Meteorol. Z. (Contrib. Atm. Sci.), Vol. 30, No. 3, 285–293 (published online February 5, 2021)

Short Note

Analysis of decadal precipitation changes at the northern edge of the Alps

Stefan Emeis*

Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology, Garmisch-Partenkirchen, Germany

(Manuscript received August 11, 2020; in revised form December 14, 2020; accepted December 15, 2020)

Abstract

Precipitation data from four weather stations in Bavaria, Germany, situated at the northern edge of the Alps have been evaluated for the period 1901 to 2019. Decadal changes have been computed as sliding 30-year averages and as the difference between the 30-year periods 1990–2019 and 1901–1930. The annual precipitation at these four stations increases, fitting in magnitude roughly to the temperature increase in the course of global warming. The number of dry days slightly increases as well as a consequence of a northward shift of the storm tracks over Europe. Due to these two features the precipitation intensity on wet days increases. The increase in maximum daily precipitation amounts is less than the increase in the annual precipitation amount. The observed maximum daily precipitation in the full four datasets is 138.5 mm at the station Hohenpeißenberg in 1999. The length of dry spells is increasing at three of the four stations as well. The overall observed precipitation patterns fit to the findings of regional climate model simulations for future climate scenarios for this region. Thus, they can be interpreted as signs that climate change is well underway in Southern Bavaria as it is in most places of the world.

Keywords: precipitation, statistics, flash floods, data analysis3mm

1 Introduction

Climate Change is more than rising temperatures. A very important climatic parameter is precipitation as part of the hydrological cycle. Thermodynamics (i.e., the Clausius-Clapeyron equation) indicate that there should be a positive correlation between the amount of precipitation and air temperature, because the saturation water vapour pressure is a clear function of temperature (see, e.g., Lenderink and van Meijgaard, 2008; Tomassini and Jacob, 2009). Thus, under the assumption of otherwise unchanged weather and circulation patterns, precipitation should increase by about 7 % for each one-degree centigrade increase in tropospheric temperature. This estimation is based on the additional assumption that relative humidity is not changed by the temperature increase (Bony et al. 2006). This is supposed to be true for hourly, local precipitation events which depend on the local water vapour content of the air (Bronstert et al., 2017). Large-scale and longer precipitation intensity should be more dependent on the latent heat flux (Bronstert et al., 2017). According to Allen and Ingram (2002) this leads to a global increase in precipitation of about 3 % per degree centigrade temperature increase.

Nonlinear processes in the atmosphere and in surface-atmosphere interactions as well as weather and circulation pattern changes will modify this simple assessment on increasing precipitation in a warming climate. Tomassini and Jacob (2009), e.g., state in their Introduction that the upper quantiles in precipitation will increase more pronouncedly than the mean precipitation. In addition, Schaller et al. (2020) documented from an overview on existing regional and global studies that the trends of mean and extreme precipitations vary considerably over Europe. Scherrer et al. (2016) show a similar variability of trends for 32 regions of Switzerland and the dependence of precipitation amounts on large-scale circulation patterns. This indicates that more in-depth and local-scale analyses are required for local assessments of the hydrological cycle. The general term 'precipitation amount' comprises features such as precipitation intensity, precipitation duration, dry spells, wet spells, and extreme events.

This paper is designed as a short contribution which analyses changes in the precipitation amount and characteristics in Upper Bavaria, Germany, in a narrow belt just north of the Alps from Kempten in the West to Reit im Winkl in the East (see Table 1 for location details), an area which – as many others – is expected to see a rise in precipitation in climate scenario simulations (see e.g., Giorgi et al., 2004). The study will analyse sliding 30-year averages and compare the 30-year period 1901 to 1930 to the available most recent 30-year period 1990 to 2019. Background for this analysis is a research project on adaptation to extreme precipitation events in this pre-alpine region. This region has been identified as a region where extreme precipitation has become more frequent throughout the year (Trömel and

*Corresponding author: Stefan Emeis, Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology, Kreuzeckbahnstraße 19, 82467 Garmisch-Partenkirchen, Germany, e-mail: stefan.emeis@kit.edu

DOI 10.1127/metz/2021/1053
Gebrüder Borntraeger Science Publishers, Stuttgart, www.borntraeger-cramer.com

Table 1: Characteristics of the four stations used in the analysis.

Station	Longitude [°]	Latitude [°]	altitude [m]	annual prec. [mm] 1901–1930 and 1990–2019	max. daily prec. [mm] and year of occurrence	remarks
Kempten	10.334797	47.723259	705	1151 1231	86.1 1978	
Hohenpeißenberg	11.010819	47.800869	977	1091 1183	138.5 1999	
Benediktbeuren	11.413941	47.706327	630	1394 1510	124.3 1999	station relocation Jul 1, 1980, 12 m higher up
Reit im Winkl	12.469775	47,675415	686	1629 1693	135.3 1977	several smaller station relocations, missing data from Nov 1, 2003 to Feb 28, 2007

Schönwiese, 2007). The aim of this study is to assess to which degree the precipitation intensity on wet days and extreme values of daily precipitation have already changed over the last 90 years.

Heavy precipitation can occur due to two completely different weather situations in Upper Bavaria: (1) blockage of northerly flows of humid air masses at the northern edge of the Alps (Nissen et al., 2013), and (2) deep convection, partly triggered by the mountainous terrain of the Alps (Peristeri et al., 2000). The first weather situation is often coupled to the occurrence of so-called Vb-cyclones (also known as Genoa lows) which intake enormous amounts of humidity when moving over the Mediterranean and which then frequently become stationary over Poland or the Czech Republic. For two or three days in sequence heavy continuous rain can downpour more than 100 litres per square metre at the northern flank of the Alps which often leads to flooding along pre-alpine rivers heading northbound towards the Danube river and a few days later in the river Danube itself. The second weather situation is linked to very warm and humid air masses which are advected from the Southwest of Europe to Southern Germany and which have become more or less stationary there, often under weak anticyclonic influence. Daytime sunshine heats the ground and delivers the energy to initiate deep convection which leads to heavy, often slow-moving thunderstorms. These thunderstorms frequently hit small parts of the area only, but may lead to up to 100 litres of rain per square metre within a few hours causing local flooding.

The first weather situation leads to large-scale rain which is usually well documented by the existing climate stations while the second weather type is a challenge for every measurement network. Typical areas covered by one thunderstorm in Germany are in the order of 400 km^2 (Zöbisch et al., 2020). This means that the diameter of such thunderstorms slightly exceeds 20 km. The area of extreme downpour often covers only small parts of the thunderstorm area. Therefore, existing measurement networks frequently fail to record extreme convective precipitation amounts. Radar coverage can help to close this gap (Lengfeld et al., 2019) but gauging radar reflectivity data in terms of precipitation rates is not simple either. In the case of several convection cells, cells closer to the radar can cast shadows which obstruct the detection of cells further away. In addition, some valleys in mountainous terrain cannot be reached by the radar network. In order to reduce the deficiencies connected with the incomplete coverage of convective precipitation, only 30-year means are considered in the following data analysis of precipitation data from four stations close to the northern fringe of the Alps in Southern Germany. New techniques such as microwave attenuation could help to circumvent the deficiencies of classical radar networks (Chwala and Kunstmann, 2019) but are outside of the scope of this paper.

2 Data and evaluation methods

This short study is based on daily precipitation sums. Publically available data of the German Meteorological Service (Deutscher Wetterdienst, DWD) is used[1]. Only four stations with sufficiently long data records have been identified in the area of interest which is the pre-alpine belt in the regions of Swabia and Upper Bavaria in the federal state of Bavaria, Germany. These four stations are Kempten, Hohenpeißenberg, Benediktbeuren, and Reit im Winkl. Station details together with the annual precipitation for the periods 1901 to 1930 and 1990 to 2019 and the maximum daily precipitation observed during the whole period can be found in Table 1. Kempten (in a wider valley) and Hohenpeißenberg (on top of an isolated hill) are about 20 to 30 km north of the Alpine foothills whereas Benediktbeuren lies directly at the foothills and Reit im Winkl even behind the first chain of foothills in a valley. The foreland station in a

[1] https://cdc.dwd.de/portal/201912031600/mapview, read on March 30, 2020

valley and the two foothill stations have similar altitudes above sea level (Table 1). Thus, the difference in the annual precipitation of about 25 % between the first two stations (called foreland stations in the following) and the latter two stations (called foothill stations in the following) reflects the station distance from the foothills.

A station relocation in Benediktbeuren in 1980 left some impact on the mean daily precipitation intensity on wet days. The values for the full year were roughly 5 to 10 percent lower than before that measure. This impact is not visible from the data for the months May to October. Thus, it may be concluded that the station relocation mainly influenced non-convective precipitation recordings which most frequently occur in the winter months. Summer-time convective precipitation recording was – if at all – influenced in a not easily detectable way. The impact of the relocation is also not discernible from the sliding 30-year averages.

The following parameters have been computed for each year of the period 1901 to 2019 from the full data set of daily precipitation sums. They are a subset of the indices listed in Zhang et al. (2011). The threshold between dry and wet days (1 mm) in the subsequent evaluation has been chosen in accordance with the setting and arguments given in Frei and Schär (1998). The respective index name used in Zhang et al. (2011) is given in brackets:

a) annual precipitation in mm for each year
b) mean daily precipitation intensity for wet days (24-hour precipitation sum (RR) > 1 mm) in mm/day for each year, computed from the annual precipitation and the number of wet days (SDII)
c) maximum daily precipitation in mm (yearly RX1day, Zhang et al. (2011) only lists a monthly RX1day) for each year
d1) numbers of days per year with RR more than 1 mm, 10 mm, 20 mm, 25 mm, 30 mm and more than 40 mm (R01 to R40, only R10 and R20 are listed in Zhang et al. (2011)) for each year. The number of days with RR more than 1 mm is called number of wet days in the following
d2) numbers of days with RR between 1 mm and 10 mm, 10 mm and 20 mm, 20 mm and 30 mm, and 30 mm and 40 mm for each year. This data has been computed from the data listed in d1) and e).
e) numbers of dry days per year (RR < 1 mm) (R00, not listed in Zhang et al., 2011)
f) longest period of consecutive dry days per year in days (longest dry spell) (CDD)

Convective precipitation is most likely to dominate in the months of May to October. Therefore, this part of the year has been evaluated separately for the period 1901 to 2019:

g) mean daily precipitation intensity for wet days (RR > 1 mm) for the period May to October in mm/day
h) maximum daily precipitation in mm for the period May to October in mm
i) numbers of dry days (RR < 1 mm) for the period May to October
j) longest period of consecutive dry days for the period May to October in days (longest dry spell).

The change in precipitation characteristics over the last 90 years has then been estimated from the above mentioned data in two ways: (1) by plotting sliding 30-year averages and (2) by comparison of the first and the last time slices, namely the two 30-year averages from 1901 to 1930 and 1990 to 2019.

Statistical significance of the observed changes has been estimated in two ways as well. (1) for each single 30-year time slice, the mean, the standard deviation, and the two extreme values have been computed in order to show the internal variation within each 30-year time slice. (2) the standard deviation for the time series of the 30-year sliding averages has been computed in order to show the variation of the data over all evaluated 89 time slices. This latter standard deviation, σ, is used to assess the significance of the found difference, D, between the first and the last time slice. Assuming a normal distribution, a trend noise ratio $D/\sigma = 1$ indicates a 69 % significance that the difference is larger than the scatter of the data (Hennemuth et al., 2013). A trend noise ratio of 1.96 indicates a significance of 95 %.

Years with missing data in the records of the station "Reit im Winkl" in the period January 2004 to February 2007 have been discarded. I.e., the "30-year average" for Reit im Winkl for the period 1990 to 2019 only contains about 27 years.

3 Results

Annual precipitation amounts (Table 1) increase by about 7 to 8 % at three of the four stations. The increase at Reit im Winkl, which is the station with the highest annual precipitation amount, is only about 4 %.

Figs. 1 and 2 show sliding 30-year averages for the maximum daily precipitation, the mean daily precipitation intensity on wet days, the number of days per year with RR > 25 mm, the number of dry days, and the duration of the longest draught (parameters c), b), d1), e), and f) defined in Section 2) for the two stations Hohenpeißenberg and Benediktbeuren plotted versus the end year of the averaging period. For parameter d1) the number of days with a total precipitation sum of larger than 25 mm is plotted. Maximum daily precipitation, mean daily precipitation intensity, the number of days with RR > 25 mm and the duration of the longest draught for Hohenpeißenberg are increasing over the evaluated period while the number of dry days stays fairly con-

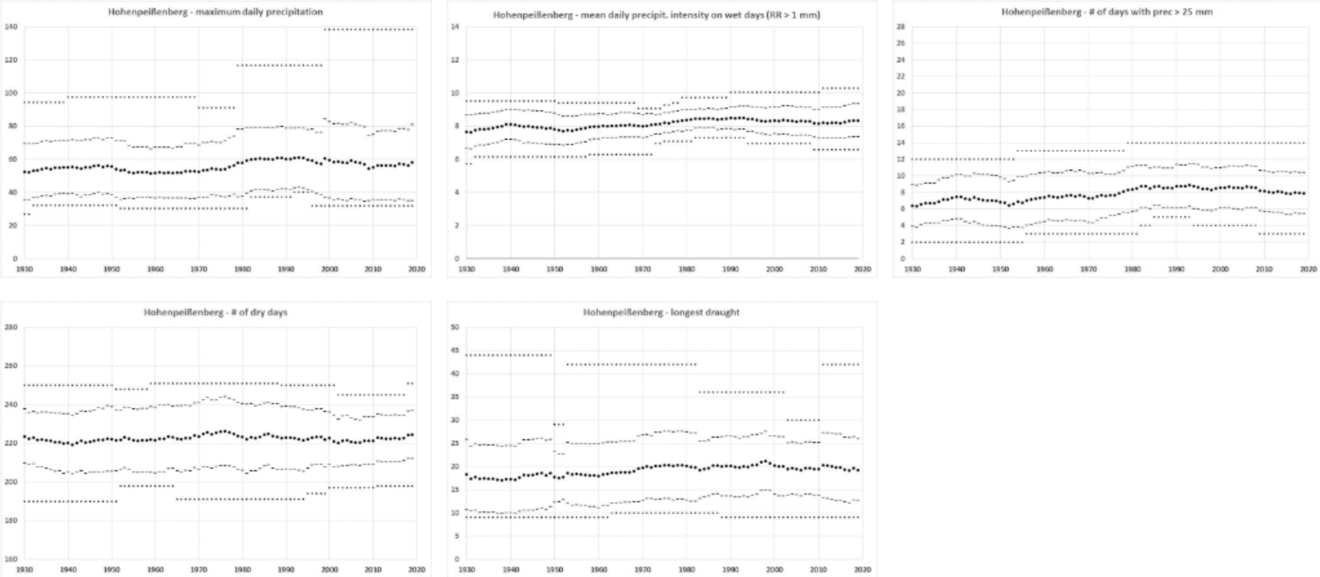

Figure 1: Precipitation data at Hohenpeißenberg, Germany. Sliding 30-year averages of annual values plotted versus the end year of the averaging period. Upper row: Left: maximum daily precipitation per year in mm, middle: mean daily precipitation intensity on wet days (RR > 1.0 mm) in mm/d, right: number of days per year with more than 25 mm of precipitation. Lower row: Left: number of dry days (RR < 1.0 mm) per year, right: length of longest draught in days per year. Bold symbols: 30-year mean value, little bars: +/- one standard deviation within the 30-year period, small bullets: extreme values of the 30-year average.

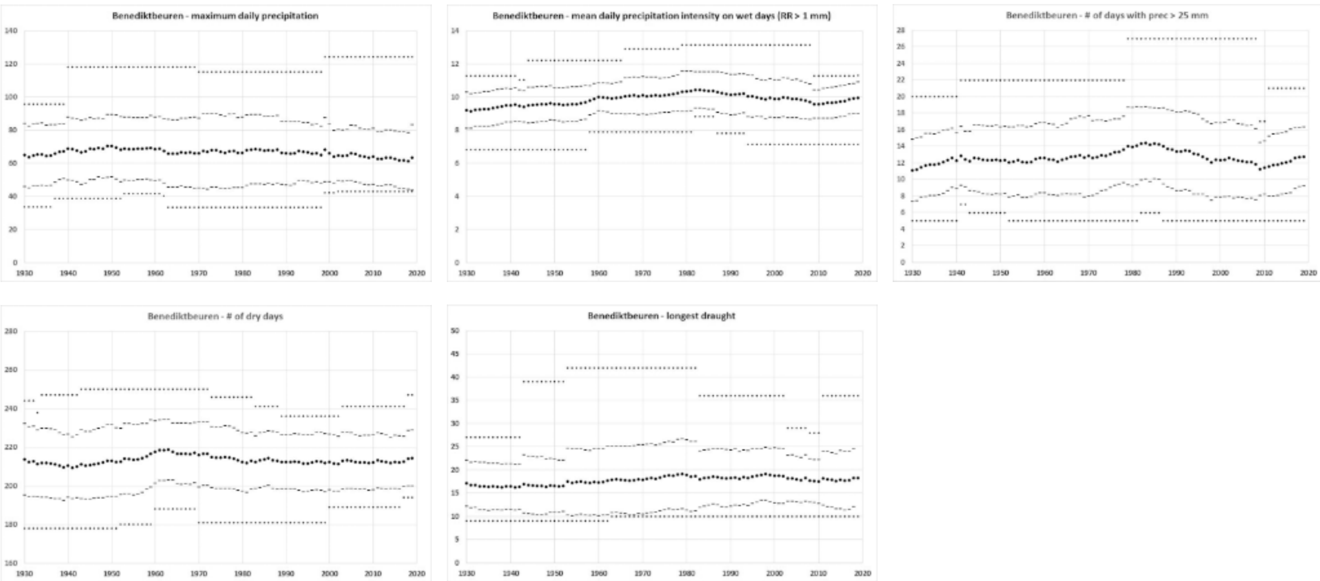

Figure 2: As Fig. 1, but for Benediktbeuren, Germany.

stant. For Benediktbeuren the mean daily precipitation intensity, the number of days with RR > 25 mm, and the duration of the longest draught are increasing while the maximum daily precipitation sum and the number of dry days is more or less at the same level at the beginning and the end of the evaluation period. For some of the plotted parameters the main increase happens between 1960 and 1990 with a maximum increase around 1980. While the curves for mean daily precipitation intensity on wet days and the number of days with RR > 25 mm at Benediktbeuren also increase for the last ten years, such a feature is not visible at Hohenpeißenberg.

Figs. 1 and 2 are also plotted in order to show the internal variability of the data within each single 30-year average. Therefore, 30-year mean values (bold symbols), plus and minus one standard deviation bounds (little bars) and extreme annual means (small bullets) are plotted in Figs. 1 and 2. The width of the plus/minus one-standard-deviation belt and – to a lesser extend – the mean values are still quite sensitive to changes of the extreme value within the respective 30-year averaging period. This can be seen from jumps in the curves for plus and minus one standard deviation and the mean value which are parallel to jumps in the extreme values.

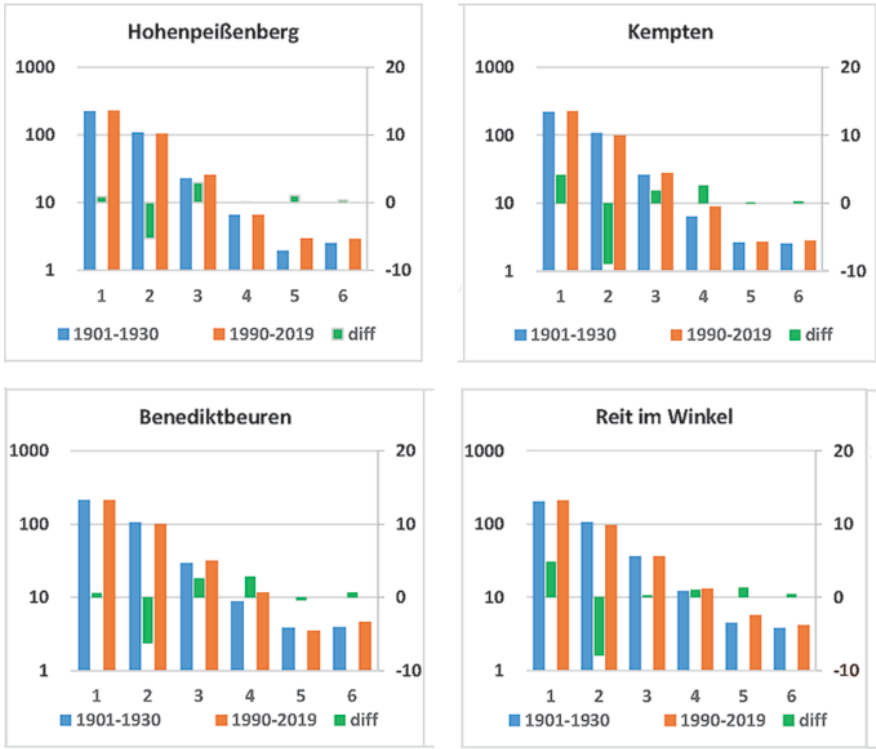

Figure 3: Comparison of two 30-year averages of number of days (logarithmic scale on the left y-axis) with precipitation amounts (RR) in six classes on the x-axis: 1) dry days (RR < 1 mm), 2) 1 mm < RR < 10 mm, 3) 10 mm < RR < 20 mm, 4) 20 mm < RR < 30 mm, 5) 30 mm < RR < 40 mm, 6) RR > 40 mm. Blue columns are for the period 1901–1930, brown columns are for 1990–2019. Green columns show the differences between the blue and brown columns (linear scale on the right).

The difference between the first 30-year slice and the last 30-year slice plotted in Figs. 1 and 2 is shown in some more detail for all four investigated stations in Table 2. This Table is split in wet day data (greenish shading) and dry day data (reddish shading). For the first parameter in this Table, the daily mean precipitation intensity, and for the last two parameters, the number of dry days and the length of the longest dry period, the evaluations are shown separately for the whole year and for the convective weather period from May to October. For the maximum daily precipitation this separation is not shown, since this maximum always occurred in the period May to October. For those parameters also plotted in Figs. 1 and 2, the numbers correspond to the leftmost and rightmost mean values depicted in Figs. 1 and 2.

Nearly all parameters at all four stations – with only two exceptions, the dry day data for Kempten and the maximum daily precipitation at the station Benediktbeuren – show an increase in the comparison of the first and last 30-year time slice of the last 90 years. The results are fairly consistent among all four stations. The largest scatter among the four stations can be observed in the maximum number of consecutive dry days which are listed in the last two lines of Table 2. The statistical significance of the difference between the data from the two time slices is given by the column just right to the column which displays the percentage change. Here the above defined ratio D/σ is listed. A ratio which exceeds 1.96 indicates a 95 % significance. These entries have been printed in bold face in Table 2. While many of the differences in the wet day data are significant at the 95 % level for three out of the four stations, only the increase in the number of dry days in the period May to October is significant at this high level for all four stations. Most of the other differences of the dry day data do not reach this significance level at all.

Fig. 3 reinterprets the data given in lines 4 to 9 of Table 2 referring to a logarithmic scale (left y-axis). The figure gives the numbers of days with precipitation amount in six different classes of precipitation amount at the four stations, again by comparing the values for the two 30-year periods 1901–1930 and 1990–2019. The six classes (see d2) and e) in the list of evaluated parameters in Section 2) are (1) dry days (less than 1 mm), (2) days with precipitation between 1 and 10 mm, (3) days between 10 and 20 mm, (4) days between 20 and 30 mm, (5) days between 30 and 40 mm, and finally (6) days with more than 40 mm of precipitation. The data has been computed by taking differences between respective Rnn values listed as parameter d1) in Section 2 above. The difference between the two 30-year periods is plotted in between the two columns in green referring to the right, linear y-axis.

It is elucidating to see not only the number of days with a rain amount above a given threshold (as is done in Table 2) but also to have some information of the num-

Table 2: Comparison of selected precipitation parameters from the four stations listed in Table 1. Averages for 1901–1930 and for 1990–2019 are given together with the change in percent. D/σ denotes the trend noise ratio computed from the absolute change between 1901–1930 and 1990–2019 and the standard deviation of the full time series of 30-year averaged data. Green shading indicates wet day data, reddish shading dry day data. Bold face indicates significance above 95 %, red indicates decreasing values.

precipit. param.	**Hohenpeißenberg**				**Kempten**				**Benediktbeuren**				**Reit im Winkl**			
	1901–1930	1990–2019	Change [%]	D/σ	1901–1930	1990–2019	Change [%]	D/σ	1901–1930	1990–2019	Change [%]	D/σ	1901–1930	1990–2019	Change [%]	D/σ
daily mean prec. intensity on wet days (full year) in mm/d	**7.7**	**8.4**	**+ 9.1**	**2.94**	**7.9**	**8.7**	**+ 10.2**	**2.38**	**9.2**	**10.0**	**+ 8.3**	**2.35**	10.1	10.7	+ 6.2	1.62
daily mean prec. intensity on wet days (May–Oct.) in mm/d	**10.0**	**10.8**	**+ 8.0**	**3.53**	**9.3**	**10.3**	**+ 11.2**	**2.46**	**11.8**	**12.5**	**+ 5.9**	**2.36**	11.5	12.1	+ 4.6	1.34
max. daily prec. (full year) in mm	52.4	58.0	+ 10.7	1.91	47.5	51.7	+ 8.7	1.23	64.9	63.5	- 2.2	0.71	60.8	68.2	+ 12.1	1.76
# days > 10 mm (full year)	**33.53**	**37.90**	**+ 13.0**	**3.11**	**37.47**	**42.20**	**+ 12.6**	**2.03**	**46.00**	**51.63**	**+ 12.2**	**3.04**	56.30	59.13	+ 5.3	1.27
# days > 20 mm (full year)	**11.00**	**12.40**	**+ 12.7**	**2.21**	**11.47**	**14.40**	**+ 25.6**	**2.39**	**16.60**	**19.67**	**+ 18.5**	**3.48**	20.33	23.04	+ 13.3	1.74
# days > 25 mm (full year)	**6.40**	**7.90**	**+ 23.4**	**2.11**	7.23	8.60	+ 18.9	1.81	**11.10**	**12.77**	**+ 15.0**	**2.22**	**12.47**	**15.41**	**+ 23.6**	**2.46**
# days > 30 mm (full year)	**4.47**	**5.83**	**+ 30.4**	**2.54**	5.17	5.50	+ 6.4	0.58	7.77	8.03	+ 3.3	0.54	**8.20**	**9.89**	**+ 20.6**	**2.09**
# days > 40 mm (full year)	2.53	2.87	+ 13.4	1.51	2.53	2.80	+ 10.5	1.35	**3.90**	**4.57**	**+ 17.2**	**2.86**	3.77	4.19	+ 11.1	0.81
# dry days (full year)	223.5	224.4	+ 0.4	0.54	219.6	223.8	+ 1.9	1.77	213.7	214.3	+ 0.3	0.31	**204.0**	**208.9**	**+ 2.4**	**2.42**
# dry days (May to Oct.)	**86.1**	**87.1**	**+ 1.2**	**2.23**	**86.3**	**89.7**	**+ 3.9**	**3.33**	**79.2**	**82.2**	**+ 3.8**	**2.34**	**77.3**	**81.8**	**+ 5.7**	**2.70**
maximum # consecutive dry days (full year)	18.2	19.3	+ 6.0	0.97	20.8	20.8	- 0.3	0.09	17.1	18.2	+ 6.4	1.33	18.3	18.8	+ 2.5	0.29
maximum # consecutive dry days (May–Oct.)	10.4	11.6	+ 11.5	1.58	12.0	11.2	- 6.7	1.68	**9.4**	**10.8**	**+ 14.9**	**2.21**	9.9	11.2	+13.1	0.36

*) no discernable difference between full year data and May to October data

ber of days with a precipitation amount within a certain range. For all four stations, the number of dry days is increasing and the number of days with precipitation amounts between 1 and 10 mm is decreasing. While the first information could also be taken from Table 2 the latter information was not obvious from Table 2. Additionally, we see a slight increase in the frequency of all classes with a precipitation amount of more than 10 mm (classes (3) to (6)) for all four stations with one small exception for the class 30 mm to 40 mm at Benediktbeuren. Although the increases and decreases are rather small, it is their consistency over all four stations which make them interpretable. Furthermore, about half of the values which entered into the computation of the data plotted in Fig. 3 were significant at the 95 % level and a few more data were close to this significance level (see Table 2).

4 Discussion

The overall finding from Table 2 is that all given precipitation parameters (with the exception of maximum daily precipitation at Benediktbeuren) as well as the number of dry days are increasing in the region represented by these four weather stations. This is only possible, if precipitation intensity on wet days is increasing. The following analysis tries to give more details on this overall change in precipitation characteristics, in order to try to find indications for the cause of the observed change. Although the stations are relatively close together, the evaluations show considerable scatter which hampers the identification of causes.

The increase in the mean daily precipitation intensity on wet days (parameter b) defined in Section 2) is in the range of 5 % to 11 % at all four stations. This increase seems to confirm the margin cited in the beginning of the introduction which can be attributed to the overall temperature increase of a little bit more than 1 °C in this area in the last 90 years (see e.g., Wastl et al., 2012). This increase is larger at the two foreland sites and less at the two foothill sites.

At three of the four stations the relative increase of the daily precipitation intensity on wet days for the whole year is larger than for the months May to October. For the two foothill stations this is also true for the absolute increase. This means that this increase is dominated by wintertime precipitation events which fits to the results given in Kunz et al. (2017).

Table 2 also shows that the number of dry days is increasing, especially in the period between May and October. The increase in the period May to October is larger at the foothill stations. Not only the sheer number of dry days but also the duration of the longest dry episode has been analysed from the data. Looking at the full year we see an increase in the length of the longest dry spell for one foreland station and the two foothill stations. Looking at the convective period May to October we see the same spatial distribution but larger margins. The results for Kempten are a bit different. Here, the duration of dry spells is longer than at the three other stations but a decrease is found in the length of the longest draught during the months May to October. At all four stations the longest dry spell occurs in the non-convective season (November to April).

Figs. 1 and 2 modify the simple explanation of increases and decreases deduced from the comparison of just two time slices given above. The plots for the mean daily precipitation intensity can be found in the middle of the upper row in both figures. For Hohenpeißenberg three phases of increase can be identified: one for 1930 to 1940, one from 1950 to 1969 and one from 1970 to 1990. Another little increase is found for the last years. This behaviour differs from the curve for the temperature increase at this site which remarkably increases for the period 1940 to 1950, from 1970 to about 2000 and from 2010 onwards[2]. Thus, other factors than the overall warming of the atmosphere impact the local precipitation characteristics. This could be circulation changes (see, e.g., Scherrer et al., 2016 or Paradise et al., 2019) as well as changes in the availability of condensation nuclei (see, e.g., Reisin et al., 1996). For Benediktbeuren an increase is seen from 1930 to about 1980, but then the curve is decreasing again until 2010. Only in the last ten years another increase is detectable which seems to fit to the temperature increase. Local temperature changes seem to be even less important for changes in precipitation intensity at this foothill site. The temporal development in Figs. 1 and 2 has always to be assessed in the light of the considerable scatter of the yearly data within each 30-year period. This scatter is visualised by the showing the standard deviations and the extreme values within the single 30-year periods as well. This yearly scatter is smallest relative to the mean value for the mean daily precipitation intensity on wet days and is largest for the number of dry days and the duration of the longest draught within each year. This behaviour is very similar for the foreland station Hohenpeißenberg depicted in Fig. 1 and the foothill station Benediktbeuren depicted in Fig. 2.

Fig. 3 shows an increasing frequency of days in the classes 3 to 6 with more than 10 mm of precipitation together with a small increase in class 1 (dry days) and a slightly larger decrease in class 2 (1 to 10 mm). The results in Fig. 3 are in line with findings of Trömel and Schönwiese (2007) who presented a similar temporal shift in the Gumbel distribution of extreme precipitation for Southern Germany. The highest relative increases are found in the classes 4 (20 to 30 mm) and 5 (30 to 40 mm) due to the overall low number of these days. This Figure demonstrates that the increase in the mean daily precipitation intensity is a consequence of a decrease of days with small precipitation amounts (1 mm to 10 mm) and a simultaneous increase of days with larger precipitation amounts (10 mm and more). Thus, we see two develop-

[2]https://www.dwd.de/DE/forschung/atmosphaerenbeob/zusammensetzung_atmosphaere/hohenpeissenberg/download/historie_pdf.pdf?__blob=publicationFile&v=6 (accessed: October 23, 2020)

ments in the precipitation characteristics: (1) an increasing annual precipitation happens at fewer wet days, and (2) within these fewer wet days, days with more intense precipitation become more frequent.

5 Conclusions

The evaluation of precipitation characteristics for 30-year time slices for a region in Southern Germany close to the Bavarian part of the Alps shows several common features which occur at all four evaluated stations and which fit to other studies mentioned above. The changes have been computed as sliding 30-year averages and as the difference between two 30-year time slices. For some evaluations data from the year as a whole has been compared to data from the convective season (May to October).

The most important changes in precipitation characteristics are:

1. The annual precipitation amount increases, roughly fitting to the magnitude of the regional temperature increase of a bit more than 1 degree centigrade in the course of global warming (Lenderink and van Meijgaard, 2008; Bronstert et al., 2017).

2. The course of the increase of the various precipitation parameters analysed in this study does not strictly follow the course of regional warming which indicates that other reasons for the increase in the shown precipitation parameters than warming have to be sought as well. These could comprise circulation pattern changes (see, e.g., Scherrer et al., 2016) and/or changes in the number of condensation nuclei (see, e.g., Reisin et al., 1996).

3. The number of dry days slightly increases. A possible explanation for this could be a northward shift of the storm tracks over Europe (Ulbrich et al., 2009).

4. The maximum length of dry spells is increasing at three of the four stations. A possible reason could be the more frequent occurrence of prolonged blocking episodes (Paradise et al., 2019) as consequences of global warming. This interpretation is supported by the fact that dry spells are longer in the non-convective season.

5. As a consequence of (1) and (3), the daily precipitation intensity on wet days increases. This increase is the clearest and most consistent signal in this evaluation. The increase in daily precipitation intensity on wet days is larger than the increase of the annual precipitation amount, because the number of wet days have slightly decreased. The decrease is exclusively caused by a decrease of days within the lowest class of wet days, i.e., days with a daily precipitation amount of 1 mm to 10 mm.

6. The maximum daily precipitation increases at the foreland stations but not so at the foothill stations. One possible reason could be that the triggering of convection at mountains is not so much a function of the air temperature but rather a function of the incoming solar radiation, which is assumed to be unchanged during global warming (Biktash, 2019).

7. The increase in maximum daily precipitation at the two foothill stations is less than the increase in the annual precipitation amount while it is about equal at the two foreland stations. The reason could be related to the one named with the previous point.

8. The maximum observed daily precipitation amount in the full four datasets is 138.5 mm at Hohenpeißenberg in 1999. Peak values at Reit im Winkl and Benediktbeuren are not much lower. The peak value for Kempten is considerably lower at 86.1 mm. Maximum 24-hour precipitation amounts could be even larger than the values just given, because extreme events do not keep to the regular reading hours at the weather stations.

It has to be kept in mind that this evaluation is based on four climate stations only and on a data record which covers only 119 years. It is the consistency in the results from these four stations for most parameters that seem to give these results nevertheless some credibility. About half of the results pass the 95 % significance level for an assumed normal distribution. In addition, the overall patterns in the conclusions (1) and (4) fit to the findings of regional climate model simulations for future climate scenarios for this region (see, e.g., Keuler et al., 2016). The differences in the results from the four stations on the other hand once again demonstrate that precipitation characteristics always can be highly variable in space and time and that local in-depth data analyses and model efforts are necessary in order to document the impact of climate change on the hydrological cycle in complex terrain.

It seems possible that the above results and conclusions can be interpreted as signs that climate change is well underway in Southern Bavaria as it is in most places of the world. Precipitation characteristics are changing in a warming climate. One of the characteristics with societal impact, the risk for flash floods, is increasing in the investigated region due to the increased daily rain intensity on wet days. Therefore, local communities and stakeholders are well advised to consider adaptation to these changing precipitation characteristics.

Acknowledgements

This work is part of project work for the research project "Climate information and flood risk" (FKZ 01LR2006D) within the joint project "RegIKlim: Adaptation to climate change on a regional scale: Increasing risks due to heavy precipitation in Upper

Bavaria (KARE)", FKZ 01LR2006, funded by the German Ministry of Education and Research based on a decision of the German Bundestag. The project will run from July 2020 to June 2023.

I thank my colleague Patrick Laux who carefully read an earlier version of this manuscript and who made valuable comments to improve the manuscript. I also wish to express my thanks to the two anonymous reviewers.

We acknowledge support by the KIT-Publication Fund of the Karlsruhe Institute of Technology.

References

Allen, M.R., W.I. Ingram, 2002: Constraints on future changes in climate and the hydrologic cycle. – Nature **419**, 224–232.

Biktash, L.Z., 2019: Influence of the Total Solar Irradiance on the Earth's Climate. – Geomagn. Aeron. **59**, 368–373.

Bony, S., R. Colman, V.M. Kattsov, R.P. Allan, C.S. Bretherton, J.-L. Dufresne, A. Hall, S. Hallegatte, M.M. Holland, W. Ingram, D.A. Randall, B.J. Soden, G. Tselioudis, M.J. Webb, 2006: How well do we understand and evaluate climate change feedback processes? – J. Climate **19**, 3445–3482.

Bronstert, A., H. Bormann, G. Bürger, U. Haberlandt, F. Hattermann, M. Heistermann, S. Huang, V. Kolokotronis, Z. Kundzewicz, L. Menzel, G. Meon, B. Merz, A. Meuser, E. Paton, T. Petrow, 2017: Hochwasser und Sturzfluten an Flüssen in Deutschland. – In: Brasseur, G., D. Jacob, S. Schuck-Zöller (Eds.): Klimawandel in Deutschland: Entwicklung, Folgen, Risiken und Perspektiven. – Springer, Berlin, Heidelberg, 87–101.

Chwala, C., H. Kunstmann, 2019: Commercial microwave link networks for rainfall observation: Assessment of the current status and future challenges. – Wiley Interdisciplinary Reviews: Water **6**, e1337.

Frei, C., C. Schär, 1998: A precipitation climatology of the Alps from high-resolution rain-gauge observations. – Int. J. Climatol. **18**, 873–900.

Giorgi, F., X. Bi, J. Pal, 2004: Mean, interannual variability and trends in a regional climate change experiment over Europe. II: climate change scenarios (2071–2100). – Climate Dyn. **23**, 839–858. DOI:10.1007/s00382-004-0467-0.

Hennemuth, B., S. Bender, K. Bülow, N. Dreier, E. Keup-Thiel, O. Krüger, C. Mudersbach, C. Radermacher, R. Schoetter, 2013: Statistische Verfahren zur Auswertung von Klimadaten aus Modell und Beobachtung, eingesetzt in Projekten und Institutionen, die sich mit Klimafolgen und Anpassung befassen. – CSC Report **13**, Climate Service Center, Germany.

Keuler, K., K. Radtke, S. Kotlarski, D. Lüth, 2016: Regional Climate Change over Europe in COSMO-CLM: Influence of emission scenario and driving global model. – Meteorol. Z. **25**, 121–136.

Kunz, M., S. Mohr, P. Werner, 2017: Starkniederschläge. – In: Brasseur, G., D. Jacob, S. Schuck-Zöller (Eds.) Klimawandel in Deutschland: Entwicklung, Folgen, Risiken und Perspektiven. – Springer, Berlin, Heidelberg, 57–66.

Lenderink, G., E. van Meijgaard, 2008: Increase in hourly precipitation extremes beyond expectations from temperature changes. – Nat. Geosc. **1**, 511–514.

Lengfeld, K., T. Winterrath, T. Junghänel, M. Hafer, A. Becker, 2019: Characteristic spatial extent of hourly and daily precipitation events in Germany derived from 16 years of radar data. – Meteorol. Z. **28**, 363–378.

Nissen, K.M., U. Ulbrich, G.C. Leckebusch, 2013: Vb cyclones and associated rainfall extremes over Central Europe under present day and climate change conditions. – Meteorol. Z. **22**, 649–660.

Paradise, A., C.B. Rocha, P. Barpanda, N. Nakamura, 2019: Blocking statistics in a varying climate: Lessons from a "traffic jam" model with pseudostochastic forcing. – J. Atmos. Sci. **76**, 3013–3027.

Peristeri, M., W. Ulrich, R.K. Smith, 2000: Genesis conditions for thunderstorm growth and the development of a squall line in the northern alpine foreland. – Meteor. Atmos. Phys. **72**, 251–260.

Reisin, T., Z. Levin, S. Tzivion, 1996: Rain production in convective clouds as simulated in an axisymmetric model with detailed microphysics. Part II: Effects of varying drops and ice initiation. – J. Atmos. Sci. **53**, 1815–1837.

Schaller, A.S., J. Franke, C. Bernhofer, 2020: Climate dynamics: temporal development of the occurrence frequency of heavy precipitation in Saxony, Germany. – Meteorol. Z. (Contr. Atm. Sci.), **29**, 335–348. DOI:10.1127/metz/2020/0771.

Scherrer, S.C., M. Begert, M. Croci-Maspoli, C. Appenzeller, 2016: Long series of Swiss seasonal precipitation: regionalization, trends and influence of large-scale flow. – Int. J. Climatol. **36**, 3673–3689.

Tomassini, L., D. Jacob, 2009: Spatial analysis of trends in extreme precipitation events in high-resolution climate model results and observations for Germany. – J. Geophys. Res. **114**, D12113, DOI:10.1029/2008JD010652.

Trömel, S., C.-D. Schönwiese, 2007: Probability change of extreme precipitation observed from 1901 to 2000 in Germany. – Theor. Appl. Climatol. **87**, 29–39.

Ulbrich, U., G.C. Leckebusch, J.G. Pinto, 2009: Extra-tropical cyclones in the present and future climate: a review. – Theor. Appl. Climatol. **96**, 117 – 131.

Wastl, C., C. Schunk, M. Leuchner, G.B. Pezzatti, A. Menzel, 2012: Recent climate change: Long-term trends in meteorological forest fire danger in the Alps. – Forest Agric. Meteorol. **162–163**, 1 – 13.

Zhang, X., L. Alexander, G. Hegerl, P. Jones, A. Klein Tank, T. Peterson, B. Trewin, F. Zwiers, 2011: Indices for monitoring changes in extremes based on daily temperature and precipitation data. – Climate Change **2**, 851–870.

Zöbisch, I., C. Forster, T. Zinner, L. Bugliaro, A. Tafferner, K. Wapler, 2020: Characteristics of deep moist convection over Germany in multi-source data. – Meteorol. Z. (Contr. Atm. Sci.), **29**, 393–407. DOI:10.1127/metz/2020/1011.