NW	dry
	CP02	S, SE	dry	CP13	N	wet
	CP03	S, SW	dry	CP14	W	wet
	CP04	W	dry	CP15	S, SW	dry
	CP05	NE	wet	CP16	S, SE	dry
	CP06	W	dry	CP17	W, NW	wet
	CP07	E, SE	dry	CP18	S, SE	dry
	CP08	SE	dry	CP19	SE	dry
	CP09	W	wet	CP20	SW	wet
	CP10	E	wet	CP21	NE	dry
	CP11	NW	wet			

Table 2. Parameters used for valley detection.

	BW	BY
L [m]	3200	3000
l [m]	1000	800
Δh_1 [m]	180	180
Δh_2 [m]	150	150
Δh_3 [m]	150	150
n [–]	30	30

Table 3. Selected station triples for statistical analysis.

	Mountain station		Valley station		Open station	
	Name (No.)	Elev. (m)	Name	Elev. (m)	Name	Elev. (m)
T-1	Hofsgrund (EY)	1023	Zastler (EV)	625	Titisee (GZ)	863
T-2	Waldbrunn (KF)	490	Eberbach(DU)	178	Spechbach (KI)	185
T-3	Eningen (CW)	705	Urach (IL)	435	Reutlingen (FT)	360
T-4	Kreuzberg (Y20)	855	Wildflecken (Y21)	507	Geroda (X43)	550
T-5	Kreuzeckhaus (A08)	1652	Garmisch (A15)	719	Uffing (C32)	730
T-6	Rauschberg (C45)	1640	Ruhpolding (C44)	692	Neukirchen (D47)	712

Table 4. Statistical test results of station groups in Baden-Wuerttemberg.

CP	KS-*p*	ANOVA-*p*	KS-*p*	ANOVA-*p*
	valley vs. mountain		valley vs. open	
	Zastler vs. Hofsgrund		Zastler vs. Titisee	
CP05	(0.01)	0.03	(0.00)	(0.00)
CP09	(0.00)	(0.00)	(0.00)	(0.00)
CP10	0.98	0.91	(0.00)	(0.00)
CP14	0.15	0.10	(0.00)	(0.00)
CP17	0.58	0.21	(0.00)	(0.00)
CP18	0.11	0.42	(0.00)	(0.00)
general	0.00	0.00	(0.00)	(0.00)
	Eberbach vs. Waldbrunn		Eberbach vs. Spechbach	
CP05	0.96	0.89	(0.03)	(0.01)
CP09	0.81	0.81	0.27	0.99
CP10	0.57	0.76	(0.00)	(0.00)
CP14	0.97	0.95	0.10	0.15
CP17	0.97	0.66	0.20	0.15
CP18	0.87	0.96	(0.00)	(0.00)
general	0.24	0.95	(0.00)	(0.00)
	Eningen vs. Urbach		Reutlingen vs. Urbach	
CP05	1.00	0.87	0.24	0.21
CP09	0.83	0.81	(0.00)	(0.00)
CP10	0.65	0.44	(0.00)	(0.00)
CP14	0.99	0.54	0.06	(0.01)
CP17	0.94	0.87	0.91	0.24
CP18	0.35	0.55	(0.00)	(0.00)
general	0.16	0.88	(0.00)	(0.00)

Table 5. Statistical test results of station groups in Bayern.

CP	KS-p	ANOVA-p	KS-p	ANOVA-p
	valley vs. mountain		valley vs. open	
	Kreuzberg vs. Wildflecken		Gerode vs. Wildflecken	
CP05	0.05	0.05	0.17	0.29
CP09	0.12	0.12	(0.02)	0.06
CP10	0.76	0.76	0.15	0.18
CP11	0.58	0.58	(0.03)	0.05
CP13	0.99	0.99	0.05	0.25
CP14	0.99	0.99	0.18	0.31
CP17	0.92	0.92	0.15	0.54
CP20	0.85	0.85	0.44	0.42
general	0.00	0.00	(0.00)	(0.00)
	Kreuzeckhaus vs. Garmisch		Garmisch vs. Uffing	
CP05	(0.00)	0.06	(0.00)	(0.01)
CP09	0.11	0.17	0.05	(0.02)
CP10	0.10	0.07	(0.03)	0.09
CP11	0.06	0.24	(0.01)	0.00
CP13	0.27	0.97	(0.01)	(0.01)
CP14	0.48	0.19	0.18	0.21
CP17	0.10	(0.03)	0.27	0.64
CP20	0.29	0.18	0.80	0.42
general	(0.00)	(0.00)	(0.00)	(0.00)
	Rauschberg vs. Ruhpolding		Ruhpolding vs. Neukirchen	
CP05	(0.00)	(0.01)	(0.00)	(0.00)
CP09	0.08	0.60	0.51	0.07
CP10	0.11	0.13	0.35	0.07
CP11	0.39	0.93	0.20	0.03
CP13	0.15	0.44	0.41	0.07
CP14	0.99	0.67	0.35	0.07
CP17	0.39	0.36	0.24	0.08
CP20	0.90	0.68	0.94	0.70
ALL	(0.00)	(0.00)	(0.00)	(0.00)

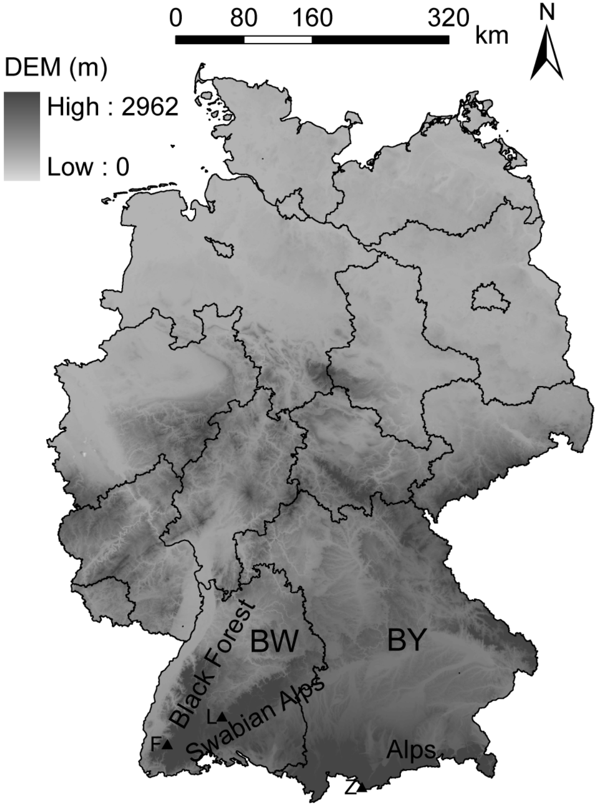
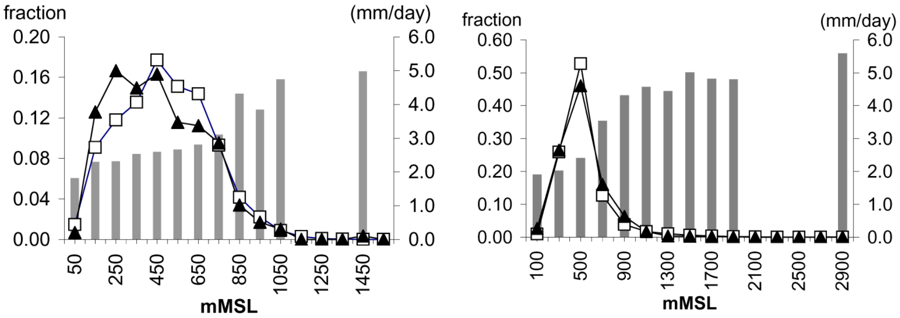


Fig. 1. Study areas (F, L and Z are the local peeks Feldberg, Lemberg and Zugspitze in the study areas, respectively.)



(a) BW (b) BY

Fig. 2. Hypsometric distribution (dark triangle, left ordinate), altitudinal distribution of rain gauges (light square, left ordinate) and mean precipitation (gray bars, right ordinate) for each elevation band in BW and BY. The hypsometric distribution was determined from a topographic data set with a resolution of 100 m.

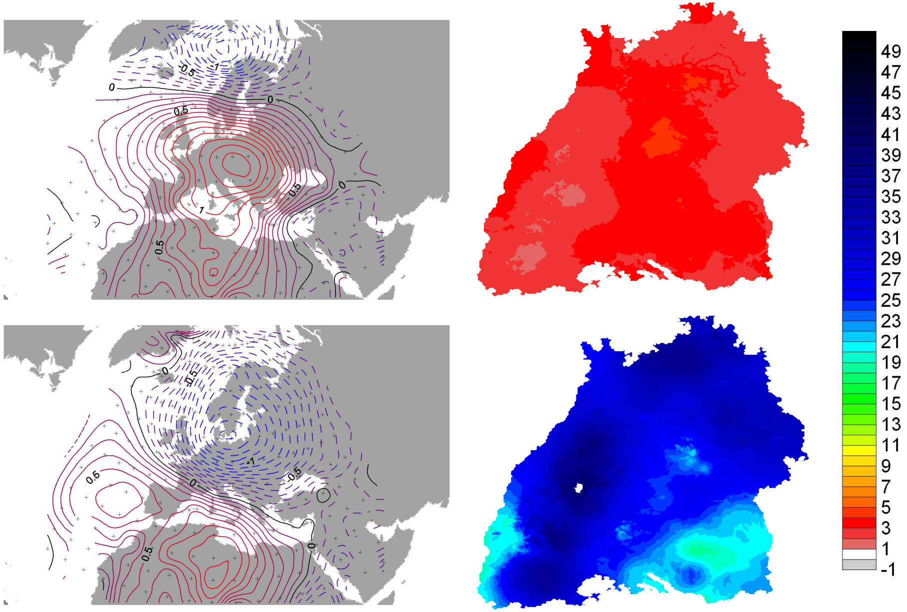


Fig. 3. Geopotential anomalies (left) and wetness index (right) of CP04 (upper) and CP10 (lower) for BW as examples.

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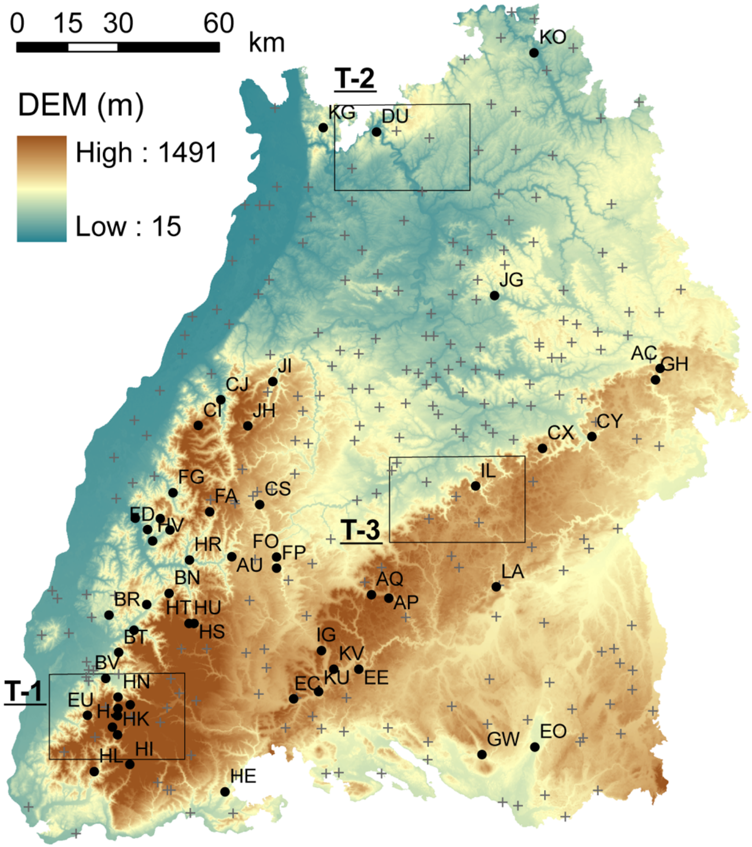

Fig. 4. Valley (solid circle) with station numbers and non-valley (cross) stations in BW.

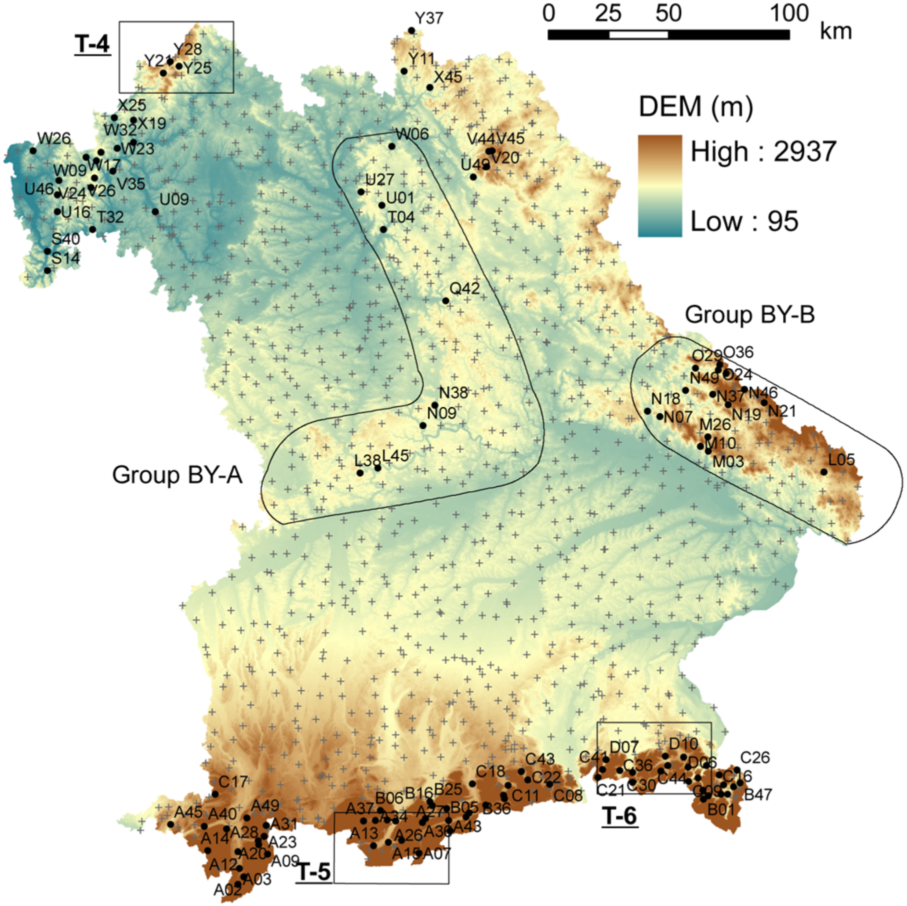

Fig. 5. Valley (solid circle) with station numbers and non-valley (cross) stations in BY.

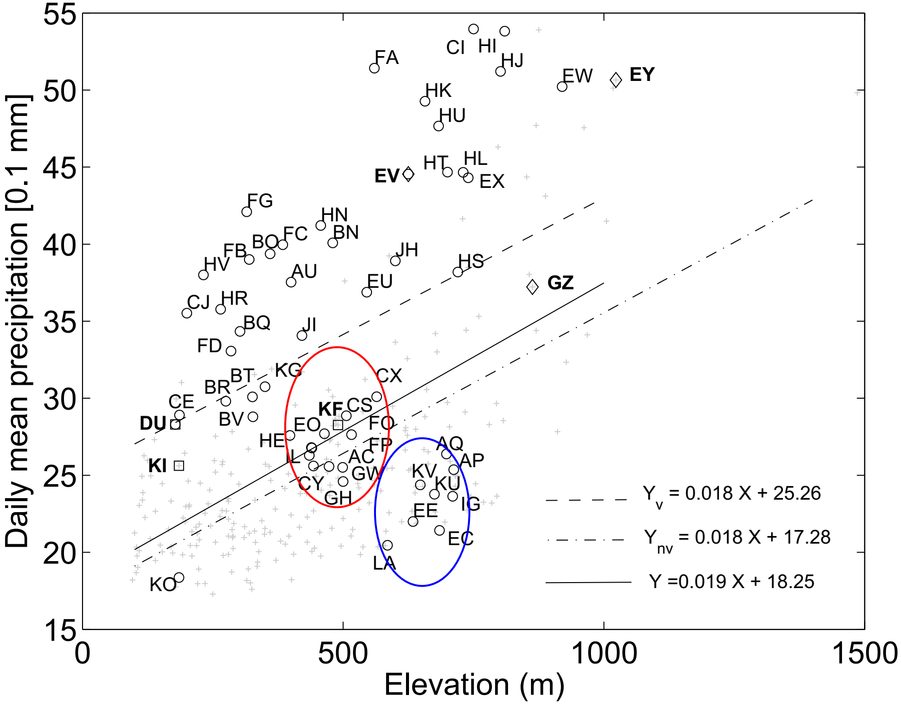

Fig. 6. Scatter plot of mean daily precipitation vs. elevation for BW.

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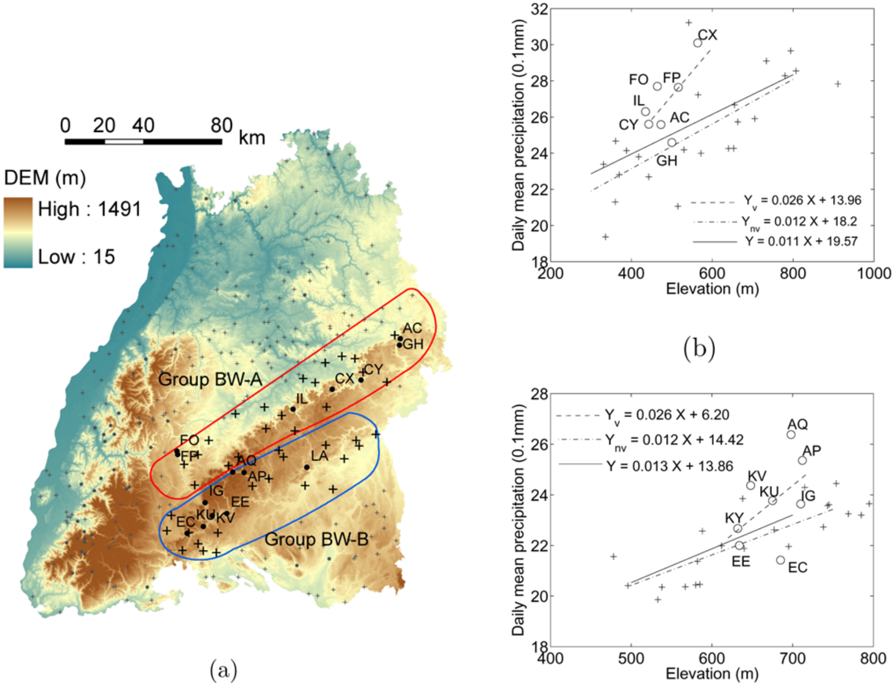


(a)

(b)

(c)

Fig. 7. Location of outlies and local scatter plots.

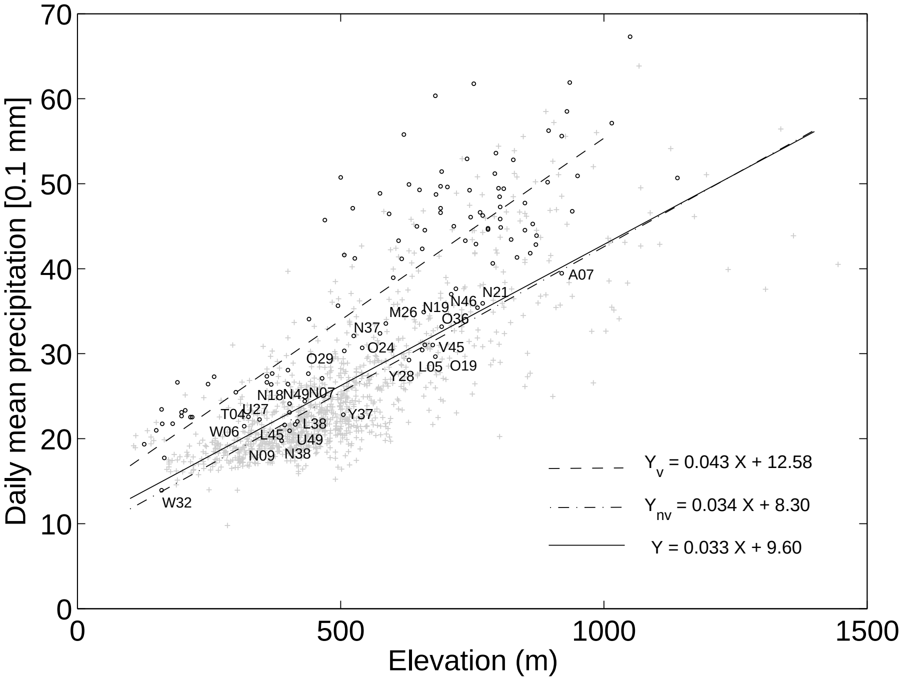


Fig. 8. Scatter plot of mean daily precipitation vs. elevation for BY.

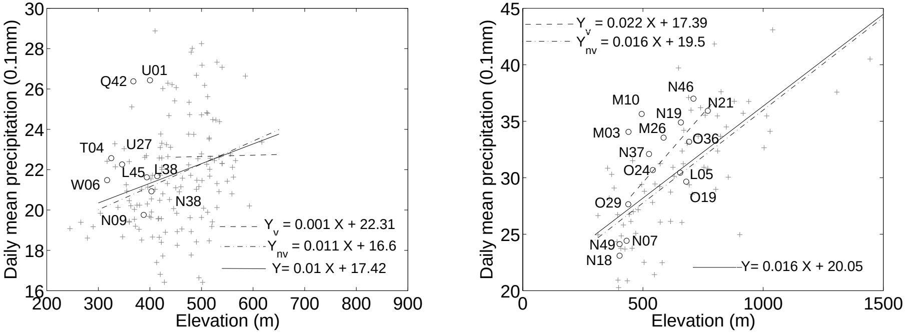
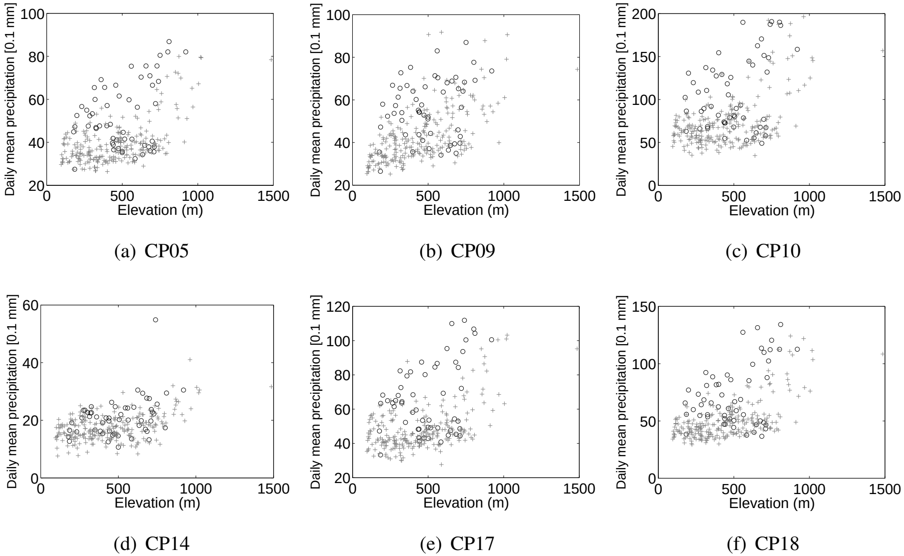


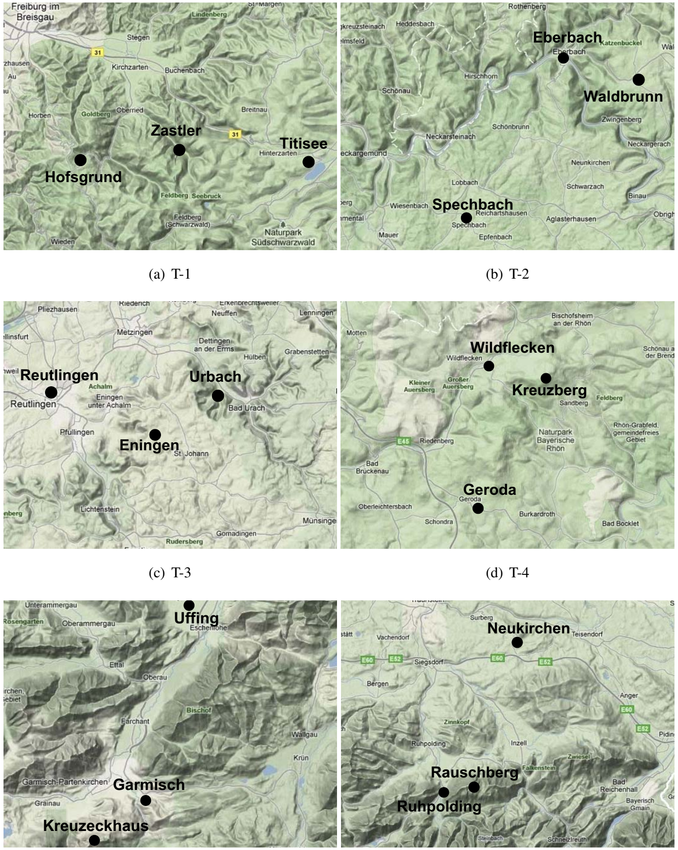
Fig. 9. Location of outliers and local scatter plot.



(a) CP05 (b) CP09 (c) CP10

(d) CP14 (e) CP17 (f) CP18

Fig. 10. Scatter plot of mean daily precipitation of wet CPs for BW.

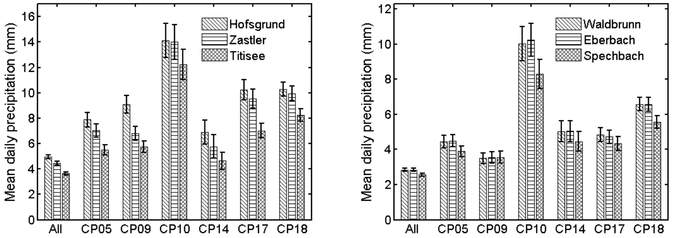


(a) T-1 (b) T-2

(c) T-3 (d) T-4

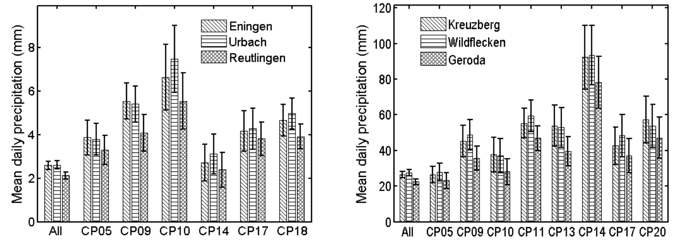
(e) T-5 (f) T-6

Fig. 11. Detailed topography of the selected the station groups.



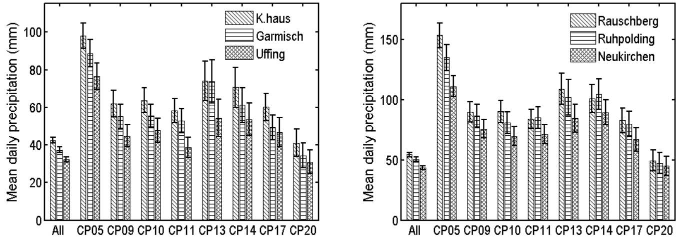
(a) T1

(b) T2



(c) T3

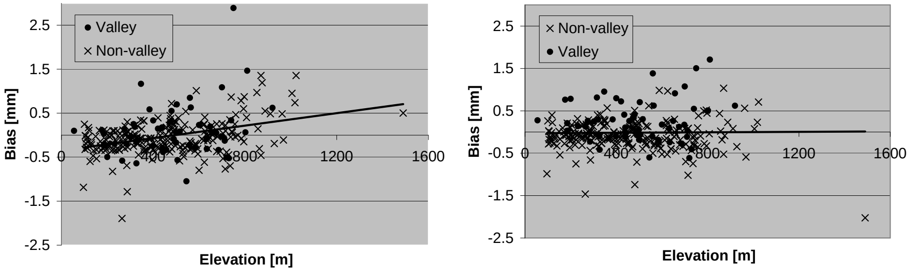
(d) T4



(e) T5

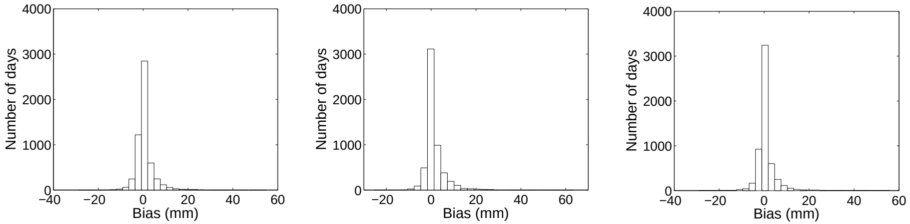
(f) T6

Fig. 12. Mean precipitation of each wet CP for the selected station groups.



(a) OK (b) EDK

Fig. 13. Bias of valley and non-valley stations for cross-validation of OK and EDK for Baden-Wuerttemberg over ~ 1960–2007.



(a) OK (b) EDK (c) EDK with surrogate

Fig. 14. Histogram of bias for different interpolation procedures at the station Zastler.