

1 *Variations in sub-daily precipitation at centennial scale*

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11 Short-term precipitation events with high intensities govern the dynamics of numerous fast
12 hydrological processes like flash floods¹ in urban areas and soil erosion² in agriculture. It is expected
13 that precipitation events will intensify as a consequence of climate change³⁻⁸. Due to data availability
14 long-term variations in precipitation rates are mostly studied based on daily precipitation recordings⁹⁻
15 ¹² while recent research suggests that variations in sub-daily precipitation are subject to higher
16 dynamics compared to daily precipitation and a more rapid intensification is likely^{4,13}. Here we show
17 that both observational data with at least 58 years of sub-daily precipitation records and a minimal
18 dynamical downscaling approach based on atmospheric re-analysis data confirm these expectations
19 with consistent results. High quantiles of precipitation are subjected to multi-decadal oscillations and
20 increased during the last 150 years. For the 2000s we found positive anomalies in high precipitation
21 quantiles relative to the reference period 1850 – 2014 of $6\% \pm 5\%$ (daily), $13 \pm 6\%$ (hourly), and $14\% \pm$
22 6% (10 min), which is consistent with Clausius-Clapeyron- (CC) and super CC-scaling, respectively.

23 These findings highlight that dynamical downscaling can help to reliably shed light on sub-daily
24 precipitation variations if small timescales are considered in the experiments.

25 Recent studies focused on unravelling the relationship between temperature and precipitation
26 which follows the Clausius-Clapeyron (CC) equation suggesting that precipitation extremes – or more
27 specifically the saturation vapor pressure – increase by 7% per degree of warming^{9,14} or even exceeding
28 this rate (super CC-scaling)^{3,4,14,15}. Trend analyses involving long-term records of precipitation extremes
29 are mostly in agreement with these findings in view of the fact that two thirds of stations worldwide
30 showed increasing trends¹². Other studies found more stations with negative than positive trends in
31 summer precipitation extremes in Europe¹⁰. Moreover, since temperature-precipitation-scaling also
32 shows decreasing rates above a certain temperature or dewpoint level, it is argued that these scaling
33 approaches are not valid under all possible conditions and thus they are not suitable for projecting
34 changes in precipitation extremes¹⁶.

35 Global Circulation Models (GCMs) and Regional Climate Models (RCMs) are capable of
36 representing changes in precipitation characteristics at longer time scales (e.g., seasonal)⁴. Their
37 applicability to reconstruct changes in sub-daily precipitation is viewed uncertain due to (i) missing
38 validation data at sub-daily time scales with sufficient record length and the (ii) uncertainties involved
39 in convection parametrizations which are needed for grid spacings larger than 5 km^{4,8}. Recent
40 convection-resolving RCMs with higher spatial resolution below 5 km do not need such
41 parameterizations and thus are viewed promising for simulating sub-daily rainfall^{4,6,8} even though they
42 are still subjected to uncertainties^{4,16}. However, coarser scale GCM and RCM simulations are still
43 capable to represent relevant characteristics of sub-daily precipitation extremes^{14,17,18}. They also
44 reproduce temporal changes and trends on decadal scales¹⁹. For climate projections on the global scale
45 convection parameterizations are still relevant since convection-permitting models are demanding in
46 terms of computational resources^{4,16}.

47 Even though the availability of long-term records of sub-daily precipitation is very limited, these
48 findings highlight the relevance of validating RCMs and GCMs in terms of their ability to predict sub-
49 daily precipitation and its sensitivity to climate variability and more specifically climate change. Climate
50 variability including both natural climate variability and anthropogenic forcing affect changes in
51 precipitation extremes over time¹³, whereby natural climate variability can mask the anthropogenic
52 signal caused by greenhouse gas emissions²⁰. While long-term records of daily precipitation are in
53 general more readily available^{1,21} and reflect higher evidence^{9–12}, only a few studies focus on sub-daily
54 precipitation^{8,13,22}. Transferring results from analyses involving daily precipitation to smaller temporal
55 scales is not reliable due to the higher temperature sensitivity of precipitation processes relevant at
56 time scales below one day⁴.

57 In this study, we address the impediment to validate sub-daily precipitation simulations under non-
58 stationary conditions imposed by climate variability and climate change through compiling long-term
59 records of sub-hourly precipitation to provide a comprehensive dataset for model validation. We
60 analyse a set of sub-daily precipitation records in Austria, Belgium, Germany and the Netherlands with
61 a temporal coverage of at least 58 years and a temporal resolution not coarser than one hour. Our
62 analyses focus on the temporal variability of sub-daily precipitation at multi-decadal to centennial time
63 scales extending earlier work^{13,22}. Based on that, we test the hypothesis that the variability found in
64 observed records can be reconstructed using a minimal dynamical downscaling approach based on
65 reanalysis data and a convection parameterization. This approach complements ongoing research on
66 temperature scaling and validating models regarding their capability to reproduce sub-daily
67 precipitation by focusing on downscaling reanalysis data. Therefore, we utilize the Weather Research
68 and Forecasting Model²³ (WRF) to downscale the Twentieth Century Reanalysis Project dataset²⁴ to a
69 spatial and temporal resolution of 30 km and 10 minutes, respectively. The spatial domain covers
70 Central Europe and the temporal coverage is 1850 – 2014, which allows one to analyse variations from
71 the end of the Little Ice Age (LIA) to near present. Since we apply a coarse regional model which needs
72 a convection parameterization to compute grid cell averages of convective precipitation that are not

73 directly comparable to station observations, we compare the observed and modelled variability in sub-
74 daily precipitation in terms of anomalies computed as mean of the 95th, 99th, and 99.5th percentiles
75 (Methods).

76 Anomalies are computed for each station in Figure 1 with overlapping sub-periods of 15 years.
77 Similarly, the same procedure is applied to the downscaled time series derived from the nearest grid
78 point of the model. Figure 2 shows a comparison of these anomalies computed for observed and
79 modelled time series at the Uccle station. Different aggregation levels have been considered in order
80 to highlight variations across process-relevant time scales. The comparison among these temporal
81 resolutions show that the variability of each aggregation level shows a similar course with three
82 maxima, the first in the early 20th century, a second one in the 1960s and another maximum in the
83 near present. Similarly, minima occur in the 1930s and the 1970s. From the variations achieved for the
84 observational data a slight tendency towards higher variability with decreasing aggregation level is
85 obvious. The downscaled anomalies match the temporal pattern of the observed anomalies very well
86 for this station. However, the differences among aggregation levels are smaller and the overall
87 variability reflects smaller amplitudes.

88 In the next step, we systematically analysed all stations in a similar way (Supplementary Figure 1)
89 and summarized the comparison for each station and aggregation level in a Taylor diagram²⁵ (Figure
90 3). Here, for reasons of readability, only stations with at least 60 years of data are shown and the full
91 record length is considered for each (the other stations are shown in Supplementary Figure 2). In terms
92 of correlation, the results suggest on average a reasonable to good match of the phase (sequence of
93 minima and maxima in the oscillating temporal course). Pearson correlations range from 0.2 to 0.95.
94 Except for Oberhausen, sub-daily anomalies show better correlations than daily anomalies. Regarding
95 the variability, the results suggest an underestimation of amplitudes, since the majority of points has
96 a normalized standard deviation smaller than 1. The RMSE ranges from around 0.5 to 1.25, whereby
97 the majority of runs is characterized by RMSE values smaller than the normalized standard deviation
98 of 1. For Uccle, we see correlations around 0.7 for 10 min and 1 h, while the correlation drops to 0.6

99 in case of daily data. Similarly, RMSE increases from around 0.7 to 1.0, also suggesting a drop in model
100 performance. The variability is underestimated for sub-daily data (< 1), while daily data matches the
101 variability well (around 1). This observation is in line with the results found in Figure 2. Good results
102 are also found for Duisburg and Soest. The model performance achieved for Andelsbuch near the Alps
103 is also good, at least for sub-daily data. In contrast, the coincidence is generally lower in case of De Bilt
104 and Oberhausen. However, apart from these deficiencies, the minimal dynamical downscaling
105 approach is capable of representing the variability of high precipitation percentiles across Central
106 Europe.

107 In order to visualize spatial patterns of variations in high precipitation percentiles computed for 10
108 min aggregation level, Figure 4 compiles a series of maps ranging from the end of the LIA to near
109 present. The maps show that anomalies are heterogeneous in terms of their spatial distribution for
110 each period considered in the maps. Some regions show higher variability (e.g., Northern Germany
111 and Northern Italy), while other regions are subjected to smaller variation (e.g., the regions around
112 the Alps). For instance, the absolute values computed for Andelsbuch are smaller than those computed
113 for the Northern European Plain (including the Netherlands and Northern Germany). The lower part
114 of Figure 4 is a time series of the spatial mean including each map and intermediate steps. The
115 temporal evolution of high precipitation anomalies is in line with those achieved for observed data.
116 From Figure 4 it is obvious that multi-decadal variations found in the observational data (which are
117 mostly in agreement when considering a cross-station comparison) seems to be valid at larger scales
118 as well. Moreover, differences in the amplitudes among different aggregation levels are also visible for
119 large spatial averages suggesting that sub-daily anomalies in high precipitation percentiles are
120 subjected to higher variability in the past 150 years.

121 The results achieved in the framework of this study highlight that high precipitation percentiles
122 are subjected to multi-decadal oscillations at the centennial scale and that these variations are
123 captured by the minimal downscaling experiment. Moreover, we were able to demonstrate that
124 different aggregation levels of the precipitation time series reflect different magnitudes of variations,

125 whereby sub-daily variations are characterized by higher magnitudes than those achieved for daily
126 time series. This outcome is in line with recent findings^{4,13}. In contrast to earlier work we utilized a
127 larger set of long-term station datasets with sub-daily resolution which allows us to more
128 comprehensively validate the minimal downscaling approach based on reanalysis data, which was
129 found to perform reasonably well, albeit its simplicity. Although the validation data is clustered around
130 the Netherlands and Western Germany, the results achieved for Andelsbuch display that the lower
131 variability found for the Alpine region is also captured by the model.

132 Nevertheless, this study is based on a range of assumptions: (i) First, due to the limitation in terms
133 of data availability, different length of time series is relevant. A direct comparison among all sites is
134 only possible when starting the analyses in 1957. (ii) From a historical overview of measuring sub-daily
135 rainfall^{26,27}, it becomes evident that the homogeneity of time series is a source of uncertainty due to
136 changes in instrumentation within long records. Little is known about changes in instrumentations for
137 most sites. For some sites, changes in instrumentation have been reported (e.g., De Bilt²⁸). We applied
138 the time series 'as is' which means that the analyses might be subjected to uncertainties arising from
139 inhomogeneities relevant for specific characteristics of the time series. (iii) The combination of 30 km
140 spatial resolution with a small domain and 10 minutes temporal resolution is not a common approach.
141 However, this setup is viewed as a compromise considering computational costs and data storage
142 requirements on the one hand and the focus on variations in rainfall characteristics rather than event-
143 based considerations on the other. Even though WRF is a proven model that has been tested for
144 various spatial resolutions^{29,30}, improved simulations are expected if the model is employed with
145 convection-resolving resolution^{6,8}. While Knist et al.³⁰ found that the super CC-scaling is not captured
146 well by a non-convection permitting resolution in WRF, the results indicate CC scaling (daily
147 aggregation level) and super-CC-scaling (sub-daily aggregation levels) .

148 Besides the limitations of the approach demonstrated here, the results are promising to better
149 validate GCMs and RCMs in terms of their capability to simulate long-term variations in sub-daily
150 precipitation. This is especially relevant, since Westra et al.⁴ identified temporal scaling across different

151 aggregation levels as one key element relevant for validating RCMs and GCMs in terms of precipitation
152 extremes. This study demonstrates that even a minimal dynamical downscaling approach is capable of
153 reconstructing temporal variation in high precipitation percentiles at the centennial scale. The latter
154 also emphasizes that trend analyses – as usually done for the past three decades only in case of sub-
155 daily rainfall – are critical, since both increasing and decreasing trends have been detected similarly
156 throughout the last decades^{10,12} for different spatial and temporal scales. Our results reveal that for
157 some stations a decline in high precipitation percentiles is found and that this decline is also computed
158 by the minimal downscaling approach. This suggests that temporal scaling as key criterion to validate
159 models should also involve the role of climate variability which might obliterate temperature-
160 precipitation scaling²⁰, at least at the decadal scale as it is evident from the time series of anomalies.

161 A better validation of downscaling approaches regarding their accuracy in sub-daily precipitation
162 modelling is highly relevant for the simulation of future climates with different modelling approaches
163 including GCMs (which still require convection parameterizations) and RCMs with improved spatial
164 resolution and hence an expected increase in the representation of precipitation processes with
165 emphasis on convection. This has also major implications on attribution studies to analyse to what
166 extent anthropogenic forcing contributes to an increase in precipitation extremes.

167 *Methods*

168 Table 1 provides a summary of the stations involved in our study, while Figure 2 shows a map
169 including the location of each rainfall station. The data was obtained from the data providers listed in
170 Table 1. Except for the most relevant meta data (e.g., coordinates, elevation) little is known about
171 other relevant information relevant for this study like changes in instrumentation or corrections
172 applied to the data. For the Uccle station, a historic overview³¹ and detailed analyses exist^{13,32}. The
173 data observed at De Bilt was also subject to numerous analyses relevant to this study^{14,22}. The De Bilt
174 dataset available to the authors was corrected by the data provider in order to account for a correction
175 of the gage height and changes in surface area of the funnel²⁸. According to the providers, the data has

176 been checked carefully which is why we utilize the data in our study 'as is'. The minimum temporal
177 resolution of all time series is at least one hour (Tab. 1). Andelsbuch , Duisburg H. (Hülsermanngraben),
178 Duisburg S. (Schmidthorst), Oberhausen, Soest, and Uccle are stations with sub-hourly time series.

179 Precipitation intensities with a temporal resolution of 10 min are computed from the end of the
180 little ice age (LIA) to near present utilizing the Weather Research and Forecasting Model (WRF)²³ forced
181 by the Twentieth Century Reanalysis Project dataset version 2c (TCRP)²⁴ which provides meteorological
182 fields at arbitrary levels every 6 h. The re-analyses dataset acknowledges the fact that radiosonde and
183 remote sensing data were not available in the 19th century, which is why surface and sea level pressure
184 were used as input to the data assimilation. This dataset has been applied in many studies that focus
185 on the climate in past periods especially those considering the end of the LIA or the early 20th century^{33–}
186 ³⁷. The following is a list of parameterizations that have been chosen for the downscaling experiment:
187 Morrison two-moment bulk microphysics³⁸; Kain-Fritsch convection scheme³⁹, Yonsei University
188 boundary layer scheme⁴⁰; Noah land surface model (LSM)⁴¹; Dudhia shortwave numerical scheme⁴²;
189 and the Rapid Radiative Transfer Model for longwave radiation⁴³. WRF was set-up for a domain
190 covering Central Europe, the Alps (to avoid coincidence of the boundary with mountain ranges) and
191 Northern Italy with a single domain covering 64 rows, 44 columns, and 40 vertical levels. This step has
192 been performed using the WRF Pre-processing System (WPS) in order to generate the 6-hourly input
193 files for the period 1851 – 2014 based on the TCRP dataset. The corresponding internal time step is
194 150 seconds. The output is 600 s corresponding to the target temporal resolution of 10 minutes, which
195 is an integral multiple of the internal time step.

196 In this study we focus on high precipitation percentiles of 95th, 99th, and 99.5th for which we explore
197 centennial scale variations. These percentiles were also studied by Lenderink et al²². Since the
198 downscaling experiment has a spatial resolution of 30 km, convective events are only considered
199 through a convection parameterization and the precipitation total per time step is an average
200 representative for a grid cell. Thus, a direct comparison of rainfall extremes (e.g., partial or annual
201 series as described by Willems¹³) derived for both the observed data and the model is not feasible.

202 However, the focus on high percentiles instead of extreme value distributions derived utilizing partial
203 or annual series is beneficial, since rolling averages over extremes along the time axis might introduce
204 oscillations caused by single extreme events⁴⁴ if not considered with special care⁴⁵.

205 For overlapping periods of 15 years¹³ the average of the 95th, 99th, and 99.5th percentiles $\hat{P} =$
206 $\overline{(P_{95}, P_{99}, P_{99.5})}$ is computed for both the station data and the corresponding grid point in the model.
207 Based on this definition, we compute anomalies for each period of 15 years $n_{\text{sub period}}$ by involving the
208 corresponding average achieved for the entire period (Eq. 1):

$$n_{\text{sub period}} = \frac{\hat{P}_{\text{sub period}} - \hat{P}_{\text{full period}}}{\hat{P}_{\text{full period}}} \cdot 100\% \quad (1)$$

209 This approach yields an annual series of anomalies in which each year represents an average
210 information of 15 years from seven years before and seven years after the considered year. These
211 anomalies are computed for different aggregation levels ranging from 10 min, to 1 h and 24 h
212 representing time scales relevant in different applications in hydrology. For instance, 10 min rainfall is
213 relevant for urban hydrology, torrential flow and flash floods, while hourly values are suitable for
214 studying floods in small catchments. The daily resolution makes the results comparable to many more
215 studies that involve daily rainfall totals only. This temporal scale is also relevant for a lot of applications
216 in hydrology ranging from floods in large river basins to water balance studies. Anomalies computed
217 for observed and modelled time series can be compared using different measures including Pearson
218 correlation. Here, we combine correlation with a comparison of the standard deviation of both time
219 series and the Root Mean Square Error (RMSE) in a Taylor diagram²⁵.

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225 Institute (KNMI), and the Royal Meteorological Institute of Belgium (KMI – IRM).

226 *Author Contributions*

227 KF designed the study, compiled the data, and performed the dynamical downscaling experiment. LT
228 further developed the statistical analyses. Both authors discussed the results.

229 *Competing Interest statement*

230 The authors declare that they have no conflict of interest.

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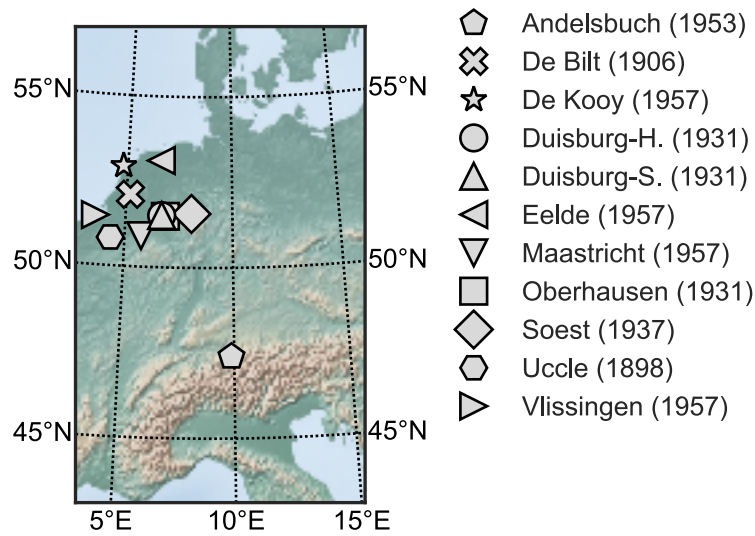
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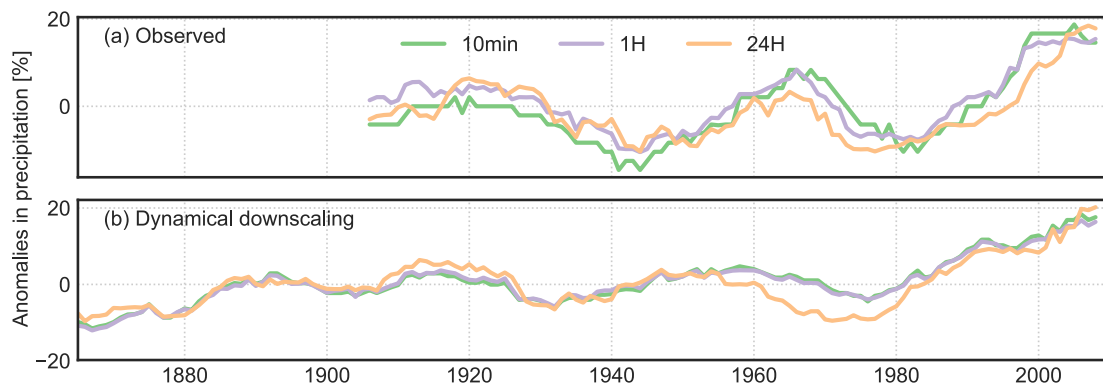
335 *Figures and tables*



336

337 **Figure 1:** Map of stations investigated in this study. The number in parentheses indicates the year
 338 when recordings began for each station.

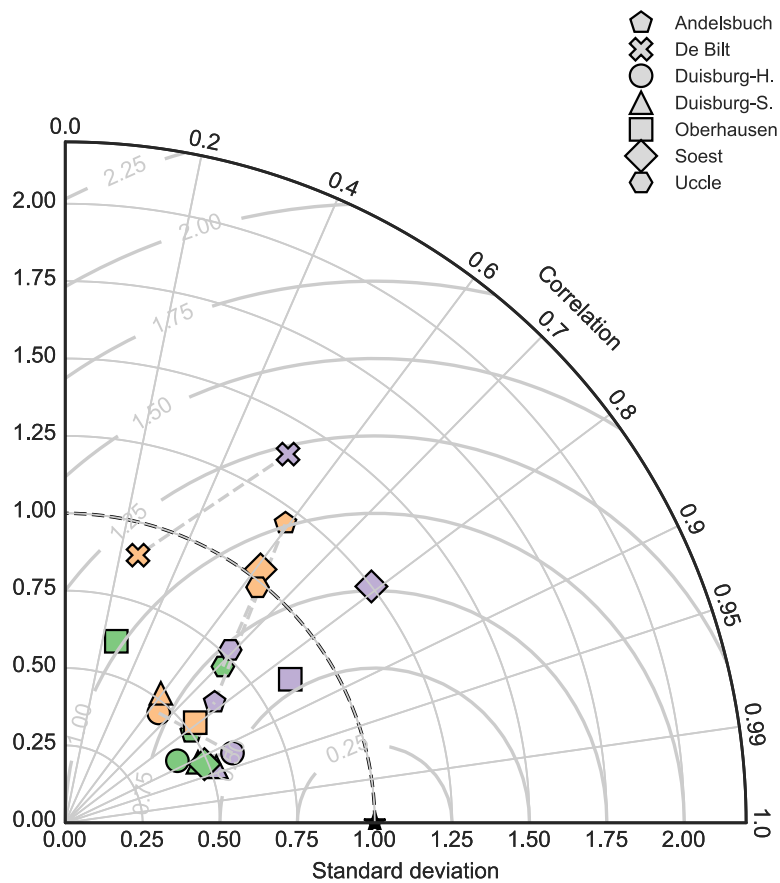
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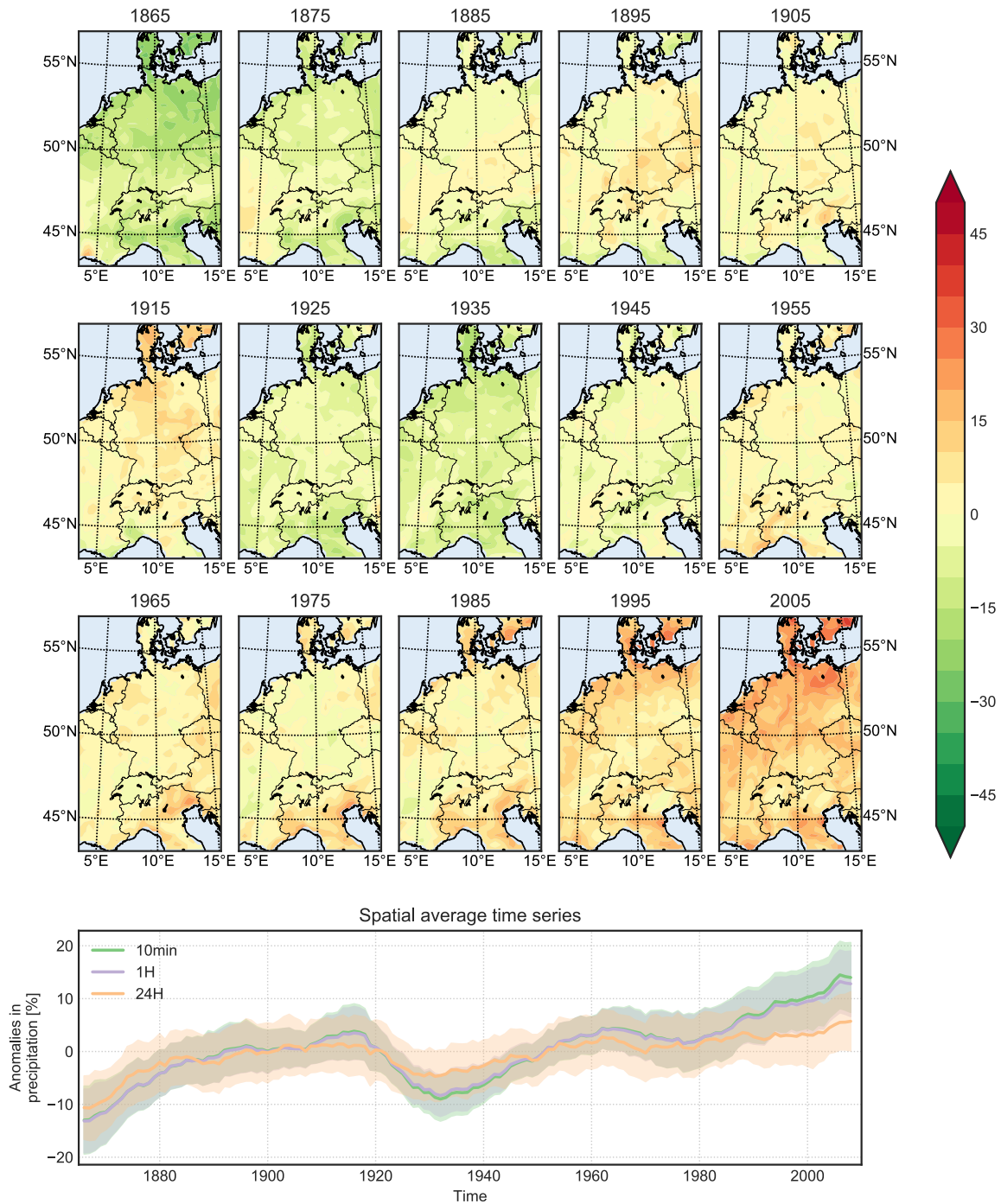
341 **Figure 2:** Anomalies computed for observed and modelled time series for the Uccle station. The input
 342 resolution of 10 min is also aggregated to 1 h and 24 h, respectively. (a) observed time series and (b)
 343 modelled time series computed utilizing the minimal dynamical downscaling approach.

344



345

346 **Figure 3:** Taylor diagram²⁵ including all stations with at least 60 years of data, mostly representing
 347 stations with sub-hourly resolution. For each station the full length of the time series is considered.
 348 Each comparison is represented by one single point. Aggregation levels are represented by different
 349 colours (10 min: green, 1 h: blue, 24 h: orange). Ordinate and abscissa refer to the standard deviation
 350 of the time series. The radial distance between each point and the origin represents the normalized
 351 standard deviation of the model run (corresponding observation is 1). The angle between the abscissa
 352 and the lines representing the shortest distance of each point to the origin is related to the correlation
 353 between observation and model run. The geometric relationship in the Taylor diagram also
 354 incorporates the central pattern root mean square error (RMSE) computed for the observation and
 355 the model run. The RMSE corresponds to the concentric isolines which are centred around the
 356 observation point. The latter has the following characteristics by definition: its standard deviation is 1,
 357 the correlation is 1 and the RMSE is 0.²⁵



359

360 **Figure 4:** Series of maps showing the spatial distribution of the anomalies in 10 minutes high
 361 percentiles precipitation for every ten years from the end of the LIA to near present. Precipitation
 362 anomalies are derived through the mean of the 95th, 99th, and 99.5th percentiles computed for moving
 363 windows of 15 years, while the reference period is 1850 – 2014. In the bottom panel the spatial

364 average of the domain shown in the maps is displayed as time series plot for different aggregation
 365 levels (10 min, 1 h, and 24 h). Coloured bands denote \pm one standard deviation. For the last decade
 366 (i.e., the 2000s) we found positive anomalies in high precipitation quantiles relative to the reference
 367 period 1850 – 2014 of $6\% \pm 5\%$ (daily), $13 \pm 6\%$ (hourly), and $14\% \pm 6\%$ (10 min). Since 1950, when
 368 anomalies were around 0% for the last time, the mean temperature increased by 1K suggesting that
 369 the aforementioned positive anomalies are in line with CC-scaling (daily aggregation level) and super-
 370 CC-scaling (sub-daily aggregation levels), respectively.

371

372 **Table 1:** List of stations involved in the study. The data was obtained from the respective data
 373 providers. The column 'Obs. Started' indicates when the time series begin and the last column denotes
 374 the temporal resolution.

Station	Country	Data provider	Obs. Started	Resolution
Andelsbuch	AT	Ministry of Sustainability and Tourism / Hydrographic Office	1953	< 1 min
De Bilt	NL	Royal Netherlands Meteorological Institute (KNMI)	1906	1 h
De Kooy	NL	Royal Netherlands Meteorological Institute (KNMI)	1957	1 h
Duisburg H. (Hülsermanngraben)	DE	Emschergenossenschaft & Lippeverband	1931	1 min
Duisburg S. (Schmidthorst)	DE	Emschergenossenschaft & Lippeverband	1931	1 min
Eelde	NL	Royal Netherlands Meteorological Institute (KNMI)	1957	1 h
Maastricht	NL	Royal Netherlands Meteorological Institute (KNMI)	1957	1 h
Oberhausen	DE	Emschergenossenschaft & Lippeverband	1931	1 min
Soest	DE	Emschergenossenschaft & Lippeverband	1937	1 min
Uccle	BE	Royal Meteorological Institute of Belgium	1898	10 min
Vlissingen	NL	Royal Netherlands Meteorological Institute (KNMI)	1957	1 h

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