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Identifying climate analogues for precipitation extremes for Denmark based on RCM simulations from the ENSEMBLES database

K. Arnbjerg-Nielsen, S. G. Funder and H. Madsen

ABSTRACT

Climate analogues, also denoted Space-For-Time, may be used to identify regions where the present climatic conditions resemble conditions of a past or future state of another location or region based on robust climate variable statistics in combination with projections of how these statistics change over time. The study focuses on assessing climate analogues for Denmark based on current climate data set (E-OBS) observations as well as the ENSEMBLES database of future climates with the aim of projecting future precipitation extremes. The local present precipitation extremes are assessed by means of intensity–duration–frequency curves for urban drainage design for the relevant locations being France, the Netherlands, Belgium, Germany, the United Kingdom, and Denmark. Based on this approach projected increases of extreme precipitation by 2100 of 9 and 21% are expected for 2 and 10 year return periods, respectively. The results should be interpreted with caution as the best region to represent future conditions for Denmark is the coastal areas of Northern France, for which only little information is available with respect to present precipitation extremes.

Key words | climate analogue, climate change, design, extreme precipitation, urban drainage

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INTRODUCTION

Climate analogues, also denoted Space-For-Time, aim at identifying locations or regions where the present climate conditions resemble conditions of a past or future climate of another location or region based on some robust climate variables that can be used as predictors of such a change. Within climate change impact studies one of the first applications of this approach was done by [Hallegatte *et al.* \(2007\)](#) who identified suitable climate analogues for 17 cities in Europe, using monthly relative changes of precipitation and monthly absolute changes in temperature as input. [van den Linden & Mitchell \(2009\)](#) used the method on the front cover of the final reporting of the European research project ENSEMBLES, hence giving the method quite some attention. [Bennion *et al.* \(2011\)](#) applied the method to find analogues for the past chemical and ecological state of selected lakes, using fossil diatom assemblages as predictors, and [Arnbjerg-Nielsen \(2012\)](#) applied the method to obtain intensity–duration–frequency (*IDF*) curves for future extreme precipitation in Denmark as one of three downscaling methods using a regional climate model (RCM) simulation from an A2 scenario. In this study, we

used climate analogues to identify locations where current climate resembles future climate in Denmark in order to estimate changes in future extreme precipitation statistics. Compared to the study by [Arnbjerg-Nielsen \(2012\)](#), the main novelty is that the RCM simulations are based on a more recent and comprehensive ensemble of simulations that allow testing of the sensitivity of the findings by means of constructing several analogue metrics and by applying split-sample tests.

DATA AND METHODS

The method consists of two main parts. In the first part, analogue metrics to describe similarity between climate characteristics at different locations for present and future climate are defined. For this part, a tool was developed based on the RCM projections from the ENSEMBLES database ([van den Linden & Mitchell 2009](#)) and the current climate data set (E-OBS) data set of observations ([Haylock *et al.* 2008](#)). This tool is hence generally applicable for

many European locations within the area covered by the ENSEMBLES simulations. The data used in the first part are described in sections ‘European data set of regional climate model simulations’ and ‘European data set of gridded observations of current climate’ and the method in section ‘Calculating climate analogue metrics’. The second part consists of identifying suitable descriptions of extreme precipitation statistics for locations that have been detected as climate analogues for Denmark. The second part is therefore mainly of interest for the case study. The data used in the second part are described in section ‘European data set of design *IDF* curves for urban drainage design’.

European data set of regional climate model simulations

All the RCMs used in this study are from the ENSEMBLES project (van der Linden & Mitchell 2009), and hence based on the A1B emission scenario (Nakicenovic *et al.* 2000). An ensemble of 13 RCMs with a spatial resolution of 0.22 degrees (approximately 25 km) and a temporal resolution of 1 day has been used, see Table 1. The time period covered by the RCMs is 1950–2100. The time periods considered from the RCMs are 1961–1990 and 2071–2100, which are selected to represent present and future conditions, respectively. The change between present and future conditions calculated from the RCMs is added to the data set of current climate (E-OBS) for each grid point when calculating the future climate for the region for which a climate analogue should be identified.

European data set of gridded observations of current climate

The E-OBS data set (Haylock *et al.* 2008; Hofstra *et al.* 2009) is used to represent current climate and estimate the climate indices for current conditions in Europe that are used for calculating the analogue metrics. E-OBS is a gridded daily data set based on the pan-European station network ECA&D (Klein Tank *et al.* 2002). It covers the time period 1951–2012 and uses the same grid as the RCMs.

European data set of design *IDF* curves for urban drainage design

The results reported by Hallegatte *et al.* (2007) and Arnbjerg-Nielsen (2012) are used as a first indication of where suitable locations to represent future Danish climate can be found. The most relevant locations seem to be France, Belgium, the Netherlands, Great Britain, Germany, and Denmark. For each of these countries national standards for design point rainfall are identified as well as statistics on extreme precipitation in the form of *IDF* curves or similar information. A summary is given in Table 2.

Calculating climate analogue metrics

In the following, the term ‘index’ denotes statistics of climatic variables while the term ‘metric’ denotes a numerical ‘distance’ describing the climatic difference between two

Table 1 | Overview of the 13 RCMs used in the study to calculate future climates

Number	RCM	GCM	Institute
1	HadRM3Q0	HadCM3Q0	UK Met Office
2	HadRM3Q3	HadCM3Q3	UK Met Office
3	HadRM3Q16	HadCM3Q16	UK Met Office
4	HIRHAM5	ARPEGE	Danish Meteorological Institute
5	HIRHAM5	ECHAM5	Danish Meteorological Institute
6	HIRHAM5	BCM	Danish Meteorological Institute
7	RACMO2	ECHAM5	Royal Netherlands Meteorological Institute
8	RCA	ECHAM5	Swedish Meteorological and Hydrological Institute
9	RCA	BCM	Swedish Meteorological and Hydrological Institute
10	RCA	HadCM3Q3	Swedish Meteorological and Hydrological Institute
11	REMO	ECHAM5	Max Planck Institute for Meteorology
12	RCA3	HadCM3Q13	Community Climate Change Consortium for Ireland
13	CLM	HadCM3Q0	Swiss Federal Institute of Technology, Zürich

A full description of each of the models can be found in van den Linden & Mitchell (2009). GCM: global climate model.

Table 2 | Overview of precipitation data and design guidelines for the relevant countries

Country	Methodology and data	Reference
France	No national regional model exists and data are difficult to obtain. Data from 50 locations have been obtained from an old publication with no information about length of records or other supporting information.	Coste & Loudet (1987)
Belgium	The precipitation series from Uccle close to Brussels has been used in numerous studies. No other data could be identified. Measurement period is larger than 100 years.	Willems (2013a)
The Netherlands	The Netherlands uses data from one gauge in de Bilt to design sewer systems throughout the country. These data were collected from 1906–1990.	Buishand & Wijngaard (2007)
Great Britain	A regional model for Great Britain exists, yielding local design storms for any location. Most records have an observation period of more than 20 years.	Faulkner (1999)
Germany	A regional model for Germany exists based on a network of gauges with measurements from 1951–2000.	Malitz G. (2005)
Denmark	A regional model for Denmark exists, yielding local design storms for any location. The model is based on data from 1979–2012. Both the regional model as well as the local precipitation time series are available.	Madsen <i>et al.</i> (2009, in preparation).

locations separated in space and/or time based on an assessment using one or more indices. A low metric corresponds to high climatic similarity, and if the metric is zero the locations are identical with respect to the applied indices.

The following indices are used to compute the metrics:

- Monthly mean temperature.
- Monthly standard deviation of daily temperature.
- Monthly mean precipitation.
- Monthly standard deviation of daily precipitation.
- Monthly proportion of dry days.
- Extreme value statistics of daily precipitation.

For each of the monthly indices, a distance metric at each location in Europe is calculated as

$$S_i = \frac{\sqrt{\sum_{k=1}^{12} (x_{c,k,i} - x_{p,k,i})^2}}{\sqrt{\sum_{k=1}^{12} x_{p,k,i}^2}}$$

where $x_{c,k,i}$ is the monthly value of index i of the current climate for each location in Europe, and $x_{p,k,i}$ is the projected monthly value of index i at the location (or average value for a region) for which a climate analogue is wanted.

Similarly, for the index based on extreme value statistics, the similarity metric is calculated as

$$S_i = \frac{\sqrt{\sum_{k=1}^N (x_{c,k,i} - x_{p,k,i})^2}}{\sqrt{\sum_{k=1}^N x_{p,k,i}^2}}$$

In this case, the metric is based on a number (N) of estimated extreme precipitation for different return periods

(T -year events). In the current setup, N is 2, using 1 and 10 year events, respectively.

Finally, an overall analogue metric is calculated as

$$S_{\text{agg}} = \sum_i w_i S_i$$

where w_i are user-defined weights for the different indices.

Denote by M the location (or region) for which a climate analogue is wanted. We will then use the term ‘climate analogue metric for location (or region) M ’ to denote the metric of the current climate at a specified location using a projected future climate at location (or region) M .

RESULTS

Metrics for future Danish climates compared to current European climate based on each index

Figure 1 shows the area used to represent the future Danish climate. It corresponds to all grid points within the E-OBS data set that are considered land cells and where the majority of the land is within the Danish borders. Figure 2 shows the spatial distribution of the climate analogue metrics for Denmark using all RCMs in calculating the projected future for 2070–2100. The two metrics based on temperature have lowest values in western and southern Europe. The metric based on mean precipitation has

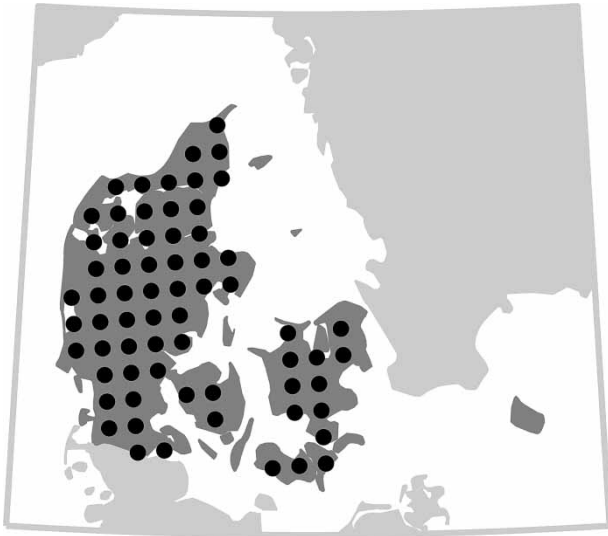


Figure 1 | Grid points used to represent future Danish climate.

lowest values along the coastline from Denmark to northern France and southern part of the United Kingdom. The three other metrics based on precipitation are more diverse with low values in several regions, especially, the metric based on extreme precipitation statistics. The metrics for extreme precipitation are clearly affected by topography, but also other factors are relevant. The reasons for the spatial heterogeneity are not the main focus of the study and will hence not be studied further.

Identifying European locations with low metric for future Danish climate

The weights used to calculate the aggregated climate analogue metric for Denmark are shown in [Table 3](#), and the corresponding metric for locations in Europe is shown in [Figure 3](#). The results shown in [Figure 3](#) are based on average

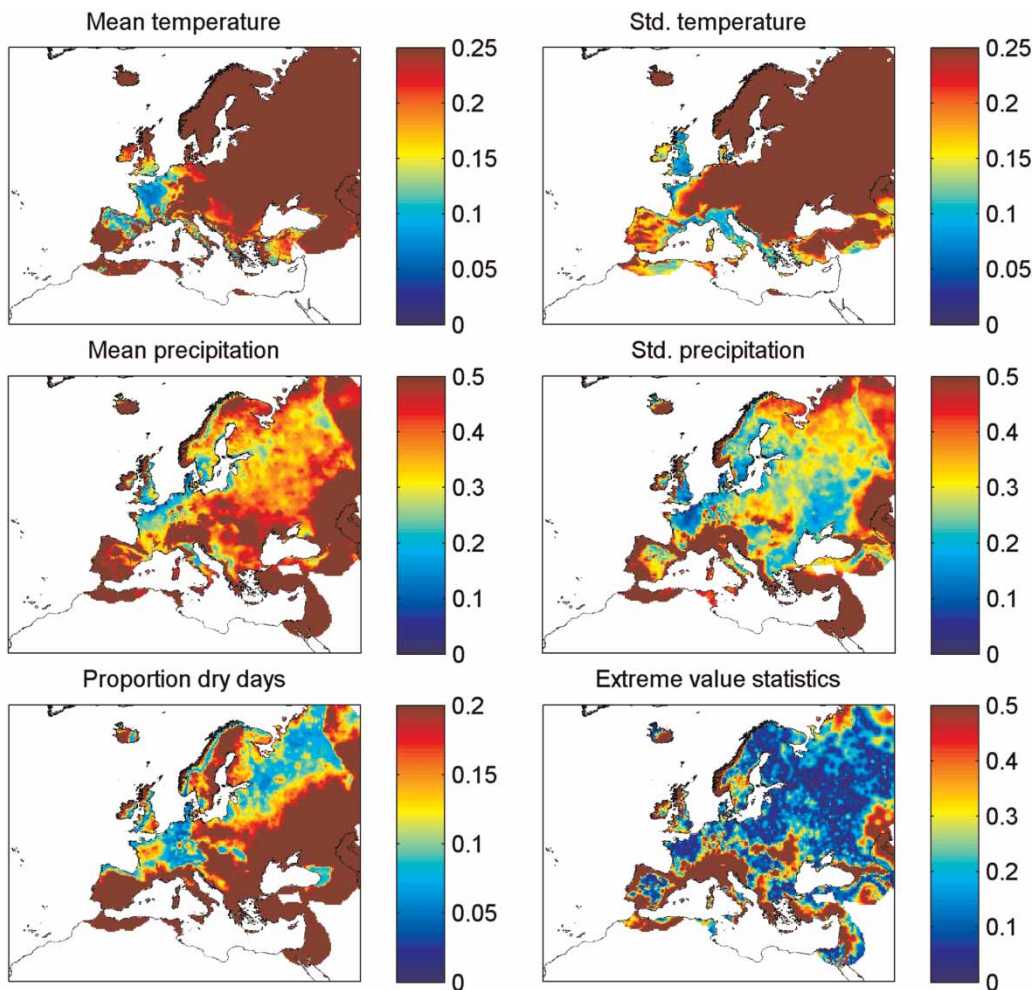


Figure 2 | Spatial distribution of the climate analogue metrics for Denmark based on each index separately. The metric is calculated for each grid point using output from the mean value of all 13 RCMs for the projected future 2070–2100.

Table 3 | Weights applied to the aggregated metric

	Main	S1	S2	S3	S4
Temperature, mean	2/9	1/7	1/4	1/5	1/2
Temperature, standard deviation	1/9	1/7	0	1/5	0
Precipitation, mean	2/9	1/7	1/4	1/5	1/2
Precipitation, standard deviation	1/9	1/7	0	1/5	0
Proportion of dry days	1/9	1/7	1/4	1/5	0
Precipitation extremes	2/9	2/7	1/4	0	0

The metric Main is the one that in the authors subjective opinion should be applied, while the weights S1–S4 correspond to other weights that have been analysed.

projected changes of the indices using all RCMs for the period 2070–2100 listed in Table 1. Since the choice of weights and RCMs may be critical to the outcome, sensitivity tests were carried out. Firstly, the weights used in the aggregation were modified from the subjectively chosen optimal set (denoted ‘Main’ weights) to more uniform weighting and use of only a subset of the indices. In total, four modifications were carried out, including the very simple weights applied by Hallegatte *et al.* (2007), where only the monthly mean precipitation and temperature indices were considered. The weights are shown in Table 3. Secondly, a split sample of the RCMs was carried out. We use the results reported by Sunyer *et al.* (2013a), who analysed the interdependency between the RCMs to define an optimum split in two samples that show the largest degree

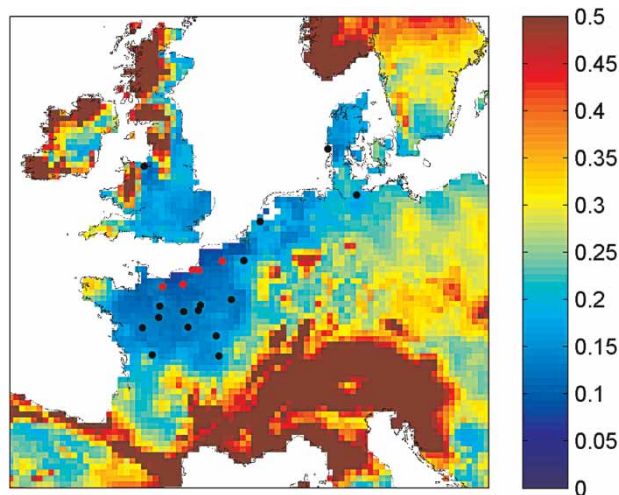


Figure 3 | All identified stations with a metric below 0.175 shown together with the metric Main for climate analogues for Denmark using all RCMs for the period 2070–2100. Stations are marked with circles. Red colour denotes the five stations with the lowest metric based on the value of the metric of the grid cell in which they are located.

of independence. These two samples correspond to, respectively, RCMs 1–6 and 7–13 in Table 1.

The results of the analysis are shown in Table 4 for selected locations in Europe. The locations are selected because they have a low climate analogue metric for Denmark using the ‘Main’ weights including all RCMs. For the countries that have a national model for *IDF* estimations (see Table 2) the location with the lowest metric is selected. For France no national model exists and hence all stations with a lower metric than the ones from the other five countries are included, corresponding to 16 locations. To avoid correlation between the French stations they are included only if the minimum distance to another location is larger than 60 km.

Table 4 shows that the ranking of locations are robust to the choice of aggregation weights and RCM sample, and in particular the French stations with the lowest metric perform equally well regardless of the choice of aggregation weight and RCM sample. All of the stations with the lowest climate analogue metric for Denmark are situated in northwestern France close to the Atlantic coast. Hence, this region seems to be a robust climate analogue for Denmark for 2070–2100.

Identifying future design rainfall for Denmark based on climate analogues

In principle, the *IDF* curves from the coastal areas of Northern France could be used directly when designing urban drainage systems in Denmark incorporating anticipated future changes. Indeed, if the optimal climate analogue had been from any of the other five countries in Table 2 this would have been the preferred procedure. However, there are two shortcomings that make this approach problematic:

- The French data only provide *IDF* curves for durations between 5 minutes and 6 hours and for return periods 1, 2, 5, and 10 years. Extrapolation to other durations and return periods are not directly possible.
- The analogue metric does not give a clear indication which station in France is the best station because the numerical values of the metric are very close. However, the differences in design intensities between these stations are quite large, and it is not clear if these differences are due to sampling uncertainty (i.e. uncertainty because of a short observation period) rather than actual differences that can be explained by the spatial patterns within the region.

Table 4 | Results for overall climate analogue metric for Denmark for 2070–2100 for all candidate European locations

Country	Stations	Metric, All, Main	Rank, All, Main	Rank, RCM 1–6, Main	Rank, RCM 7–13, Main	Rank, All, S1	Rank, All, S2	Rank, All, S3	Rank, All, S4
F	Caen	0.089	1	2	1	1	1	2	4
F	Saint-Quentin	0.093	2	1	2	2	2	1	1
F	Rouen	0.100	3	3	3	3	3	3	2
F	Abbeville	0.107	4	4	5	5	5	5	3
F	Lille	0.110	5	5	6	6	4	7	7
GB	Liverpool	0.111	6	7	4	4	6	4	6
DK	Esbjerg	0.123	7	9	7	7	7	6	18
F	Le Mans	0.130	9	8	8	9	8	10	8
F	Chartres	0.128	8	6	9	8	10	12	13
F	Orleans	0.135	10	11	10	10	11	14	12
F	Reims	0.137	11	10	11	11	9	18	16
F	Bretigny	0.140	12	12	14	12	15	17	17
F	Angers	0.144	13	13	15	15	18	16	14
F	Alencon	0.145	14	15	13	14	12	11	10
NL	Amsterdam	0.147	15	19	12	13	13	8	5
F	Paris	0.154	16	14	18	16	21	13	15
F	Poitiers	0.155	17	18	17	17	17	15	9
F	ChateauxChinon	0.156	18	17	16	18	14	19	19
F	Auxerre	0.161	19	16	19	21	16	21	20
B	Uccle	0.170	20	21	20	19	19	9	11
D	Luebeck	0.171	21	20	21	20	20	20	21

Each column is described by three attributes, metric or rank (value or internal ranking), what RCMs are used to calculate the metric (All, RCM 1–6, RCM 7–13), and weights (Main, S1–S4, as defined in Table 3).

Therefore, the approach taken is to identify a relative change in the design intensities for return periods of 2 and 10 years, known as delta change factors or climate factors (Arnbjerg-Nielsen 2012). This factor can then be compared to results using other downscaling approaches and also allow extrapolation to other return periods and/or durations.

Figure 4 shows the *IDF* curves from the French stations for a return period of 2 years as well as the regional mean of the current Danish recommended design intensities (Madsen *et al.* in preparation). There is quite a variation between the French stations as discussed above. There is no clear distinction between the French and Danish *IDF* curves, showing both smaller and larger precipitation intensities depending on location and duration. The shape of the Danish curve for the current climate is slightly different, especially for the short durations. This is most likely because the French *IDF* curves are constructed using a two-parameter description, whereas the Danish *IDF* curves are constructed using a three-parameter description.

The *IDF* curves shown in Figure 4 and similar curves constructed for the 10 year return period are used to derive mean, minimum, and maximum climate factors for durations between 5 minutes and 6 hours, see Figure 5.

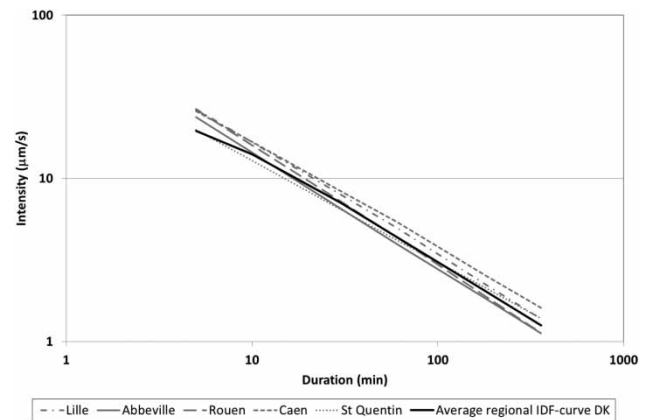


Figure 4 | *IDF* curves for the best five French stations compared to the current regional average *IDF* curve in Denmark for a return period of 2 years.

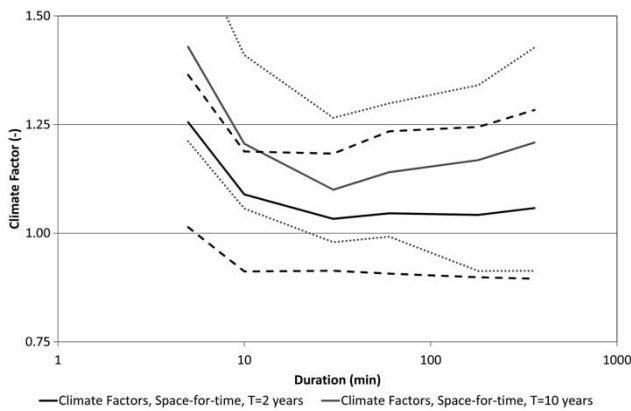


Figure 5 | Calculated mean climate factors for each duration for return periods 2 and 10 years based on the five French stations. Solid lines indicate mean values, and dashed and dotted lines indicate the maximum and minimum climate factor for 2 and 10 year return periods, respectively.

Based on the calculated values the mean climate factor for a return period of 2 years is 1.09 with a range between 0.89 and 1.36, and the corresponding values for a 10 year return period are 1.21 with a range between 0.91 and 1.69.

DISCUSSION AND CONCLUSION

The results of this study show that the coastal area of northwestern France is a good climate analogue for Denmark for the period 2070–2100 when using a moderate climate scenario such as A1B. It is robust to the choice of climatic variables that are used to identify the region and there is no other area in Europe that has an equally good resemblance with the anticipated future climate for Denmark.

The available *IDF* curves from this French region are used to calculate climate factors for anticipated future extreme precipitation statistics in Denmark. These factors are relatively low compared to other findings, in particular Arnbjerg-Nielsen (2012) and Sunyer *et al.* (in press). Arnbjerg-Nielsen (2012) used a climate analogue method for the same region and reports higher climate factors than found here. This is mainly due to a change in recommended design intensities for current climate, but also because of the use of different RCM projections. This highlights the importance of the uncertainty of observations in relation to assessing future climatic changes as discussed in Sunyer *et al.* (2013b) as well as the importance of natural climate variability as highlighted by, e.g. Willems (2013b). Sunyer *et al.* (in press) also reports higher climate factors by using other downscaling approaches, a delta change

method for extreme events and a weather generator approach. However, as discussed by Sunyer *et al.* (in press) and others (e.g. Gregersen *et al.* 2013) these downscaling approaches have weaknesses, especially for sub-daily precipitation extremes. Hence, the climate analogue is a valuable tool for identifying properties of future precipitation extremes because it can utilise more robust information from the regional climate models and can combine different climatic indices that are expected to represent extreme precipitation regimes. The risk of lack of suitable extreme precipitation data from the identified region is a shortcoming of the method as our case study clearly indicates.

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