CLIMATOLOGY OF PRECIPITATION IN THE VOSGES MOUNTAIN RANGE AREA

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ABSTRACT

The aim of this work is to study the climatology of atmospheric precipitation in the study area situated in north-eastern France. It is shown that the Vosges mountain range, due to its position almost perpendicular to the prevailing western airflow, affects the spatial and temporal distribution (and thus the seasonality) of precipitation at a regional scale. This is carried out by computing the daily rainfall at 14 meteorological stations over the period 1950–2011. Different levels of rainfall resolution were examined – at first the annual rainfall which varies greatly between the windward side and the highest part of the Vosges mountain range and the Upper Rhine Plain (the difference is as large as 1700 mm per average year), then the monthly rainfall and distribution of precipitation within the year and finally the daily rainfall variability. Three categories of stations were determined according to their annual precipitation distribution: (i) mountain stations with a winter precipitation maximum, (ii) leeward slope stations with two precipitation maxima, i.e. in winter and summer and (iii) leeward stations located in the Upper Rhine Plain eastward of the Vosges with a summer precipitation maximum. Quantitative methods of ombric continentality demonstrate that the Vosges represent a limit between oceanic and a more continental climate. However, the empirical formulas are not satisfying and further research is required.

Keywords: climatology, precipitation variability, ombric continentality, leeward effect, the Vosges

1. Introduction

The distribution of atmospheric precipitation is not uniform in space and time (e.g., Prudhomme, Reed 1998). Taking into consideration the potential impact of precipitation on human beings (e.g., lack of precipitation causes drought, while its excess generates floods) and the incompleteness of knowledge about this domain (Šálek 2007), further research is required. Thus the aim of this study is to contribute to the research concerning atmospheric precipitation using the standard climatological methods (with annual, monthly and daily rainfall resolution) and studying the degree of ombric (rainfall) continentality, while taking into account the potential influence of orography on the precipitation distribution.

The studied area comprises the Vosges, a relatively low-elevation mountain range, situated in north-eastern Metropolitan France near the border with Germany and Switzerland, and their surroundings – the Upper Rhine Plain in particular. The reason for such a choice of area is, that the Vosges represent one of the first orographic barriers to the Westerlies from the Atlantic Ocean (air masses come mostly from West or South-West, in 40.5% of days out of the period 1985–1987, as explained e.g., in REKLIP 1995) which is due to their extension in the north-northeast and south-southwest direction. Another hypothesis is that a limit between oceanic and more continental climate (with a different distribution of precipitation within a year) occurs in this area. The last motivation is that the chosen area (Figure XVII in Colour appendix) presents a considerable altitudinal variability (up to 1300 m) – the Grand Ballon, the highest vosgian peak reaches 1424 metres above sea level (thereafter ASL), while the Upper Rhine Plain keeps a relatively constant altitude of approximately 200 meters and less (Sell et al. 1998).

Among the factors influencing climate variability (and therefore precipitation variability) in the studied area are altitude, slope exposure and geographical position (in the sense of distance and direction from the Vosges), along with specifics of the local relief (convexity vs. concavity) etc. It should be noted that vosgian slopes are typically steeper on the eastern (Alsatian) side, close to the Upper Rhine Plain, than those of the western (Lorraine) part (Troux, Quillé 1951); this influences the precipitation patterns too.

As aforementioned, the orientation of the Vosges mountain range forms a perpendicular orographic barrier to the prevailing western airflow; therefore it would be expected (Barry, Chorley 2003) that on the windward side and on the mountain ridges may occur an orographic intensification of precipitation mainly due to the reinforcement of air uplift while the phenomenon of rain shadow is characteristic for the leeward side (in our case it concerns mainly the Upper Rhine Plain). However at the local scale the description of the precipitation pattern gets more complicated, as many factors and conditions need to be accounted for.

Regarding climate continentality, we recognize two types of continentality in general – thermal and ombric (relating to temperature and precipitation respectively).

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This study analyses only the second one. According to the degree of continentality, we distinguish oceanic, semi-continental and continental climates (e.g., Sobíšek et al. 1993). In European mid-latitudes the oceanic climate is typically humid, with relatively high and uniform temporal distribution of precipitation (with the exception of a small peak in winter at the west coasts). In contrast, the continental climate is generally much drier (precipitation peaks during summer) and the distribution of precipitation is uneven. The semi-continental climate has some combination of the characteristics of oceanic and continental climates (Zíková 2009).

The climate of the studied area is usually classified as temperate and semi-continental and generally under the prevailing influence of western airflow rich in water vapour (e.g., Sell et al. 1998). One of the most important climate characteristics of the region is its well-marked spatial and temporal variability (Météo-France 2008). Both are related to relief (topography), degree of continentality and the related seasonal of the precipitation.

Besides, the mean annual air temperature varies between 10 °C (plain), 7 °C (800 metres ASL) and 5 °C for 1200 m in the Vosges (Sell et al. 1998; Mühr 2007). In terms of average annual rainfall, the variability is much more pronounced. The windward side and the main mountain ridge of the Vosges is the most humid (the average annual rainfall surpassing 2000 mm) whereas less precipitation falls on the leeward side. The minimal rainfall is in the Upper Rhine Plain, typical of the rain shadow (e.g., town Colmar with less than 550 mm per year considered as one of the driest place in Metropolitan France) (Sell et al. 1998). Climate patterns are more pronounced in winter, with winter cyclones more frequent and intense in winter than in summer (Bürger 2010).

Overall, this paper emerges from the need to enhance the knowledge concerning the climatology of atmospheric precipitation in relation to orography in the Vosges area. This will be accomplished by analysing 14 meteorological stations over the studied area, there providing a potential framework for estimating atmospheric precipitation. Some of the results shown here could be specific to the study area but others could be transferable to other orographic regions.

2. Data and methods

The map output for the Vosges mountain range area was processed through the ArcGIS cartographical software (version 9.3.1) operating with geographic information systems (GIS) provided by ESRI (Environmental Systems Research Institute; available from http://www.esri.com/) – using their basemaps (e.g., towns). The topology background was adopted from the Marine Geoscience Data System (project of Columbia University in New York) using their software GeoMapApp (version 3.1.6). This application (http://www.geomapapp.org/) provides a visualisation of the Global Multi-Resolution Topography (GMRT) terrain model, with node spacing of 100-meters. For continental surfaces, NED (National Elevation Dataset) was used.

Access to the meteorological daily data was granted by the Météo-France network. The daily rainfall obtained covered the period from 1950 to 2011 (i.e. 62 years) from 14 meteorological stations (see Figure XVII

Tab. 1 Geographical position, average annual rainfall $\overline{Ra}$ and year with missing data of 14 studied meteorological stations.

Meteorological station (number | name)		Northern latitude [°]	Eastern longitude [°]	Altitude [m ASL]	Average annual rainfall $\overline{Ra}$ [mm]	Year with a missing observation
1	Sewen – Lac Alfeld	47.82	6.87	620	2,334	1952–60, 1964, 2002, 2004, 2006–08
2	Wildenstein	47.98	6.96	560	2,070	1950–56, 1957, 1958, 1960, 1961, 1992
3	Sewen – Foerstel	47.81	6.91	505	1,907	1950–58, 1968, 1974, 1975, 1977, 1978
4	Longemer	48.07	6.95	745	1,865	1961, 1962
5	Mittlach – Erbe	48.01	7.03	552	1,834	1963–72, 1974, 1975, 1976
6	Le Hohewald	48.41	7.35	785	1,226	1952, 1953, 1955, 1963, 1964, 1975, 1976, 1977, 1982, 1983, 1984
7	Aubure	48.20	7.22	796	1,084	1950–1970, 1986, 1989, 2010
8	Strasbourg	48.58	7.77	139	730	–
9	Barr	48.41	7.46	193	722	1953, 1970
10	Kayserberg	48.14	7.27	248	703	1950, 1965, 1967, 1968, 1977, 1978
11	Neuf – Brisach	48.03	7.58	195	640	2002, 2003
12	Ebersheim	48.31	7.49	164	621	–
13	Rouffach – Chs	47.95	7.29	208	612	1961, 1962, 1971, 1981, 1982, 1987, 1989, 1990, 2004
14	Oberentzen	47.94	7.38	205	606	1956, 1964

in Colour appendix). The dataset was not continuous (Table 1) – some series were interrupted within the observation period (with the exception of the stations *Ebersheim* and *Strasbourg*), mostly in winter or summer. The list of meteorological stations is presented in Table 1, which displays the geographical position of the studied stations, the average annual rainfall ($\overline{Ra}$) as well as any years with at least one day of missing observations. While some data were available during the listed years (the listed years do not mean that for all the year we have "no data", however, data from these years were omitted when calculating the average annual rainfall). The stations are listed in order of their average annual rainfall ($\overline{Ra}$) for the studied period, from greatest (*Sewen-Lac Alfeld*, no. 1) to least (*Oberentzen*, no. 14). The meteorological stations displayed in Figure XVII are divided according to their average annual rainfall in intervals of 500 mm. The first interval includes stations with annual rainfall between 500 mm and 1000 mm; no station had less than 500 mm.

Any time period containing missing values was discarded in the calculations. That is, for the daily resolution, only days with missing precipitation data were omitted, while for the monthly resolution, the whole (incomplete) months were discarded if data were missing, even on a single day. Listing all the days with missing values in Table 1 is beyond the scope of this paper.

It was chosen not to homogenise the data because inaccuracies may occur – especially in the case of outlying values (extreme precipitation), contrary to original data. Homogenization of the dataset may result in filtering out of the marginal values (Štěpánek 2007). Another reason is that future research will examine these extremes.

The standard climatological approach was used on the collected data. This consists in analysing rainfall from large to small temporal levels (e.g., years to days) and of the rainfall variability (Sobíšek et al. 1993). For some cases, 5 meteorological stations were selected as representative of a part of the studied area (their position is indicated in Figure XVII) – *Longemer* (no. 4), the sole representative of the windward side of the Vosges, *Sewen-Lac Alfeld* (no. 1) and *Wildenstein* (no. 2), both situated closest to the main mountain crest, *Aubure* (no. 7) located on the leeward side but still in the Vosges, and finally *Oberentzen* (no. 14), which represents purely a leeward lowland station (within the rain shadow area) in the Upper Rhine Plain.

2.1 Annual rainfall and distribution of precipitation within an average year

Firstly the average annual rainfall ($\overline{Ra}$) was analysed using Microsoft Excel 2010 within the period 1950–2011 for each station in order to determine the general magnitude of rainfall in the examined area. Then the average monthly rainfall ($\overline{Rm}$) was studied for each station and each month, allowing to ascertain the variability of precipitation within an average year. The calculation was based on the following equations:

$$\overline{Ra} = \frac{\sum_{i=1}^{j} Ra_i}{n}, \tag{1}$$

$$\overline{Rm}_{J-D} = \frac{\sum_{i=1}^{j} Rm_i}{n}, \tag{2}$$

where i is the i-th year; j last year with observations and n represents the total number of years with observations (J-D signifies months from January to December), while Ra_i (Rm_i) is the sum of the daily rainfall (Rd) within a year (month) i and the number of days within the year (month) i.

It is important to note that for the entire study the afore described procedure was followed.

Subsequently, the season (or day) of highest concentration of precipitation within the analysed period (1950–2011) was determined for the five characteristic meteorological stations. The method shows the intra-annual variability of precipitations. The yearly centre of gravity of rainfall was computed using the percentage of $\overline{Rm}$ in $\overline{Ra}$ expressed as a vector with a direction representing a month and magnitude equal to this percentage. The closer in value these percentages are for each month, the more uniformly the precipitation is distributed in an average year. The results were plotted into a polar chart (Figure XIX in Colour appendix) which was divided into 12 parts corresponding to each month in a year (30° for every month). The 12 coordinates for the 5 examined stations were found this way, aligned in the graph. The centre of gravity (resultant vector) for each station was calculated as the sum of 12 vectors representing 12 months for such stations. The date (placed on the "auxiliary" circle in Figure XIX) was matched with each centre of rainfall gravity, i.e., the resultant vector, to indicate the centre of gravity of the humid period.

Finally to make the graph more meaningful, a dashed "average" circle (with magnitude equal to the average of resulting vectors for five stations) was added into the graph. The radius of this circle Rm_{result} centred at the origin of the polar coordinate system was calculated as:

$$|Rm_{\text{J–D}}| = \sqrt{\left[\left(\frac{\sum_1^n Rx_{J-D}}{n}\right)^2 + \left(\frac{\sum_1^n Ry_{J-D}}{n}\right)^2\right]}, \tag{3}$$

$$Rm_{result} = \frac{\sum_J^D |Rm_{J-D}|}{12}, \tag{4}$$

where $|Rm_{\text{J–D}}|$ means the value (calculated as a distance of a vector using the Pythagorean theorem) of a resultant average monthly rainfall for all stations from January (J) successively up to December (D). This results in 12 values. The variable n is the number of examined stations (in our case equal to 5); Rm_{result} represents the sole resultant average monthly rainfall (for all months – from January to December).

2.2 Ombric continentality

The ombric continentality was also examined. Three empirical formulas describing the degree of ombric continentality were selected: (i) the time of the half annual rainfall, (ii) the degree of continentality by Hrudička (1933) and (iii) Markham's index of uneven distribution of precipitation (F).

The time of the half annual rainfall (i) represents the time in months counted from April to reach the half of the annual average rainfall ($\overline{Ra}$). The shorter the calculated time, the greater the ombric continentality (Hrudička 1933).

The degree of continentality k (ii) proposed by Hrudička (1933) is calculated as follows:

$$k = \frac{12(l-35)}{\sqrt{s_z}} \ [\%], \tag{5}$$

where l is the percentage of the sum of the average monthly rainfall from April to September in the average annual rainfall and s_z is the sum of the average monthly rainfall for the cold period (from October to March) expressed in milimeters.

When the increase of the k value is greater, the ombric continentality is becoming more pronounced and the distribution of precipitation in an average year less uniform.

The last approach (iii) involved the use of the precipitation seasonality index F (Markham 1970). This index has been applied in several studies to demonstrate the degree of annual inequality in the distribution of precipitation or the degree of ombric continentality (e.g., in the Climate Atlas of Czechia, Tolasz et al. 2007). In this paper, it was calculated for five selected meteorological stations as follows (Shver 1975):

$$F = \frac{R}{\sum_{i=1}^{12} r_i} \times 100 \ [\%], \tag{6}$$

where F is the percentage of the magnitude of the resultant vector R (calculated as the sum of vectors representing monthly rainfall r_i, where i = 1, 2,…, 12) divided by the total annual rainfall (equal to the scalar sum of all monthly rainfall).

Notice that the monthly rainfalls were transformed into vectors (with two components) as in the previous case (the determination of a day with the highest concentration of precipitation) described above. In general, lower value of F means more balanced distribution of precipitation within a year and thus typically lower degree of ombric continentality (Brázdil et al. 2009).

2.3 Variability of monthly and daily rainfall

The best way to express the inter-monthly and inter-daily variability seemed to be to plot a curve resembling a cumulative distribution function. The monthly (daily) rainfall data were arranged in descending order. The largest observation was assigned the order number 1, the second largest the order number 2, and so on until all observations had an order number. A quotient of an order number and the absolute number of observations was calculated (e.g., 62 for a station measuring within the whole studied period of 62 years) – in this case identical to the largest order number. This quotient was expressed as a percentage and then subtracted from "100" (to form a complement to 100).

Using this approach, we got the values on the y-axis in Figures XXI and XXII, and the x-axis values in Figures XXIII and XXIV (Colour appendix).

In Figure XXII (in Figure XXIV), the values on the x-axis (y-axis) were equal to the monthly (daily) rainfall related to the average monthly rainfall (daily rainfall from days with observations and exceeding 0.0 mm divided by the number of days with this rainfall), expressed as a percentage. For a higher significance of results, the values on the axis expressing the monthly rainfall (Rm) or daily rainfall (Rd) were divided by the average (monthly or daily) rainfall ($\overline{Rm}$, $\overline{Rd}$). Notice that the inter-monthly variability was expressed only for five selected meteorological stations comparing the months of January and July (as is standardly used in climatological research – e.g., Votavová 2010).

3. Discussion of results

3.1 Average annual rainfall

The values of average annual rainfall ($\overline{Ra}$) calculated by (1) are recorded in the Table 1. Comparing Table 1 with Figure XVII, the mountainous stations (and mostly south-western stations) show a far greater average annual rainfall (> 1000 mm/year) than the leeward side. The average annual rainfall at *Sewen-Lac Alfeld* station (no. 1, with 2334 mm/year) is almost four times greater than at *Oberentzen* (no. 14 with 606 mm/year). This difference is significant, considering the short distance in the west-east direction (only about 70 km). The results demonstrate the important role of the Vosges mountain range as a precipitation barrier, thus leading to the phenomenon of rain shadow in the Upper Rhine Plain (making it relatively dry).

It should be noted that – despite the general trend – the stations situated easternmost in the studied area do not show low values of $\overline{Ra}$. In the case of *Strasbourg* (no. 8), this is because the Vosges are not as high in its surroundings and thus the rain shadow is less pronounced in this region (REKLIP 1995, Bürger 2010).

Neuf-Brisach (no. 11) could be perceived as a station standing at the windward side of Schwarzwald, near-by is Totenkopf (557 m ASL), part of the Tertiary volcano Kaiserstuhl (Scholz 2008).

The dependency between the altitude of a station and its $\overline{Ra}$ was not proved. One explanation is that the altitude does not represent a decisive factor influencing the rainfall in the studied area. For example, Bankanza (2011) states that for the most humid summers in the Czech Republic (1997, 2002) the slopes and altitudes in the surrounding area were much more important than the altitude of the measuring station.

It is interesting that at *Longemer* station (no. 4), which is the westernmost station and is the only one on the windward side (Table 1, Figure XVII), the average annual rainfall is not the highest as might be expected (1865 mm contrary to, e.g., *Wildenstein* (no. 2) with 2070 mm/year). The reason could lie in the fact that the windward effect is more pronounced close to the main mountain ridge than on the windward side, because the windward western slopes are not so steep, which causes a gradual (not abrupt) air uplift. This might postpone the onset of precipitation. This relationship was described e.g., by the UTD ("upslope-time-delay") model proposed by Smith (2003). Another hypothesis is that *Longemer* station (no. 4) is not situated south-easternmost where the highest rainfall is reached because of the prevailing western and mainly south-western airflow in the studied area as mentioned above (e.g., REKLIP 1995).

3.2 Average monthly rainfall

The resulting values of the average monthly rainfall ($\overline{Rm}$) calculated using formula (2) are represented in Figure XVIII. The uneven monthly distribution of precipitation within an average year is clearly evident – the most humid month is December for the seven first meteorological stations (e.g., at *Sewen-Lac Alfeld* (no. 1) it is about 300 mm), whereas for the remaining seven stations it is the summer months (most frequently June and August, e.g., 67 mm per August at *Oberentzen* station, no. 14). This demonstrates the undeniable spatial and temporal differences in distribution of precipitation and the role of the Vosges mountain range as the most significant factor.

Three categories of stations were distinguished on the basis of the precipitation course of $\overline{Rm}$ in an average year (apparent in Figure XVIII):

(i) stations with one peak of precipitation in winter (the five first meteorological stations – e.g., *Wildenstein*, no. 2),

(ii) stations with two peaks – one main and one incidental (four stations), which could be divided into 2 groups according to the predominant maximum in winter (*Le Hohewald*, no. 6 and *Aubure*, no. 7) or in summer (*Barr*, no. 9 and *Kayserberg*, no. 10),

(iii) stations with one peak in summer (six stations – e.g., *Neuf-Brisach*, no. 11).

It is almost surprising that the annual course of precipitation changes almost gradually from the west (i) to the east (iii) of the studied area with the accompanying progressive decrease of $\overline{Ra}$ (curves between different categories do not cover almost each other – Figure XVIII). This could be generated by the increasing ombric continentality in the west-east direction manifested by the progressive weakening of winter maximum and the gradual increase of summer maximum of precipitation, with the summer maximum dominating for category (iii) stations. This can be explained by a greater participation of convective precipitation in summer for this category (e.g., Sládek 2005). In category (ii) with two maxima of precipitation, the summer convection and the winter intensification of the oceanic western circulation both create local precipitation maxima (McCabe 2001) – the convection is minority for the first group of stations, whereas it prevails in the second group of this category. The higher winter's wind velocity and winter's intensified atmospheric circulation is deciding in the case of category (i) (Heyer 1993).

The role of the Vosges in the course of precipitation could lie in an intensified transition from category (i) to (iii), thus amplifying the transition from oceanic to more continental climate.

3.3 Average day of the highest concentration of precipitation

In Figure XIX the average day with the highest concentration of precipitation within the examined period (1950–2011) is identified using formulas (3) and (4). It leads to an analogous conclusion as in the previous case – meteorological stations closer to the west, that is, category (i) stations, reach the highest concentration of precipitation in winter – in December (e.g., on the 19th of December for *Wildenstein*) whereas precipitation at *Oberentzen* station, category (iii), reaches a maximum on average in July (on the 5th of July). Thus the centre of rainfall gravity is dependent on the geographical position of the stations (Figure XVII).

From Figure XIX, the increase of ombric continentality is also evident. The vectors head towards December for category (i) but get shorter gradually with decreasing $\overline{Ra}$ (Table 1) up to the smallest magnitude of vector for category (ii) – here represented by *Aubure* station (no. 7). Then for category (iii), the vector increases in its magnitude even as $\overline{Ra}$ continually decrease, but the direction is now oriented to summer months, as seen for the *Oberentzen* station (no. 14), which has its vector pointed to July. It is interesting to notice that the influence of orography must represent a very important factor for the studied area, which is manifested by the immediate weakening of winter maximum just after reaching the main crest. Thus the role of Vosges as a generator of ombric continentality can be confirmed (Bürger 2010).

Moreover, from the graph on Figure XIX the ratio between the average rainfall circle (illustrated by a dashed line) and the asymmetrical curve of monthly rainfall dependencies for individual stations can be observed.

With decreasing asymmetricity of the annual distribution of rainfall, the annual course of precipitation is more balanced and the peak of the highest concentration of precipitation is less pronounced. In an ideal case (such as for rainfall in equatorial areas) no peak can be recognized (Kottek et al. 2006; Trefná 1970), the form of the rainfall dependency approaches a circle and the resultant vector is zero. In our case, the shape of the dependency for the *Aubure* station (no. 7) is the most similar to an average circle. Thus the rainfall at *Aubure* station (no. 7) shows the most balanced concentration – with the winter peak (on 6th of December) just a little greater than the summer secondary peak (in May). This is manifested also by the smallest resulting vector out of the list.

However, this method is not without disadvantages: the information value of the results is limited, because when adding vectors of the same magnitude but opposite directions, their sum would be equal to zero. Hence, the vector would indicate that the highest rainfall for a station occurs in another month that is not counterbalanced. This has partially occurred in the case of *Aubure* (no. 7) where the magnitude of the resultant vector pointing to winter is reduced by the secondary summer maximum.

Nevertheless, the unquestionable advantage of this method lies in accenting the real centre of gravity of precipitation which is much more representative as a result than the bare comparison of $\overline{Rm}$.

3.4 Evolution of annual rainfall

The evolution of annual rainfall (*Ra*) in time during the period 1950–2011 was also explored (as well as for the months January and July) as you can see in Figure XX. But the results of linear trend and moving 5-year average were not statistically significant – the index of determination was on the order of single hundredths, hence the trend curves were not represented in the graph.

Points of inflexion were also studied. The humid (or dry) year is often followed by the opposite extreme (e.g., dry year 1970 followed by a wet one in 1971 or the humid 1985 was succeeded by the dry 1986).

Afterwards, the peaks were compared with literature to see whether or not they were followed by a hydrological (or another) response (e.g., minimum by a drought, maximum by a flood). In a majority of cases, the local maxima of *Ra* were also followed by floods (Schäfer et al. 2012). For example, the year 2001, which was the most humid year for the majority of examined stations (the highest annual rainfall of 3170 mm was collected at *Sewen-Lac Alfeld* station, no. 1), and was also marked by an extreme rainfall in the end of December (264 mm were measured from 28th and 29th of December at *Sewen-Lac Alfeld* meteorological station, no. 1) that was followed by an overflowing of the Moselle, Meuse, Erlenbach and Thur rivers; even a landslide happened with one fatality (IHMÉC 2008).

Minima of *Ra* were frequently followed by a hydrological and agronomical drought. In 2003 the meteorological drought which was transformed even into a socio-economical drought was recorded in almost whole of Western Europe (Söder et al. 2009). In Metropolitan France, it caused (with the heat wave) 15,000 casualties from the 4th to the 20th of August (Hémon, Jougla 2003). Concerning the earlier dry episodes, Amigues et al. (2006) demonstrated that the meteorological drought of 1976, 1991 and 1996 was followed by the pedological or hydrological one.

No available information was found about the adverse impact of the meteorological drought in 1971, even though the data in Figure XX suggest that this episode should have been quite significant. At *Sewen-Lac Alfeld* as well as at the *Strasbourg* station (no. 1 and no. 8) the annual rainfall for 1971 was only about half of the average (1200 mm contrary to $\overline{Ra}$ = 2330 mm at no. 1 and 432 mm in contrast to $\overline{Ra}$ = 730 mm on average at station no. 8). This could be related to the insufficiency of data or due to a systematic error resulting from the conversion of values of solid precipitation to values of liquid precipitation that was much more error-prone in the past (e.g., Štěpánek 2007). The winter period 1970/1971 was not only extremely cold but also rich in precipitation – e.g., from the 1st to the 10th of March in 1971, 25 cm of new snow cover was recorded in North-Western France (Fondevilla 2004). Another reason could lie in the anemo-orogaphic system after Jeník (1961) – the examined station could be at a non-favourable place to accumulate snow (snow could be taken away by wind) as observed for example at Giant Mountains (*Krkonoše* in Czech) situated in the Czech Republic.

3.5 Inter-monthly variability

The inter-monthly variability examined through cumulative distribution curves for the months of January and July is documented in Figure XXI. The variability between the determined categories is greater in winter than in the summer period – the curves are farther apart and oscillate more in winter (from 4 to 670 mm in January compared to 13–347 mm in July). This could be connected with the more frequent occurrence of extra-tropical cyclones in the winter period (Gulev et al. 2001). The cyclones are generally moving from west to east across the Vosges mountains and as a consequence the rain shadow is more present in winter (REKLIP 1995), so that the left outliers are missing in the January curves in Figure XXI. Hence the spatial variability of precipitation is significant in January. However since the January curves are more linear, the precipitation should be more evenly temporally distributed.

The absolute inter-monthly variability is the greatest for the mountainous (i) category of stations (e.g., *Wildenstein*, no. 2). It is interesting that for these stations a relatively few dry months of July are observed whereas dry January is much more frequent for lowland stations – category (iii). The determined categories above (see section 3.2) are evident in January in contrast to July where the differences are less obvious.

To improve data readability, five stations were selected as representatives to compare the inter-monthly variability of rainfall value months for January and July in Figure XXII. The July variability for the most frequent values is smaller than the variability in January. The divergence from the linearity becomes much more visible for the July curves. This could be related to the fact that in July, the precipitation is less predictable (e.g., Buizza et al. 2009), contrary to January where the precipitation is greater and more regular. The convection nuclei arise relatively chaotically and their temporal and spatial distribution is hard to predict (McGuffie, Henderson-Sellers 2005). The missing left outliers for January, and thus the less frequent occurrence of outliers compared to July is also better visible in the relative expression of values.

3.6 Ombric continentality

The ombric continentality was studied using three quantitative empirical formulas – the two latest calculated as indicated in (5) and (6). The resulting values are listed in Table 2.

The two first characteristics show the expected values. The degree of continentality increases with the decreasing $\overline{Ra}$ – this is shown by the simultaneous decrease of the time of half annual rainfall (precipitation is more concentrated in the summer months) and the increasing Hrudička's index *k*. However, contrary to what might be expected, the most continental station is not *Oberentzen* (no. 14) but *Neuf-Brisach* station (no. 11). This could be related to the fact that the highest concentration of precipitation is in the summer months but due to the effect of Schwarzwald, it is not reaching the lowest value of $\overline{Ra}$. This is in agreement with REKLIP (1995), where it is stated that the Schwarzwald precipitation maxima are in summer months and not in winter like in the Vosges.

The three distinct categories of stations can be also clearly identified from the same two characteristics – category (ii) stations have values of the time of half annual rainfall between 5.5 to 6.5 and values of *k* between 5.0 and 12.0. Note that the definition of continental climate proposed by Hrudička (1933), states that the half annual rainfall time must be less than 3 months; by this strict definition, none of these stations is continental. The stations of category (i) and the first group of category (ii) are "oceanic" and the remaining stations are "continental in transition" after the author definition.

However, by the definition of *k*, Hrudička (1933) as well as Nosek (1972) indicated that the smallest value (k = 0.8%) should have been reached at Tórnshavn, the capital city of the Faroe Islands, whereas in the studied area the meteorological station *Sewen-Foerstel* (no. 3) shows a value of 0.6%. This raises some doubts about the empirical formulas concerning the degree of ombric continentality – for example for the meteorological station Valentia in Ireland less than 35% of precipitation is attained in summer (Mühr 2011), hence the numerator in equation (5) is smaller than zero and thus the *k* value is then negative, which is not consistent with the interpretation of *k* proposed by Hrudička.

Concerning Markham's index *F*, the values were calculated for every year of the studied period for the five selected stations (in Table 2 only the average values are listed). The results do not correspond well with the explanation of this index normally found in literature (Tolasz et al. 2007; Brázdil et al. 2009) – for the most oceanic stations, category (i), a smaller value of *F* would be expected according to all the previous results, but

Tab. 2 Degree of continentality for 14 examined meteorological stations for the period 1950–2011.

Meteorological station (number | name)		Time of the half annual rainfall [month]	Degree of continentality *k* [%] by Hrudička	Markham's index *F* [%] for five selected stations
1	Sewen – Lac Alfeld	7.4	0.9	19
2	Wildenstein	7.2	1.7	15
3	Sewen – Foerstel	7.5	0.6	–
4	Longemer	6.8	3.1	10
5	Mittlach – Erbe	7.2	1.6	–
6	Le Hohewald	6.5	5.2	–
7	Aubure	6.5	5.4	5
8	Strasbourg	4.9	17.0	–
9	Barr	5.7	11.0	–
10	Kayserberg	5.6	11.7	–
11	Neuf – Brisach	4.7	21.7	–
12	Ebersheim	4.9	18.2	–
13	Rouffach – Chs	5.1	16.2	–
14	Oberentzen	5.0	18.0	14

these stations show on the contrary the greatest value in the examined area! This could be caused by the same type of error – addition of opposite vectors – as in the case of the centre of gravity of precipitation, mentioned above. But more probably this is caused by a misinterpretation of this index *F*. The index represents whether or not the precipitation is distributed evenly in a year. This means that its values have to be the smallest for the category (ii) with two maxima (neither the summer nor the winter maximum significantly surpasses the other), in Table 2 represented by the *Aubure* station (no. 7). This is obvious from the form of the near-elliptical shape of the curve and the minimal magnitude of resultant vector in Figure XIX.

Thus the index *F* should be interpreted that it could reach high values not only for continental stations but also for purely oceanic stations that are dominated by a winter maximum of precipitation. Small values of *F* are obtained, with a changing time of the maximum or two regular opposing maxima. It should be noted that no relationship between *F* and either the altitude of the station or *Ra* was recognized, and no trend was identified either.

3.7 Daily precipitation totals

The variability of the daily rainfall (*Rd*) was examined. The results of the cumulative distribution functions are presented in Figure XXIII. In term of the absolute values, it can be assumed that a higher variability occurs for category (i) stations situated in the Vosges, compared to category (iii) stations in the Upper Rhine Plain. This statement is consistent with the results of the cumulative distribution function for January and July (Figure XXI).

It is interesting that even in the daily resolution, the effect of the Vosges mountain range is clearly present – most of the precipitation falls in the area of the main crest, somewhat less at the leeward slopes and significantly less precipitation in the Upper Rhine Plain. The curves for the three categories of stations do not cross each other, with the exception of the category (ii) and the category (iii), where outliers of *Kayserberg* station (no. 10) lay in some cases below the outliers for *Strasbourg* station (no. 8).

To make the results clearer, the curves were related to the average daily rainfall ($\overline{Ra}$) only for five selected stations (Figure XXIV). The new curves of the stations situated in the Vosges mountain range differ from the curve of the *Oberentzen* station (no. 14) situated in the Upper Rhine Plain. For *Oberentzen*, the interval of values is much smaller on the x-axis and y-axis compared to the others. Thus the variability of precipitation in the area of the rain shadow is different compared to the mountainous stations – the intensified convection in summer in the lowland stations could not surpass the maxima of category (i) stations. This is supported by the fact that the difference between the average daily rainfalls is about 7 mm: 10.9 mm at *Sewen-Lac Alfeld* (no. 1) in contrast to 3.8 mm for *Oberentzen* (no. 14).

For the category (i), i.e. oceanic stations, precipitation took place on more than 50% of the days, compared to the lowland *Oberentzen* (no. 14) with at most 40% days with precipitation. This supports the statement that for the category (iii) stations the precipitation is more concentrated.

The highest daily totals are typically situated in the Vosges mountain range and the intensified convection in summer in lowland stations could not surpass this maximum.

Nevertheless, the shape of the curves could be influenced by the outliers (extreme precipitation). Thus these outliers could be interesting for future research in this field.

With regards to the absolute daily maxima, surprisingly, in a majority of cases these do not occur at the month of maximum of precipitation. For example, for *Wildenstein* (no. 2), 157 mm of rain fell on the 30th of May in 2000, rather than in December. The very same day a total daily maximum for all the 14 examined stations and the whole study period was reached at the *Mittlach-Erbe* station (no. 5) at 190.5 mm. To examine the synoptic situation is beyond the scope of this paper. However, this is quite frequent in other areas. That is, intensification of convection in one year in summer can produce relatively higher rainfall than in a standard period of maximum rainfall (Heyer 1993). But notice that for the most humid and the driest station the absolute daily maximum occurred in the month of maximum rainfall (169.1 mm for *Sewen-Lac Alfeld* on 29th of December and 68.9 mm on 15th of August for *Oberentzen*).

4. Conclusion

This paper describes a climatological research in a region influenced by orography (the Vosges mountain range and their lee) – from annual to daily rainfall resolution. Three categories of stations are identified based on the differences in the annual temporal distribution of precipitation.

For the first time in the studied area, the ombric continentality is quantitatively described. The Vosges cause a relatively fast transition into a more continental climate in their lee with a maximum of precipitation in summer (Upper Rhine Plain) and not in winter (like in the Vosges). However, some difficulties with empirical formulas are found (e.g. Hrudička's index *k*). For future research in this area it would be interesting to determine a real limit between oceanic climate and climate in transition.

The analysis using the shape of the cumulative distribution function has never been applied before for this region. Nevertheless, the influence of outliers (extreme values) can be high. Thus it is strongly recommended for future research to examine these values.

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RESUMÉ

Klimatologie srážek v oblasti Vogéz

Předmětem článku je klimatologie oblasti Vogéz na základě denních úhrnů atmosférických srážek 14 studovaných meteorologických stanic z oblasti pohoří a jeho závětří (Hornorýnská nížina) za období 1950–2010. Pro odlišnosti v ročním chodu srážek byly stanice rozděleny do tří kategorií: (i) horské s jedním výrazným srážkovým maximem v zimě, (ii) stanice na závětrných svazích se dvěma srážkovými maximy – letním a zimním a (iii) stanice ryze závětrné nacházející se v nížině východně od Vogéz s jedním letním srážkovým maximem. Metody kvantitativního hodnocení stupně ombrické kontinentality vedou ke zjištění, že Vogézy tvoří hranici mezi oceánickým a kontinentálním, resp. přechodným podnebím. Další výzkum zejména extrémních denních úhrnů srážek je však žádoucí.