

The role of large-scale dynamics in an exceptional sequence of severe thunderstorms in Europe May/June 2018

Susanna Mohr¹, Jannik Wilhelm¹, Jan Wandel¹, Michael Kunz^{1,2}, Raphael Portmann³, Heinz Jürgen Punge¹, Manuel Schmidberger¹, Julian F. Quinting¹, and Christian M. Grams¹

¹Karlsruhe Institute of Technology (KIT), Institute of Meteorology and Climate Research (IMK), Karlsruhe, Germany

²Center for Disaster Management and Risk Reduction Technology (CEDIM), Karlsruhe, Germany

³Institute for Atmospheric and Climate Science, ETH Zurich, Switzerland

Correspondence: Susanna Mohr (mohr@kit.edu)

1 **Abstract.** Over three weeks in May and June 2018, an exceptionally large number of thunderstorms hit vast parts of western
2 and central Europe, causing precipitation of up to 80 mm within one hour and several flash floods. This study examines the
3 conditions and processes that made this particular thunderstorm episode exceptional. Besides a description of the synoptic set-
4 ting and the severity of the convective hazards, it is shown how processes interact across scales, from large-scale dynamics with
5 atmospheric blocking to meso-scale cut-off lows to regional convective environment to local-scale thunderstorm occurrences.

6 During the episode, a blocking situation persisted over northern Europe. Initially, the southwesterly flow on the western flank
7 of the blocking anticyclone induced the advection of warm, moist, and unstably stratified air masses. Due to the low-pressure
8 gradient associated with the blocking anticyclone, these air masses were trapped in western and central Europe, remained
9 almost stationary and prevented a significant air mass exchange. In addition, the weak geopotential height gradients led to
10 predominantly weak flow conditions in the mid-troposphere and thus to low vertical wind shear that prevented thunderstorms
11 from developing into severe organized systems. Due to a weak propagation speed in combination with high rain rates, several
12 thunderstorms were able to accumulate enormous amounts of precipitation that affected local-scale areas and triggered several
13 torrential flash floods.

14 Atmospheric blocking also increased the upper-level cut-off low frequency on its upstream regions, which was up to 10
15 times higher than the climatological mean. Together with filaments of positive potential vorticity (PV), the cut-offs provided
16 the meso-scale setting for the development of a large number of thunderstorms. During the 22-day study period, more than
17 50 % of lightning strikes can be linked to a nearby cut-off low or PV filament. The exceptionally persistent low stability over
18 three weeks combined with a weak wind speed in the mid-troposphere has not been observed during the past 30 years.

19 **Keywords:** Europe, thunderstorms, severe convective storms, heavy rain, flash floods, atmospheric blocking, weather regimes, cut-off lows, potential vorticity

20 1 Introduction

21 Historically, the period from May to mid of June 2018 was among the most active periods of severe convective storms associated
22 with heavy rain, hail, convective wind gusts and even tornadoes over large parts of western and central Europe (WetterOnline,

23 2018a, b, c; DWD, 2018a). More than 1,500 reports of hazardous weather events were documented by the European Severe
24 Weather Database (ESWD; Dotzek et al., 2009). Rainfall totals of up to 90 mm within a few hours caused (pluvial) flash floods
25 in various municipalities. Gust speeds of up to 30 m s^{-1} led to numerous fallen trees and severely damaged buildings. For
26 example, from 26 May to 1 June 2018, thunderstorms caused insured losses of about 300 million USD and overall losses of
27 about 430 millions USD according to Munich Re's NatCatSERVICE (Munich Re, 2019). Thus, it was the costliest convective
28 storm event in western Europe that year.

29 In general, the development of convective storms results from scale interactions of different processes in the atmosphere. It is
30 well known that deep moist convection depends on three necessary but not sufficient ingredients (e.g. Johns and Doswell, 1992;
31 Trapp, 2013): (i) convective instability over a layer of sufficient depth, (ii) sufficient moisture in the lower troposphere, and (iii)
32 a suitable lifting mechanism for the triggering of convection. The first two requirements are usually controlled by processes
33 on the synoptic scale. The latter can occur at different scale ranges. For example, lifting mechanisms on the mesoscale include
34 orographic lifting, horizontal convective rolls, or gravity waves (e.g. Wilson and Schreiber, 1986; Browning et al., 2007;
35 Barthlott et al., 2010), whereas large-scale lifting can be related to drylines or cold fronts (e.g. Bennett et al., 2006; Kunz et al.,
36 2020). A further relevant condition for the evolution of deep moist convection is the vertical wind shear, which is decisive not
37 only for the organizational form, the longevity and thus the severity of the convective storms (e.g. Weisman and Klemp, 1982;
38 Thompson et al., 2007; Dennis and Kumjian, 2017), but also for their propagation (Corfidi, 2003).

39 The general synoptic situation during the thunderstorm episode 2018 investigated in this study was similar to that prevailing
40 over a 15-day period in May/June 2016, where also an exceptionally large number of thunderstorms caused several flash floods,
41 primarily in Germany (Piper et al., 2016; Bronstert et al., 2018; Ozturk et al., 2018). During the episode in 2016, a blocking
42 anticyclone over the North Sea and Scandinavian region prevented an exchange of the dominant unstably stratified air masses
43 over several days. In addition, low wind speeds throughout the troposphere caused the thunderstorms to be almost stationary
44 with the effect of torrential rain accumulations in several small regions (Piper et al., 2016, hereinafter referred to as PIP16).

45 Atmospheric blocking, with a typical lifetime of several days to weeks, is a quasi-stationary, persistent flow situation that
46 modulates the large-scale extratropical circulation (Rex, 1950a, b; Barriopedro et al., 2006; Woollings et al., 2018). Such
47 blocks typically occur either in a *dipole configuration* with an accompanying cut-off low on the equatorward side (Rex, 1950a;
48 Tibaldi and Molteni, 1990) or they adopt an *omega-shape* with cut-off lows forming at the flanks of the blocked region (Dole
49 and Gordon, 1983). In the potential vorticity (PV) framework, a cut-off low is an upper-level closed anomaly of stratospheric
50 high PV air (e.g. Wernli and Sprenger, 2007; Nieto et al., 2007a, 2008). PV anomalies, in general, have a far-field impact
51 on the meteorological conditions in their surroundings (cf. Hoskins et al., 1985). Below the positive PV anomaly, isentropes
52 bend upward, resulting in reduced static stability and increased lifting. Due to an induced cyclonic circulation anomaly, the
53 positive PV anomaly favours isentropic gliding up and thus ascent along the isentropes that usually bend upward towards the
54 pole. Finally, when the positive PV anomaly propagates, air masses ascend isentropically at the PV anomalies' upstream side.
55 These three mechanisms associated with lifting are intrinsic to upper-level positive PV anomalies in general. Additionally, at
56 the flanks of a mature PV cut-off, small meso-scale filaments of positive PV often separate and are advected away, particularly
57 when the PV cut-off gradually decays (Portmann et al., 2018). When such a positive PV filament moves over air masses that are

58 conditionally or potentially unstably stratified, the associated lifting indirectly contributes to convective initiation (triggering)
59 and thus – if the air parcel reaches its level of free convection – to release of Convective Available Potential Energy (CAPE)
60 and to removal of Convective Inhibition (CIN). The effect of large-scale PV anomalies accompanied by cut-off lows on deep
61 moist convection (in relation to severe precipitation events) has already been observed in other studies showing for Europe that
62 this is an important mechanism for convection due to the associated patterns of advection and vertical motion (Roberts, 2000;
63 Morcrette et al., 2007; Browning et al., 2007; Russell et al., 2012).

64 At first, atmospheric blocking was primarily known for its conjunction to extreme weather events such as cold spells and
65 heatwaves (and associated droughts; e.g. Pfahl and Wernli, 2012a; Bieli et al., 2015; Schaller et al., 2018; Röthlisberger and
66 Martius, 2019). But in peripheral locations upstream and downstream of the blocks can also create environmental conditions
67 conducive for deep moist convection development. Thus, the link to heavy precipitation events (including flood events) has
68 already been intensively investigated in past years (e.g. Martius et al., 2013; Grams et al., 2014; Piaget et al., 2015; Sousa et al.,
69 2017; Lenggenhager et al., 2018; Lenggenhager and Martius, 2019). A new study by Mohr et al. (2019) now shows a statistical
70 relationship between convective activity (based on lightning data) and specific blocking situations in the European sector. They
71 found a block over the Baltic Sea frequently associated with increased thunderstorm occurrences because of southwesterly
72 advection of warm, moist and unstable air masses on its western flank. In addition, such situations are usually associated with
73 weak wind speed at mid-tropospheric levels and thus weak vertical wind shear over the thunderstorm area with the consequence
74 that thunderstorms become often stationary and rarely develop into large organized convective systems. Recently, Tarabukina
75 et al. (2019) also demonstrate a correlation between the annual variation of summer lightning activity in Yakutia (Russia) and
76 the frequency of atmospheric blocking in Western Siberia.

77 The primary objective of this paper is to examine the conditions and processes that made this particular thunderstorm episode
78 in 2018 unique. We focus on the process interaction across scales, i.e. from the large-scale dynamics such as atmospheric
79 blocking to meso-scale PV cut-off lows and small PV filaments to modifications of the convective environment to local-
80 scale thunderstorm occurrences. Further objectives are to highlight the synoptic setting during the thunderstorm episode, to
81 demonstrate the severity of the events, and to place the event in a historical context.

82 The paper is structured as follows: Section 2 presents the different data sets and the methods used. Section 3 starts with a
83 description of the thunderstorm episode in 2018 by investigating different observation data such as lightning information, haz-
84 ardous storm reports, rain gauge measurements, and radar-based storm tracks estimating the propagation speed. Subsequently,
85 the synoptic situation prior to and during the examined thunderstorm episode is investigated by analyses of the large-scale flow
86 situation, backward trajectories, accompanied weather regimes, and environmental conditions such as instability, moisture, or
87 mid-tropospheric wind speed. Furthermore, we examine the role of PV cut-off and PV filaments on the development of deep
88 moist convection. Then, Section 4 puts the results in a historical context, whereby the exceptional nature of the thunderstorm
89 episode is assessed by relating the observed rainfall totals, the prevailing environmental conditions, and the occurrence of
90 cut-off systems to long-term data records. Finally, Section 5 and Section 6 discuss and summarize the main results and draw
91 conclusions.

92 **2 Data and methods**

93 The study area includes parts of central and western Europe – France, Benelux (Belgium, Netherlands, Luxembourg), Germany,
94 Switzerland and Austria (see Fig. 1). The study period extends over three weeks from 22 May to 12 June 2018, where most of
95 the thunderstorms and associated hazard such as heavy rain, hail and convective wind gusts occurred (see Sect. 3). To highlight
96 the synoptic situation prior to the episode and to emphasise that severe convection during the study period was embedded in
97 a longer lasting unusual large-scale flow situation, we considered an extended study period from 1 May to 20 June 2018. For
98 the purpose of climatological comparison, the 30-year period from 1981 to 2010 (1 May to 30 June) was the reference period
99 (unless otherwise indicated).

100 **2.1 Observation data**

101 For the description of the thunderstorm episode in 2018, we use different observation data. Lightning data offer the best
102 spatially homogeneous coverage for a complete thunderstorm detection, but does not discern according to severity. For this
103 purpose, we use eyewitness reports of the ESWD and precipitation observations (station-based and gridded-based). Radar-
104 based storm tracks permit an investigation of the propagation speed of the convective cells. Some investigations are limited
105 to Germany, for which data were available (storm tracks, REGNIE), but enable a deeper insight into the exceptional nature of
106 the phenomena. Additionally, the atmospheric conditions are examined with data from various sounding stations. Some data
107 records are also available consistently and homogeneously over long-term periods, which allow us to compare the episode with
108 historical conditions/events.

109 **2.1.1 Lightning data**

110 Lightning data are obtained from the ground-based low-frequency lightning detection system operated by Siemens as part of
111 the EUCLID network (EUropean Cooperation for LIghtning Detection; Drüe et al., 2007; Schulz et al., 2016; Poelman et al.,
112 2016). Available for the whole study domain, the data are projected on an equidistant grid of $10 \times 10 \text{ km}^2$ and accumulated
113 over 6-hour periods centered around the timesteps in ERA-Interim (e.g. for the 06 UTC reanalysis the lightning period is
114 03–09 UTC). This allows the data to be linked to the cut-off lows (see Sect. 2.5). We consider all types of flashes including
115 cloud-to-ground, cloud-to-cloud, and intra-cloud flashes, whereas polarity or peak current are not investigated.

116 **2.1.2 ESWD reports**

117 We use reports of heavy rain, hail (diameter $\geq 2 \text{ cm}$), and convective wind gusts $\geq 25 \text{ m s}^{-1}$ from the European Severe Weather
118 Database (ESWD; Dotzek et al., 2009; Groenemeijer et al., 2017). The ESWD is a step-by-step quality controlled (four levels)
119 database providing detailed information about severe convective storms in Europe, mainly based on reports from storm chasers,
120 eyewitnesses, voluntary observers, meteorological services, and news media. We consider all records with a quality level QC0+
121 and above. Using a homogeneous data format, these observations contain information about hazardous weather events such as

122 location, time, intensity, and damage-related information. For a detailed description of the event reporting criteria see ESSL
123 (2014).

124 2.1.3 Rainfall totals

125 Daily rainfall totals of 232 stations distributed across the domain (41°N–58°N, 4°W–20°E) were collected from the European
126 Climate Assessment and Dataset (ECA&D), a database of daily meteorological station observations across Europe (Klein Tank
127 et al., 2002). In addition, hourly and daily data were obtained from Météo-France (1223/1935 stations with hourly/daily data),
128 the Royal Netherlands Meteorological Institute (KNMI; 50/322), the German Weather Service (DWD; 958/810), MeteoSwiss
129 (952/0), and the Central Institution for Meteorology and Geodynamics (ZAMG; 254/0). For statistics of 1-hour and 3-hour
130 extreme rainfall events, we applied the same severity thresholds used in the ESWD (ESSL, 2014), which amount to 35 and
131 60 mm, respectively (Wussow, 1922; Nachtnebel, 2003). Note that the 24-hour criterion of 170 mm was not measured at any
132 of the stations.

133 Statistical return periods of single heavy precipitation events are estimated using regionalized precipitation data (*REGion-*
134 *alisierte NIEderschläge*, REGNIE) provided by DWD (DWD, 2018b). REGNIE is a gridded data set of 24-hour totals (from
135 06 UTC to 06 UTC on the next day) based on approximately 2,000 climate stations more or less evenly distributed across
136 Germany. The REGNIE algorithm interpolates the measurement data to a regular grid of 1 km² considering altitude, exposure,
137 and climatology (Rauthe et al., 2013). The data covering only Germany are available since 1951. The long-term availability of
138 REGNIE over almost 70 years is the decisive advantage compared to other data sets such as RADOLAN (merger between radar
139 and station data; DWD, 2019), which have a higher spatial and temporal resolution but are only available for 20 years. Note
140 that the REGNIE time series are affected by temporal changes in the number of rain gauges considered by the regionalization
141 (Rauthe et al., 2013). For our purpose, the homogeneity of the data are sufficient.

142 Statistical return periods of REGNIE totals are quantified using the Generalized Extreme Value (GEV) distribution (e.g.
143 van den Besselaar et al., 2013; Ehmele and Kunz, 2019). The Fisher-Tippett Type I distribution, also known as the Gumbel
144 distribution (Gumbel, 1958; Wilks, 2006), has been extensively used in various fields including hydrology for modelling
145 extreme events, i.e. to estimate statistical return periods or return values (Sivapalan and Blöschl, 1998; Rasmussen and Gautam,
146 2003). The Gumbel cumulative distribution function (CDF) for the precipitation totals R is given by:

$$147 \quad F(R) = \exp \left[-\exp \left(\frac{\zeta - R}{\beta} \right) \right], \quad (1)$$

148 with ζ and β as location and scale parameters, respectively. For their estimation, we use the Method of Moments (Wilks, 2006,
149 Chap. 4) and considered the 67-year period from 1951 to 2017 (summer half-year from April to September):

$$150 \quad \beta = \frac{\sigma\sqrt{6}}{\pi} \quad \& \quad \zeta = \bar{R} - \delta \cdot \beta, \quad (2)$$

151 with σ as the standard deviation, \bar{R} as the mean of the REGNIE sample and δ as the Euler-Mascheroni constant ($\approx .0.5772$).

152 The return period t_{RP} is directly related to the probability of occurrence of the threshold $P(R \geq R_{trs}) = t_{RP}^{-1}$ so that the CDF

153 is given by $F(R) = 1 - t_{RP}^{-1}$. The resulting equation to estimate t_{RP} is:

$$154 \quad t_{RP}(R) = \left[1 - \exp \left(- \exp \left(\frac{\zeta - R}{\beta} \right) \right) \right]^{-1}. \quad (3)$$

155 **2.1.4 Storm tracks computed from radar reflectivity**

156 Storm motion vectors are computed from three-dimensional (3D) radar reflectivity data from the radar network of DWD.
157 The data, which includes 17 radar stations with dual-polarization Doppler radars, are combined and interpolated into a radar
158 composite with a spatial resolution of $1 \times 1 \text{ km}^2$ (Cartesian grid). The temporal resolution of the individual scans is 15 minutes.
159 Radar reflectivity is available on 12 equidistant vertical levels extending from 1 km to 12 km above ground level. For the
160 whole period between 2005 and 2018, which is used to relate the storm motions computed for the investigation period to the
161 climatology (Sect. 4.1), data were stored in six reflectivity classes only. The two highest classes, which are considered here,
162 range from 46 to 55 dBZ and ≥ 55 dBZ.

163 To identify storm tracks, the cell-tracking algorithm TRACE3D (Handwerker, 2002) was adapted to the DWD radar compos-
164 ite in Cartesian coordinates. Once the algorithm detects a convective cell core, it can be re-detected in consecutive time steps
165 and merged into an entire cell track. Storms are defined by having a minimum reflectivity core of 55 dBZ (corresponding to the
166 highest class) and a vertical extent of at least 1 km. Thus, only severe convective storms frequently associated with hazardous
167 weather are considered. Thunderstorms above the 55 dBZ threshold usually form a well-defined core of high reflectivity that
168 can be easily and reliably tracked. Based on TRACE3D, information about width, length, duration, and propagation speed, as
169 well as direction, is available for each individual thunderstorm track. Note that we mainly use tracking to estimate the propaga-
170 tion speed and direction of the cells (Sect. 3 and Sect. 4.1). Even if weaker cells are not detected using the 55 dBZ thresholds,
171 it can be assumed (cf. Video Supplement for two representative days) that they cannot move with higher speeds. More details
172 about data and the tracking method can be found in Puskeiler et al. (2016) and Schmidberger (2018). Due to a lack of 3D radar
173 data for the other countries in 2018, our investigation refers only to severe convective storms that occurred in Germany.

174 **2.1.5 Sounding stations**

175 Atmospheric conditions are estimated from vertical profiles of temperature, moisture, wind speed and direction at seven sound-
176 ing stations provided by DWD and the Integrated Global Radiosonde Archive (IGRA) from the National Climatic Data Center
177 (Durre et al., 2006). These stations are distributed over the entire domain: Bordeaux (44.83°N , 0.68°W) and Trappes (48.77°N ,
178 2.00°E) in France; Essen (51.41°N , 6.97°E), Stuttgart (48.83°N , 9.20°E), and Munich (48.24°N , 11.55°E) in Germany; Pay-
179 erne (46.82°N , 6.95°E) in Switzerland, and Vienna (48.23°N , 16.37°E) in Austria (see Fig. 1). Other sounding stations could
180 not be used because of multiple gaps in the time series.

181 Atmospheric stability can be estimated by indices such as CAPE as well as by the surface-based Lifted Index (SLI; Galway,
182 1956). The latter, which we use in the following, has proven to be as suitable as CAPE in several studies (e.g. Huntrieser et al.,
183 1997; Sánchez et al., 2009; Westermayer et al., 2017; Rädler et al., 2018). There are studies, in which SLI has even shown a
184 better prediction skill than CAPE (e.g. Haklander and van Delden, 2003; Manzato, 2003; Kunz, 2007; Mohr and Kunz, 2013).

185 In addition to the SLI, we also investigate the horizontal wind speed in 500 hPa (V500). Both variables are analysed at 12 UTC,
186 several hours ahead of peak thunderstorm activity in central and western Europe (Wapler, 2013; Piper and Kunz, 2017; Enno
187 et al., 2020).

188 2.2 Model data

189 We use the European Centre for Medium-Range Weather Forecasts (ECMWF) high-resolution operational analysis data and
190 ECMWF ERA-Interim reanalysis (Dee et al., 2011) to describe the large-scale meteorological conditions and calculate weather
191 regimes (see Sect. 2.3), perform kinematic backward trajectories (see Sect. 2.4), and identify cut-off lows (see Sect. 2.5).
192 ECMWF analysis is available 6-hourly interpolated to a regular grid with 0.125° horizontal resolution. ERA-Interim used for
193 the historical analysis is available 6-hourly interpolated to a regular grid at 1.0° horizontal resolution. Beside the atmospheric
194 stability (based on SLI), we examine in the study V500, the bulk wind shear (BWS; directional shear) as wind difference
195 between 10 m and 500 hPa calculated by vector subtraction (e.g. Thompson et al., 2007), 500 hPa geopotential height (Z500)
196 and the vertically integrated water vapor (IWV).

197 2.3 North Atlantic-European weather regimes

198 The large-scale flow conditions in the Atlantic-European region are characterized in terms of a definition of seven year-round
199 weather regimes based on 10-day low-pass-filtered 500 hPa geopotential height anomalies (Grams et al., 2017). The regimes
200 are identified by k-means clustering in the phase-space spanned by the seven leading empirical orthogonal functions (EOFs).
201 Based on these seven clusters, an active weather regime life-cycle is derived from the normalized projection of each 6-hourly
202 anomaly in the cluster mean following Michel and Rivière (2011). Thereby, time steps with weak projections are filtered out
203 (no regime). An active regime life-cycle persists for at least 5 days but fulfills further criteria as described in Grams et al.
204 (2017).

205 Our weather regime definition is in line with ‘classical’ concepts of four seasonal regimes for Europe (e.g. Vautard, 1990;
206 Michelangeli et al., 1995; Ferranti et al., 2015), but reflects important seasonal differences. Three of the seven regimes are dom-
207 inated by a negative Z500 anomaly and enhanced cyclonic activity (see Supplementary Fig. 1). These are the *Atlantic Trough*
208 (*AT*) regime with a trough extending towards western Europe, the *Zonal regime* (*ZO*) with cyclonic activity around Iceland, and
209 the *Scandinavian Trough* (*ScTr*) regime with a trough shifted towards the east. The remaining four regimes are characterized by
210 a positive Z500 anomaly centered at different locations and therefore referred to as ‘blocked regimes’. These are the *Atlantic*
211 *Ridge* (*AR*) regime, with a blocking ridge over the eastern North Atlantic and an accompanying trough extending from east-
212 ern Europe into the central Mediterranean, the *European Blocking* (*EuBL*) regime, with a blocking anticyclone extending from
213 Western Europe to the North Sea, *Scandinavian Blocking* (*ScBL*), with high-latitude blocking over Scandinavia, and *Greenland*
214 *Blocking* (*GL*) with a blocking ridge over the Greenland-Icelandic region.

215 **2.4 Lagrangian Analysis Tool**

216 The path of the air masses during the thunderstorm period from 22 May to 12 June is traced by calculating 10-day kine-
217 matic backward trajectories from ERA-Interim using the Lagrangian Analysis Tool (LAGRANTO, Wernli and Davies, 1997;
218 Sprenger and Wernli, 2015). The trajectories are initialised every 6 hours on each day of the study period from the nearest
219 ERA-Interim grid points to the surrounding site and its immediate neighbours to the north, south, east, and west (Fig. 1 yel-
220 low squares). In order to represent the Lagrangian history of moist, low-tropospheric air masses that contributed to the severe
221 thunderstorms, trajectories are initialised every 50 hPa between 950 and 600 hPa.

222 **2.5 Identification of PV cut-off low and matching with lightning data**

223 We identify upper-level cut-off lows based on PV on the 325 K isentropic surface from ERA-Interim using the algorithm of
224 Wernli and Sprenger (2007) and Sprenger et al. (2017). The optimal level for the inspection of weather systems on isentropic
225 surfaces depends on the season. The specific level of 325 K used here is motivated by previous studies (cf. Röthlisberger et al.,
226 2018) and the inspection of isentropic PV charts for our case. The algorithm searches for closed areas of PV larger than 2 PVU,
227 which are disconnected from the main PV reservoir that expands across the North Pole.

228 Following earlier approaches to match weather objects with surface weather (e.g. cyclones and precipitation; Pfahl and
229 Wernli, 2012a, b), the identified PV cut-off lows (including their PV filaments) are then related to thunderstorm events using
230 lightning data on the $10 \times 10 \text{ km}^2$ grid cells. We utilize the smallest distance approach to link a grid cell in the lightning data set
231 to a grid point in the PV cut-off data set. The different grid sizes between the model and observation data sets require matching
232 multiple grid cells (lightning data) to one PV cut-off grid point. This means if a grid point shows the presence of a PV cut-off,
233 all flashes from the associated grid cells are linked to it.

234 To account for the far-field impact of lifting and destabilization by a PV cut-off, we expand the PV cut-off mask by a buffer.
235 This scale is estimated from the typical Rossby radius of deformation

$$236 \quad L_R = \frac{N \cdot H}{f_0} \quad (4)$$

237 associated with a PV cut-off. Here, N is the Brunt-Väisälä frequency, H is the scale height, and f_0 is the Coriolis parameter.
238 For characteristic values in mid-latitudes with $N = 0.01 \text{ s}^{-1}$ and $f_0 = 10^{-4} \text{ s}^{-1}$, N/f_0 is typically in the order of 100. A
239 scale height of 10 km leads to a Rossby deformation radius of 1,000 km, which is typical for synoptic scales. We assume that
240 some of the PV cut-offs during the study period have a vertical extent of less than 10 km. Therefore, we chose a conservative
241 deformation radius (buffer) of about 500 km. The robustness of the chosen deformation radius is investigated both qualitatively
242 and quantitatively. We found that a change in the radius of 100 km, for example, leads to an increase or decrease of around
243 10 % in the total amount of lightning strikes associated with a PV cut-off during our study period (see Supplement Sect. 2).
244 Such small changes do not affect the qualitative interpretation of our results.

245 2.6 Persistence analysis

246 Days with constant atmospheric conditions tend to form temporal clusters of certain weather phenomena (here thunderstorms)
247 lasting of several days (events). This behavior can be described statistically by the concept of persistence. The event length
248 or duration n is determined by the number of days, on which a certain criterion is fulfilled (e.g. thunderstorm day or certain
249 atmospheric conditions). Each day is assigned either the value 1 (event day = criterion fulfilled) or 0 (non-event day = criterion
250 not fulfilled). Within a seven-day sequence, we allow one non-event day (skip day, not counted in the total length n) without
251 breaking the event. This means that an event lasting up to 7 (14/21) days may contain at most 1 skip day (2/3 skip days). For
252 more information on the concept see PIP16.

253 In the study, we investigate the co-occurrence of low stability (using SLI) and low mid-tropospheric wind speeds (using
254 V500). For this purpose, the same thresholds as in PIP16 are chosen, which were used to investigate the exceptional atmospheric
255 conditions of a similar thunderstorm episode. We employ their basic criterion, which is fulfilled if both conditions apply:
256 $SLI < 0 \text{ K}$ and $V500 < 10 \text{ m s}^{-1}$ (TH_{BC}). In addition, we also discuss our results in context with the strict criterion, which is
257 fulfilled with $SLI < -1.3 \text{ K}$ and $v_{500hPa} < 8 \text{ m s}^{-1}$ (TH_{SC}).

258 3 Description of the thunderstorm episode 2018

259 The period from the first of May to mid-June 2018 was characterized by a large number of thunderstorms that spread across
260 the study area, several of which were associated with heavy rainfall, hail, and strong wind gusts (see ESWD reports in Fig. 2a).
261 Lightning strikes were recorded on each day, and the affected area ranges between 100 km^2 on 19 June and $1,140,000 \text{ km}^2$ on
262 27 May (accumulations of the $10 \times 10 \text{ km}^2$ grid cell).

263 The three-week period from 22 May until 12 June was the most active thunderstorm episode in May/June 2018 with a total
264 of 868 heavy rain, 144 hail, and 145 convective wind gust reports based on the ESWD. The highest number (152 reports)
265 was issued on 29 May, followed by 31 May (137 reports), most of them reporting heavy rainfall leading to several flash floods
266 and landslides, which destroyed buildings, vehicles, streets and even railway tracks (DWD, 2018a; WetterOnline, 2018b).
267 On average, an area of $758,000 \text{ km}^2$ – twice the size of Germany – was affected by lightning per day, with the result that
268 thunderstorms covered the entire study area. As shown in Figure 2b, most of the severe weather reports during the episode
269 came from the western part of France, Benelux, central and southern Germany, and the easternmost part of Austria. While the
270 spatial distribution of the ESWD reports shows several regional gaps due to an under-representation of eyewitness reports, for
271 example, in Central and southeastern France (cf. Groenemeijer et al., 2017; Kunz et al., 2020), thunderstorm days are observed
272 throughout the study area (see Supplementary Fig. 4). The extraordinarily large number of thunderstorms, several of them
273 severe, and the unusual persistence of that situation over three weeks motivated us to select that time frame as the study period.

274 Figure 3 summarizes the evolution of 1-hour (1 h) and 3-hour (3 h) rain gauge measurements in the study area exceeding the
275 ESWD heavy rain criteria of 35 mm and 60 mm, respectively. The 1 h criterion was fulfilled during the study period 167 times
276 (Fig. 3a) and an average of about 7.6 stations per day with a variability between one and 20 stations. This highest number of
277 stations belongs to the day with the second most ESWD severe weather reports (31 May). The 3 h criterion was reached 38

278 times, with a maximum of at least 5 stations on three days. The location of the respective stations shows heavy rain events in
279 all of the countries under consideration without any clustering (Fig. 3b,c).

280 During the episode, the thunderstorms developed mainly as isolated cells and clusters of several cells, the latter preferably
281 in the early evening and night. Only on a few days (e.g. on 22 May or 1 June) larger mesoscale convective systems (MCS)
282 formed, which persisted during the night and early morning. Animated images of radar reflectivity can be found in the Video
283 Supplement for two representative days: 27 and 31 May. The two animations show a large number of both isolated thunder-
284 storms with a short lifetime of approximately 30 min (radar visibility, i.e. period of precipitation) and cell clusters persisting
285 over several hours. Most cells moved very slowly or even remained stationary on the two days.

286 The slow movement of the convective cells, a prominent feature of the entire thunderstorm episode, was mainly due to the
287 low wind speed at mid-tropospheric levels (cf. Sect. 3.1.2). According to the cell tracking (Germany only; see Sect. 2.1.4),
288 about half of all cells reaching a radar reflectivity of at least 55 dBZ had a propagation speed of less than 5 m s^{-1} (47.3 %
289 from 480 cells); only a few cells (1.5 %) had a speed above 15 m s^{-1} (Fig. 4). Mean, standard deviation, and median values are
290 5.9 m s^{-1} , $\pm 2.9 \text{ m s}^{-1}$, and 5.2 m s^{-1} , respectively, which is almost half of the long-term statistics (cf. Sect. 4.1; see also the
291 propagation speed of some record-breaking 1 h and 3 h rainfall totals in Table 1). The predominant propagation direction was
292 from southeast to northwest (26.3 % of the detected cells). However, several cells moved in completely different directions on
293 the same day – a clear sign that the propagation was not only determined by the (weak) mid-tropospheric wind, but also by
294 internal dynamic effects induced by cold pools or by pressure disturbances (Markowski and Richardson, 2010; Houston and
295 Wilhelmson, 2012). Examples of different track directions of neighbouring cells can be seen in the radar animation on 27 May
296 (14 to 15 UTC, at the coordinates: $x \sim 250 \text{ km}$ & $y \sim 600 \text{ km}$) or on 31 May (21 to 22 UTC; $x \sim 400 \text{ km}$ & $y \sim 700 \text{ km}$).

297 A detailed look at the chronological sequence during the episode (Fig. 2b) shows that thunderstorms associated with heavy
298 rainfall and small hail with diameters of around 2 cm were restricted to Benelux and western Germany on 22 May. Some entries
299 report flash floods and mudslides, for example in the Heilbronn area (SW Germany). Two days later, on 24 May, the federal
300 state of Saxony (eastern Germany), the east of Austria, and parts of Belgium were hit by torrential rain accumulations. The
301 German station Bad Elster-Sohl in Saxony (see Fig. 1) on the border to the Czech Republic, for example, measured a record of
302 $86.3 \text{ mm}/3 \text{ h}$ and $154.9 \text{ mm}/24 \text{ h}$. On 26 May, several wind reports with gust speeds of up to 29 m s^{-1} (Poitiers, France; see
303 Fig. 1) and hail reports indicating hailstones with a diameter of up to 5 cm were recorded in the French coastal region near the
304 Bay of Biscay.

305 The subsequent time frame from 27 May to 1 June was the most active both in terms of the area affected by lightning and
306 the number of ESWD reports (Fig. 2a). Widespread thunderstorms were observed mainly in Benelux, Germany, and France,
307 but also sporadically in Switzerland and Austria, many of them associated with large rain accumulations and subsequent
308 flooding, hail between 2 and 4 cm in diameter, and damaging wind reports. Many of record-breaking 1 h and 3 h rainfall
309 totals occurred within this period (Table 1). For example, the weather station Bruchweiler (see Fig. 1), located in the west of
310 Germany, measured a 24 h rain accumulation of 145.0 mm on 27 May (Note that the station only provides reports for the full
311 24 hours). However, the rain fell in a period of 3 hours, with 60 mm falling in just 50 min (see also Supplementary Fig. 5a). The
312 corresponding track, derived from TRACE3D, has a short length of 21 km and a low propagation speed of 5.7 m s^{-1} (Table 1).

313 A second example is on 31 May the exceptionally high 1 h rain accumulation of 85.7 mm measured at Diethenhofen close to
314 Nuremberg in the south of Germany (see also Fig. 3b), listed high in the ranking of highest 3 h rainfall totals as well. The
315 station was fully hit by an isolated system, which was relatively stationary. The rain rate above 60 mm was present over 35 min
316 (see also Supplementary Fig. 5b and Video Supplement).

317 In the first half of June, some hail stones and heavy rainfall were still reported almost daily somewhere in the study domain,
318 though less frequently than before. Towards the end of the study period, convective activity increased again. Especially on the
319 last day of the study period, on 12 June, the proportion of gust reports (indicating wind speeds between 25 and 31 m s⁻¹) to
320 all reports was very large. Thereafter, when environmental conditions became more stable (cf. Sect. 3.1), thunderstorms rarely
321 occurred. The area affected by lightning decreased considerably and no further severe weather reports were archived in the
322 ESWD.

323 As we will show later (Sect. 3.1.2), very low wind shear values prevailed across the study area. In a few cases, deep-layer
324 shear magnitudes were sufficient (BWS up to 20 m/s) for the development of severe storms, with large hail up to 5 cm in
325 diameter recorded in Southwest France on 26 and 9 June and in southern Germany on 11 June. However, these were exceptional
326 cases.

327 3.1 Synoptic overview

328 The synoptic situation prior to the thunderstorm episode in 2018 was embedded in a longer lasting unusual large-scale flow
329 situation. At the beginning of the extended study period, a large-scale mid-tropospheric area of high geopotential stretched out
330 from the Azores over central Europe and the Baltic to western Russia (Fig. 5a), attended by a corresponding prolonged lower-
331 level high-pressure system (not shown). This configuration was associated with the advection of warm and relatively dry air
332 masses over large parts of Europe. In the second week of May, the pattern transitioned into a blocked situation over Europe (see
333 Sect. 3.1.1). The geopotential height at 500 hPa depicts the typical *Omega*-like structure with high geopotential over central
334 Scandinavia, flanked by one pronounced trough upstream over the Northern Atlantic and one downstream over Western Russia
335 (Fig. 5b). Subsequently, the two troughs turned into enclosed cut-off lows filled with relatively cold air and finally merged
336 into one system located over central Europe on 15 May (not shown). In the third week of May, the cut-off moved slowly
337 northeastward on an erratic track while gradually dissipating over central and eastern Europe, leaving a moderately warm and
338 dry air mass with weak gradients over central Europe (Fig. 5c).

339 The study period from 22 May to 12 June was characterized by a rather stationary and persistent synoptic situation with a
340 pronounced blocking ridge stretching from Iceland over the North Sea to Scandinavia and Northeast Europe (Fig. 6a). As a
341 consequence of the synoptic setting during this episode, the mid-tropospheric flow was weak over most parts of Europe (see
342 Sect. 3.1.2). On average, the ridge was flanked by long-wave troughs: one on the western side with the axis pointing from Baffin
343 Bay to Newfoundland, the other on the eastern side stretching from the Barents Sea to Kazakhstan, while the ridge remained
344 relatively stationary centered over the North Sea region (Fig. 5c-f).

345 A noticeable feature in the mean 500 hPa geopotential height for this episode is a locally enclosed geopotential minimum
346 over the Bay of Biscay and its surroundings (Fig. 6a) that emerges from repeating/transient cut-off lows forming on the up-

347 stream side of the blocking ridge. On 25 May (Fig. 5d), a cut-off low (C1a) approached Iberia – which merged in the next
348 days with the cut-off located over the Celtic Sea (C1b) – and contributed to convective initiation for several storms, first in
349 France and then in Benelux and Germany (cf. Fig. 2 and Sect. 3.3). In the following days, a new cut off (C2; not shown) formed
350 west of Spain, which subsequently influenced the weather there and disappeared relatively quickly. On 1 June, another cut-off
351 (C3) advanced from the Atlantic (Fig. 5e), which, together with C1, contributed to convective activity over France and central
352 Europe (see also ESWD reports on heavy rain in Fig. 5e/f, blue dots). Then, C3 developed into a shallow low-pressure zone in
353 central Europe, where several convergence lines formed. In addition, this situation provided very moist air (IWV well above
354 30 kg m^{-2} over large areas) until 9 June in eastern France and central Europe (Fig. 5e,f). In the end phase of the study period,
355 the next cut-off low (C5) with its associated fronts and convergence lines affected the western half of France and central and
356 southern Germany and lasted until 12 June (Fig. 5f). Simultaneously, a cut-off (C6) over the British Isles influenced the weather
357 in northern Europe.

358 The geopotential anomalies at the 500 hPa level, calculated as the deviation from the climatological mean (1981–2010),
359 exhibit for the study period significant positive values of up to 200 gpm west of Norway (Fig. 6a). In contrast, the area over
360 southwestern Europe is reflected by negative geopotential anomalies of more than 50 gpm. Qualitatively similar anomaly
361 patterns are seen in the sea-level pressure distribution (not shown). Simultaneously, the IWV (Fig. 6b) showed distinct positive
362 anomalies of up to 9 kg m^{-2} with a 22-day average of $24\text{--}28 \text{ kg m}^{-2}$. This finding is in line with the sequential progression
363 of several cut-off lows approaching southwestern Europe and leading to repeating the advection of warm and moist air masses
364 towards central and western Europe during the study period.

365 3.1.1 North Atlantic-European Weather Regimes

366 In terms of the North Atlantic-European weather regimes, the large-scale flow situation in May was dominated by simultane-
367 ously active life cycles of a Zonal regime (ZO; dark red in Fig. 7a) and European Blocking (EuBL; green). Climatologically,
368 the Zonal regime is characterized by a negative 500 hPa geopotential height anomaly centered over southern Greenland and
369 Iceland, accompanied by a weak positive anomaly over central Europe (cf. Supplementary Fig. 1). The climatological Euro-
370 pean Blocking regime is characterized by a strong positive geopotential height anomaly over the North Sea region, and a weak
371 negative anomaly over Baffin Bay.

372 The strong projection in both regimes in May suggests that both the cyclonic anomaly in the Icelandic region and the positive
373 anticyclonic anomaly over Europe were pronounced but altered in their intensities – as discussed in the previous section. The
374 alternating dominance of either regime in the first three weeks of May (Fig. 7a) reflects the change of zonal to meridional cir-
375 culation and the persistent blocking situation during our study period. It is striking that enhanced convection and thunderstorm
376 activity over Europe co-occurred with a weakening of the projection in the Zonal regime (see Section before). Specifically, the
377 first period of widespread thunderstorms (9–16 May; cf. Fig. 2) coincides with a weakening of zonal conditions and a domi-
378 nance of European Blocking from 11 to 18 May. This is interrupted by more zonal conditions from 19 to 21 May, leading to a
379 pronounced decrease in convective activity. The convectively most active period from 26 May to 1 June co-occurs with a very
380 strong projection into European Blocking and ends when the blocking decays. On 3 June, a transition into the Atlantic Ridge

381 regime occurs, with blocking shifting into the Northeast Atlantic and western Europe, which coincides with the last episode of
382 an increased number of convective events from 6 to 12 June.

383 **3.1.2 Local-scale environmental conditions**

384 During the entire May/June period, atmospheric stability was very low over large parts of the study domain as indicated by
385 sounding data (Fig. 7b). The SLI reached negative values almost every day at 12 UTC at one sounding station at least. During
386 the first thunderstorm episode from 9 to 16 May with several heavy rain and hail events (cf. Fig. 2), several stations already
387 show negative SLI values at some days. During the study period, all soundings (with a few exceptions) exhibit permanently
388 negative SLI values; most of the time the values are far below the basic/strict criterion of PIP16 (cf. Sect. 2.6). For example, the
389 median of the SLI during the study period was lower than -3.0 K for Stuttgart, Munich, Vienna, Trappes, and Payerne. Such
390 low values represent very conducive conditions for thunderstorm formation (e.g. Haklander and van Delden, 2003; Manzato,
391 2003; Sánchez et al., 2009; Kunz, 2007; Mohr and Kunz, 2013). In the ECMWF analysis (Fig. 8a), the SLI average over
392 the study period (12 UTC) was negative for most parts of the domain except for northern Germany, where thunderstorms
393 occurred infrequently. Furthermore, over large parts of the study domain, the strict criterion was also reached. Due to the
394 upcoming westerly flow at the end of the study period, instability decreased significantly and SLI returned to positive values
395 less conducive for deep moist convection (Fig. 7b).

396 Due to the weak geopotential height gradients that prevailed during the study period (Fig. 6), horizontal wind speed in the
397 mid-troposphere was likewise exceptionally low. During the first half of May, 500 hPa wind speed (V500) was already low
398 in the sounding data with values rarely exceeding 15 m s^{-1} (Fig. 7c), but further dropped significantly at the beginning of the
399 study period. Averaged over the entire study period, median V500 was 7 m s^{-1} at the Essen sounding station; at Stuttgart,
400 Munich, and Vienna values were even lower at around 5 m s^{-1} . At the other three stations in France and Switzerland, the
401 median was between 8 and 10 m s^{-1} . The observations are in line with ECMWF analysis, where V500 was between 5 and
402 10 m s^{-1} on average (particularly low in large parts of Germany and Austria; Fig. 8b).

403 Due to the very low wind speed near the surface, V500 is almost similar to BWS from ECMWF analysis (12 UTC; Fig. 8c).
404 Mean values of BWS between 5 and 10 m s^{-1} across the study area (except of the Pyrenees region) are a strong indication that
405 the majority of storms did not developed into highly organized convective systems, MCS or supercells. The following analyses
406 are relying on V500 instead of BWS, especially because of the very unusually low wind speed at 500 hPa. It should be noted
407 that the values for the speed shear are even lower compared to BWS ($3-9\text{ m s}^{-1}$; not shown).

408 **3.2 Air mass origin and paths during the event**

409 The investigation of sounding data revealed an exceptional air mass, which conserved its key properties conducive to convection
410 in the entire study period. This finding together with the low-pressure gradient associated with the blocking anticyclone over
411 the European sector (Fig. 6) suggests that the air mass was relatively stationary in western and central Europe during the study
412 period. To test this hypothesis, 10-day kinematic backward trajectories are calculated to investigate the Lagrangian history

413 and paths of moist, lower-tropospheric air masses. Though backward trajectories are started from all six sounding stations,
414 Bordeaux, Stuttgart, and Vienna are chosen as representative locations for the following analysis.

415 The median trajectory pathways during the entire study period 22 May to 12 June consistently show that air masses originated
416 west of the sounding stations and reached those in a southwesterly flow (Fig. 9a). Already ten days prior to reaching the area of
417 the sounding stations, two thirds of the air masses were located over the Atlantic-European sector. Though about 50 % of the
418 air masses were transported over a distance of 5,000 km (Fig. 9b), the median distance from their initial location (i.e. Bordeaux,
419 Stuttgart, Vienna) never exceeded 2,000 km (Fig. 9c). This clearly indicates that air masses re-circulated while approaching the
420 area of the sounding stations. Five days prior to arriving at the location, trajectories were mostly located over Europe (bold
421 ellipses) and within a radius of 1,000 km around the sounding stations.

422 3.3 Thunderstorms related to cut-off lows

423 Having shown that a quasi-stationary air mass, which was conducive to convection prevailed over vast parts of central Europe
424 during the study period, we now explore cut-off low activity that can prepare the atmosphere for convective initiation due to
425 the associated large-scale lifting. The blocking situation over central Europe and the North Sea during the study period was
426 accompanied by a negative geopotential height anomaly over the Iberian Peninsula (Fig. 6), which corresponds well with a sig-
427 nificantly enhanced frequency of PV cut-offs of more than 50 % in the Bay of Biscay region (Fig. 10a). This region of enhanced
428 PV cut-off frequencies expands over much of Spain, western France and some parts of the British Isles with frequencies often
429 above 25 %, but does not reach Germany or eastern Europe. The fact that relatively high PV cut-off frequencies expand over
430 a larger region of western Europe (Fig. 10a) underlines that multiple individual PV cut-offs form on the upstream flank of the
431 blocking ridge (see Fig. 5), and intermittently move across Iberia, France, the British Isles, the North Sea, and Germany.

432 In such a configuration, filaments of positive PV that separate from the main PV cut-off may favour lifting on their down-
433 stream flank and help to initiate deep moist convection over larger areas. This relation is exemplified by a 2-day period from
434 31 May to 1 June representing the end of the period with the highest lightning activity and number of ESWD reports. Here,
435 more than 700,000 lightning strikes were measured over the study domain (black bars in Fig. 11) and more than 70 % of these
436 can be attributed to PV cut-off activity (light grey bars). On 31 May, in the early afternoon, thunderstorms primarily affected
437 Belgium and the Netherlands first (Fig. 12a), before lightning activity re-emerged over central and northern France, Switzer-
438 land, and various parts of Germany (Fig. 12b). Several of these events were documented by heavy rain reports in the ESWD
439 (cf. Fig. 2). During the following night, the slow-moving multicellular system moved from Switzerland northwards affecting
440 the southwestern and the western parts of Germany (Fig. 12c,d; cf. Sect. 3). While the system dissipated in the late morning
441 over the border region of Germany and Belgium, severe thunderstorms developed again over eastern and northern Germany,
442 Czech Republic, western Poland, and the Pyrenees (Spain; Fig. 12e,f). The link to upper-level PV filaments becomes apparent
443 by carefully investigating the 6-hour evolution of the identified cut-off low masks (Fig. 12; cf. Sect. 2.5). Additionally, the area
444 of negative ω values indicates upward vertical motion over larger areas (light blue). Generally, such ascent downstream of a
445 trough/PV cut-off due to vertically increasing advection of PV in combination with layer thickness advection and destabiliza-
446 tion underneath the high PV air, which is well represented in our example.

447 On 31 May, a narrow trough approached from the Atlantic to Iberia (cf. Fig. 5e), accompanied by the cut-off low (C3),
448 which together with C1 forms the identified masks of the PV cut-offs region in Figure 12a. In particular, C1, located above
449 France at that time, and the associated areas of ascent (light blue) correspond well with the regions of thunderstorm activity
450 in southeastern Germany, central France and the Netherlands in the late afternoon (Fig. 12b). From 12 UTC until 18 UTC the
451 next day, this trough narrowed while moving gradually northeastward accompanied by enhanced lightning activity moving
452 from Central France and southern Germany to northeastern Germany and Poland (Fig. 12e,f). It is especially apparent that the
453 multicellular system, which developed in the evening hours of 31 May (Section 3), emerged in a region of negative ω values
454 ahead of the trough (Fig. 12c). On 1 June ascent occurs further to the east over Austria, the Czech Republic and northeastern
455 Germany (Fig. 12e), which agrees well with the location of thunderstorm initiation.

456 The above discussion of PV filament evolution and lightning activity from 31 May to 1 June revealed an apparent link of this
457 feature with lightning activity confined to the downstream side of PV filaments, where lifting is favoured. Considering the entire
458 study period, we found 54 % of the lightning linked to a nearby PV cut-off (Fig. 11). Examining individual days reveals that
459 on the day with the highest number of lightning detections (29 May) over 85 % of these events can be linked to a PV cut-off.
460 Six out of eight days with the highest number of lightning flashes were the days from 27 May to 1 June. During this period,
461 more than 75 % of the lightning strikes can be connected with one of the PV cut-offs. We conclude that cut-off low activity
462 provided the necessary environment that favoured lifting within the prevailing unstable air mass and thus indirectly contributed
463 to convective initiation of widespread thunderstorms in western and central Europe during this period.

464 4 Historical context

465 In this section, we assess the exceptional nature of the thunderstorm event, by relating the observed rainfall totals, the prevailing
466 environmental conditions, and the occurrence of cut-off systems to long-term data records.

467 4.1 Return periods of rainfall and propagation speed of convective cells

468 To estimate the severity of the rainfalls with respect to the rainfall climatology, we computed return periods (RPs) for each
469 day during the study period in the REGNIE long-term record based on Equation (3). Afterwards, we determined the highest
470 RP (largest 24-hour rain total) for each grid point. This analysis is restricted to Germany due to the availability of long-
471 term (> 50 years), high-resolution (1 km^2) gridded rainfall data. REGNIE data derived from measurements at climate stations
472 certainly underestimate precipitation peaks, but this is the case both for the study period and the 67-years reference period.

473 Extreme precipitation generally occurred locally, and only a few smaller regions were affected by high rainfall totals ex-
474 ceeding RPs of 5 years (Fig. 13). RPs in excess of 10 years were restricted to the southern parts of Germany (south of 52°N),
475 except for a few grid points south of Berlin. Most of the precipitation fields with higher RPs occurred as clusters; for example,
476 those near the border to France in Rhineland Palatinate and the Saarland (near Saarbruecken), northeast of Stuttgart, around
477 Bad-Elster Sohl, or north of Munich. Several local maxima have RPs of up to 50 years, but a few hot spots, unevenly dis-
478 tributed in southern Germany, reach values in excess of 200 years (e.g. the observation in Bad Elster-Sohl; cf. Sect. 3). Several

479 hot spots have an almost circular shape with the highest value located in the center. This does not appear to be an artefact of
480 insufficient gauge density, as most events are represented by multiple gauges (not shown). Instead, it likely reflects the very
481 slow propagation of storms.

482 This characteristic likely reflects the very slow propagation of the thunderstorms, which was substantially lower during the
483 study period compared to climatology (Fig. 4). Generally, convective storms detected between 2005 and 2017 (May/June: 3,428
484 cells) show significantly higher values of $10.2 \pm 4.9 \text{ m s}^{-1}$ (mean \pm std) and 9.5 m s^{-1} (median) compared to $5.9 \pm 2.9 \text{ m s}^{-1}$
485 and 5.2 m s^{-1} in the study period. Only 14.4 % of all detected cells show values below 5 m s^{-1} , which differs significantly from
486 the proportion in the study period with 47.3%. 15.5 % of the events propagated with a speed of at least 15 m s^{-1} (study period
487 only 1.5%; cf. Sect. 3.1.2).

488 4.2 Environmental conditions

489 We begin the analysis of the environmental conditions by comparing the SLI and V500 values observed at the seven sounding
490 stations during the study period with comparably low values during a 30-year period. The latter is represented by the annual
491 minimum of 22-day (same duration as study period) running mean values for May and June during 1981 and 2010. The box-
492 and-whisker plots (Fig. 14) on the left represent conditions during our study period (all 22 daily values) and on the right the
493 historical situation (in sum 30 values). Thus, each of the 30 values taken into account in the right box-plot of each station has
494 the same temporal dimension (running mean of a 22-day period) as the median in the left box-plot of each station. Recall that
495 the low values for both SLI and V500 were the peculiarity during the 2018 thunderstorm episode.

496 Both for atmospheric stability and mid-tropospheric flow speed, the interquartile range (the middle 50 % of all values) of
497 the left box-plot is mostly lower than the interquartile range of the right box-plot, illustrating the exceptional environmental
498 conditions of the 2018 thunderstorm episode. This applies in particular to the stations in Germany and Austria; stations in
499 France and in Switzerland tend to overlap (slightly) between the two interquartile ranges. As already mentioned in Sect. 3.1.2,
500 a large portion of SLI and V500 values during the event (left box-plot) are well below the basic and strict thresholds (cf.
501 Sect. 2.6).

502 To elaborate on both the peculiarity of the co-occurrence of low stability and weak mid-tropospheric flow and its persistence,
503 we investigate the probability of concurrent events (CE) by following the methodology of PIP16 (see Sect. 2.6) using the
504 same basic criterion. The CE duration for each of the seven sounding stations during the extended study period in 2018 varies
505 between 5 (Trappes) and 28 days (Munich; cf. legend in Fig. 15). At all three German stations, the defined concurrent conditions
506 prevailed over an extraordinarily long period (Essen: 17 days incl. 3 skip days; Stuttgart: 21 days incl. 1 skip days; Munich 28
507 days incl. 3 skip days).

508 In order to assess the occurrence probability of long-duration CEs, we compare the CE duration for the 2018 thunderstorm
509 episode with a frequency analysis of CE between 1981 and 2017 (May/June; Fig. 15). In doing so, the different amount of a
510 certain event persistence with the length n from the past between 1981 and 2017 are determined for each sounding station.
511 Subsequently, the relative frequency of the event persistence n per station in Figure 15 is determined by dividing the absolute
512 number of event persistence by the total number of all events. For example, the total number of all events is approximately

513 100 for Trappes, Bordeaux, and Essen, approximately 150 for Stuttgart and Payerne, and approximately 200 for Munich and
514 Vienna reflecting the climatological distribution (north-to-south and west-to-east gradient) of atmospheric stability (Mohr and
515 Kunz, 2013).

516 The exceptional nature of the atmospheric conditions in 2018 is supported by the fact that, for example, the maximum event
517 persistence of 19 days between 1981 and 2017 (observed in Vienna) was exceeded in 2018 by two of the considered sounding
518 stations (Stuttgart, Munich). Additionally, when examining the individual stations, it can be seen that the CE duration of 2018
519 at the stations Stuttgart, Essen, Munich and Payerne have never been observed since 1981. The same applies to the Stuttgart
520 sounding compared with the results in PIP16, where so far a maximum CE event persistence of 16 days (1960–2014, but
521 summer half-year) has been calculated. Furthermore, the relative frequency of CE at the other stations (Trappes, Bordeaux,
522 Vienna) is also rare (0.5–2 %).

523 **4.3 Cut-off lows**

524 In May and June, cut-off lows particularly affected southern Europe and the Mediterranean region. The highest frequency
525 during the climatological period from 1981 to 2010 is found over Portugal and Turkey but with values of around 4 % (contour
526 in Fig. 10b; cf. Nieto et al., 2007b; Wernli and Sprenger, 2007). This means that during a 22-day period (same time horizon of
527 the study period) in May and June an average of 0.9 days (4 % of 22 days) with PV cut-off can be expected. During the 2018
528 thunderstorm episode, the anomaly of the PV cut-off frequency from the climatological mean was exceptionally large with
529 maximum values of around 40 % confined to northern Iberia and the Bay of Biscay in western Europe. This means that in 2018
530 a PV cut-off was up to 10 times higher than the climatological mean, resulting in 9 additional days. The region of anomalous
531 PV cut-off activity expands northward over the British Isles and the adjacent Atlantic Ocean and the North Sea, still with an
532 excess of 20 % (additional 4 days compared to climatological mean). In other regions, PV cut-off occurrence was similar to
533 the climatological mean. As an orientation, note that the standard deviation of the cut-off low frequency between 1981 to 2010
534 (May/June) is 3 % over northern Iberia and the Bay of Biscay and between 1 and 2 % over the British Isles (not shown). We
535 conclude that the unusual blocking situation over Europe effectively caused cut-off formation on its upstream flank, which then
536 supported a (synoptic) lifting mechanism – the third ingredient for thunderstorm development, together with instability and
537 available moisture.

538 **5 Discussion**

539 In this study, we investigated the synoptic characteristics of an unusual three-week period of thunderstorm activity in central
540 Europe in May/June 2018. Interestingly, atmospheric blocking was key to providing the large-scale setting conducive for
541 convection in its vicinity. Because of the influence of large-scale mechanisms related to the block and affecting the entire
542 continent, a very high number of thunderstorms affected large parts of western and central Europe during an unusually long
543 period of three weeks. At the beginning of the thunderstorm period, southwesterly flow induced the advection of warm and
544 moist air masses into central Europe. Several studies have identified such a flow to provide convection-favouring conditions

545 (e.g. van Delden, 2001; Kapsch et al., 2012; Mohr, 2013; Merino et al., 2014; Wapler and James, 2015; Nisi et al., 2016; Piper
546 et al., 2019; Mohr et al., 2019). Subsequently, the low pressure gradient associated with the blocking anticyclone over the
547 (adjacent) European sector prevented a significant air mass change. Thus, moist and conditionally unstable stratified air masses
548 were trapped in a stationary flow on the southern flank of high pressure for more than three weeks (and were re-circulated).
549 A few authors have already identified atmospheric blocking as a relevant influencer for widespread thunderstorms. PIP16, for
550 example, showed that the exceptional thunderstorm episode in 2016 in Germany was related to the sequence of Scandinavian
551 and European Blocking. Santos and Belo-Pereira (2019) identified a blocking-like dynamical structure in addition to a Western
552 European and a Scandinavian trough to be responsible for approximately three-quarters of all hail events across Portugal. By
553 combining ERA-Interim reanalysis and lightning detections over a 14-years period, Mohr et al. (2019) found that the presence
554 of a block over the Baltic Sea is frequently associated with increased odds of thunderstorm occurrence due to convection-
555 favouring conditions on its western flank (southwesterly advection of warm, moist and unstable air masses).

556 Upper-level cut-off lows or filaments of high PV that separate from the main PV cut-off were key in creating conditions
557 conducive for convective activity on the meso-scale. Accompanying lifting provides a weak but persistent ascent, which serves
558 to precondition the thermodynamic environment by adiabatic cooling, thereby increasing CAPE and reducing CIN (Markowski
559 and Richardson, 2010). Or it can generate instability, if an entire column is lifted bodily until complete saturation in case of
560 potential instability. On several days during the peak thunderstorm activity, we found that the majority of thunderstorms (based
561 on lightning detections) can be related to a PV cut-off. Lifting associated with these cut-offs prepared the atmosphere for
562 convective initiation on the downstream flank. Note that the initiation processes themselves are typically associated with phe-
563 nomena such as convergence lines, orographic lifting, thermally driven circulations, and boundary-layer thermals (Markowski
564 and Richardson, 2010). The large positive anomaly in PV cut-off frequency, which seems to be relevant for the exceptionally
565 high number of thunderstorms during the study period, in turn was also related to atmospheric blocking. The latter repeatedly
566 lead to the elongation of troughs on its upstream flanks, which finally led to several cut-off lows. The general flow patterns
567 consisting of this spatially extended ridge flanked by troughs persisted over a period of three weeks.

568 Heavy rain events are a result of continuously high rain rates, whereby the duration of an event is linked to its propagation
569 speed and the size of the convective system (Doswell et al., 1996). In addition, a high concentration of water vapour at low
570 levels in the presence of strong updrafts, high environmental relative humidity, significant cloud depth below the freezing level
571 contribute to maximize rain accumulations, and potentially weak vertical wind shear, which tend to be correlated with weak
572 mid-tropospheric winds (Markowski and Richardson, 2010). Due to the low propagation speeds, which contributes to long
573 rainfall duration during the thunderstorm episode in 2018, and high rain rates (60 mm h^{-1} continuously over 50 min), some of
574 the thunderstorms were able to produce torrential amounts of rain locally. Furthermore, the stagnant flow at mid-tropospheric
575 levels and thus the low vertical wind shear as a consequence of the blocking (cf. PIP16; Mohr et al., 2019) were also conducive
576 and frequently prevented most thunderstorms from developing into organized systems such as large MCS or supercells (cf.
577 Weisman and Klemp, 1982; Doswell and Evans, 2003; Markowski and Richardson, 2010). Most of the thunderstorms formed
578 as short-lived isolated cells or slow-moving multicellular clusters.

579 6 Summary and Conclusions

580 In our study, we investigated an exceptionally large number of thunderstorms in western and central Europe over a three-week
581 period, mid-May to mid-June 2018, using a combination of observational data and model data to gain a more holistic view of
582 the prevailing dynamical and thermodynamical conditions and the decisive trigger mechanisms for this unusual thunderstorm
583 episode. Additional data over a climatological period helped to place the event in its historical context. The 2018 thunderstorm
584 episode was exceptional in several respects: (i) the unusual large number of several thousand thunderstorms that caused more
585 than 5 million lightning strikes (all types) in the study area; (ii) the combination of low stability (negative Lifted Index) and
586 low wind speed at mid-tropospheric levels ($\leq 5 \text{ m s}^{-1}$ at some locations) that prevailed almost every day during the 22-day
587 period; (iii) the large cut-off low frequency that contributed to convective initiation for the majority of convection development;
588 and (iv) the high rainfall totals with several new records (e.g. Dietenhofen 86 mm/1 h) mainly as a consequence of the low
589 propagation speed of the storms in combination with high rain rates leading to several pluvial flash floods.

590 The other main conclusions drawn from our analyses are:

- 591 – Atmospheric blocking, albeit frequently associated with heatwaves and droughts, provided large-scale environmental
592 conditions favouring convection in its vicinity when unstably stratified air masses are advected into Europe and/or be-
593 come entrapped in stagnant flow.
- 594 – In the present paper, blocking is accompanied by a high cut-off frequency on its upstream side, which together with
595 filaments of high PV provided the meso-scale setting for deep moist convection. Compared to climatology, the number
596 of cut-off lows in parts of the study area during the study period was up to 10 times higher.
- 597 – The exceptional persistence of low stability combined with weak wind speed in the mid-troposphere prevailing over
598 more than three weeks in some regions, especially in Germany and Austria, has never been observed during the past
599 climatological period of 30 years. This situation was similar to the 2016 thunderstorm episode documented by PIP16,
600 but with a much longer persistence.
- 601 – Blocking often associated with low mid-tropospheric wind speeds/low wind shear (cf. Mohr et al., 2019) reduces the
602 development in severe organized convective systems. However, because of the low propagation speed of the storms
603 related to the low-pressure gradient within the block, torrential rainfalls can occur on a local scale.

604 A growing understanding of the relationship between atmospheric blocking and deep moist convection can enhance – due
605 to the associated persistence – the forecast horizon of thunderstorms on sub-seasonal time scales beyond the classical weather
606 forecast time scale of a few days. This may, for example, help with disaster management, large outdoor activities, and the
607 agriculture sector. It is only helpful, however, if blocked areas are correctly predicted. Recent studies show that this remains
608 a challenge for present numerical weather prediction and climate models (Ferranti et al., 2015; Grams et al., 2018), which,
609 for example, underestimate the blocking frequency in the Atlantic-European sector (Quinting and Vitart, 2019; Attinger et al.,
610 2019).

611 In future, we intend to investigate statistically some of this study's results, such as the relationship between blocking, cut-
612 off lows, air mass transport, and thunderstorm probability. Furthermore, we want to distinguish between different hazard
613 types (hail, heavy rain, gusts) and associated types of thunderstorms and blocking regimes that reveal possible differences in
614 atmospheric processes.

615 *Acknowledgements.* The authors thank the various national weather service (DWD; MeteoSwiss; Météo-France; Royal Netherlands Me-
616 teorological Institute, KNMI; Zentralanstalt für Meteorologie und Geodynamik; ZAMG), the European Climate Assessment and Dataset
617 (ECA&D) project, the Blitz-Informationdienst von Siemens (BLIDS; namely Stephan Thern), the Integrated Global Radiosonde Archive
618 (IGRA) and the European Severe Storms Laboratory (ESSL) for providing different observational data sets. In addition, we thank the Euro-
619 pean Centre for Medium-Range Weather Forecasts (ECMWF) for providing the operational analysis and the ERA-Interim reanalysis data.
620 The data analysis and visualisation was partly done using the NCAR Command Language (UCAR/NCAR/CISL/VETS, 2019). Furthermore,
621 we thank Michael Sprenger (ETH Zurich) for compiling the ERA-Interim PV cutoff climatology and Florian Ehmele (KIT) for the post-
622 processing of the REGINE data (return periods). The contributions of CMG, JFQ, and JaWa were funded by the Helmholtz Association
623 as part of the Young Investigator Group „Sub-Seasonal Predictability: Understanding the Role of Diabatic Outflow“ (SPREADOUT; grant
624 VH-NG-1243). We acknowledge the constructive comments two anonymous reviewers, which helped to improve the quality of the paper.

625 *Data availability.* REGINE (doi:10.1127/0941-2948/2013/0436), German precipitation data, and 3D radar data used in this paper are freely
626 available for research and can be requested at DWD. Tracks of severe convective storms were calculated from the DWD radar data and are
627 not freely available, but can be made available on request to Michael Kunz for research. Data from ECA&D can be downloaded via the
628 project website (<https://www.ecad.eu>), from Météo-France via https://donneespubliques.meteofrance.fr/?fond=rubrique&id_rubrique=26,
629 from MeteoSwiss via [https://www.meteoswiss.admin.ch/home/services-and-publications/beratung-und-service/datenportal-fuer-lehre-und-](https://www.meteoswiss.admin.ch/home/services-and-publications/beratung-und-service/datenportal-fuer-lehre-und-forschung.html)
630 [forschung.html](https://www.meteoswiss.admin.ch/home/services-and-publications/beratung-und-service/datenportal-fuer-lehre-und-forschung.html), and from ZMAG via <https://www.zamg.ac.at/cms/de/klima/produkte-und-services/daten-und-statistiken/messdaten>. Sound-
631 ing data are available from the Integrated Global Radiosonde Archive ([https://www.ncdc.noaa.gov/data-access/weather-balloon/integrated-](https://www.ncdc.noaa.gov/data-access/weather-balloon/integrated-global-radiosonde-archive)
632 [global-radiosonde-archive](https://www.ncdc.noaa.gov/data-access/weather-balloon/integrated-global-radiosonde-archive)) and data from the ESWD can be obtained via <https://www.eswd.eu> (see terms and conditions for academic or
633 commercial use). Lightning data are not freely available, but can be requested from the Blitz-Informationdienst von Siemens (<http://blids.de>).
634 ECMWF ERA-Interim reanalysis and operational analysis are also online available via <https://apps.ecmwf.int/datasets/data/interim-full-daily>
635 and the TIGGE webpage (control forecast step 0; <https://apps.ecmwf.int/datasets/data/tigge>). The methods to detect cut-off lows based on
636 these data are given in Wernli and Sprenger (2007) and Sprenger et al. (2017) and for weather regimes in Grams et al. (2017).

637 *Author contributions.* All KIT authors jointly conceived the research questions of the study, continuously discussed the results and wrote the
638 text passages for their respective contribution. SM analysed the ESWD data and together with JaWi the environmental conditions during the
639 thunderstorm episode and in a historical context. In addition, SM wrote the introduction part together with CMG and the discussion/summary
640 part of the paper together with MK and prepared the final draft version of the paper. JaWi also described the synoptic overview and the rainfall
641 statistics in 2018, which were produced by HJP. The return periods of rainfall were investigated by MK, who also examined the lightning data.

642 Based on LAGRANTO, JQ performed backward trajectory analysis. MS contributed with the analyses of the storm track data (propagation
643 speed of convective cells). RP generated the PV cut-off data and its relationship to lightning activity was analysed by JaWa and CMG. In
644 addition, CMG contributed with the analysis of the weather regimes. Finally, all co-authors edited the final draft and provided substantial
645 comments and constructive suggestions for scientific clarification and further improvements.

646 *Competing interests.* The authors declare that they have no conflict of interest.

647 *Supplement.* The supplement related to this article is available online at: <https://doi.org/10.5194/jn-0-1-2020-supplement>.

648 *Video supplement.* Video supplement related to this paper is available from the Repository KITopen at:
649 <https://doi.org/10.5445/IR/1000118571> and <https://doi.org/10.5445/IR/1000118574>.

650 References

- 651 Attinger, R., Keller, J. H., Köhler, M., Riboldi, J., and Grams, C. M.: Representation of atmospheric blocking in the new global non-
652 hydrostatic weather prediction model ICON, *Meteorol. Z.*, 28, 429–446, <https://doi.org/10.1127/metz/2019/0967>, 2019.
- 653 Barriopedro, D., García-Herrera, R., Lupo, A. R., and Hernández, E.: A climatology of Northern Hemisphere blocking, *J. Climate*, 19,
654 1042–1063, <https://doi.org/10.1175/JCLI3678.1>, 2006.
- 655 Barthlott, C., Schipper, J. W., Kalthoff, N., Adler, B., Kottmeier, C., Blyth, A., and Mobbs, S.: Model representation of boundary-
656 layer convergence triggering deep convection over complex terrain: A case study from COPS, *Atmos. Res.*, 95, 172–185,
657 <https://doi.org/10.1016/j.atmosres.2009.09.010>, 2010.
- 658 Bennett, L. J., Browning, K. A., Blyth, A. M., Parker, D. J., and Clark, P. A.: A review of the initiation of precipitating convection in the
659 United Kingdom, *Q. J. R. Meteorol. Soc.*, 132, 1001–1020, <https://doi.org/10.1256/qj.05.54>, 2006.
- 660 Bieli, M., Pfahl, S., and Wernli, H.: A Lagrangian investigation of hot and cold temperature extremes in Europe, *Q. J. R. Meteorol. Soc.*, 141,
661 98–108, <https://doi.org/10.1002/qj.2339>, 2015.
- 662 Bronstert, A., Agarwal, A., Boessenkool, B., Crisologo, I., Fischer, M., Heistermann, M., Köhn-Reich, L., López-Tarazón, J. A., Moran, T.,
663 Ozturk, U., Reinhardt-Imjela, C., and Wendi, D.: Forensic hydro-meteorological analysis of an extreme flash flood: The 2016-05-29 event
664 in Braunsbach, SW Germany, *Sci. Total Environ.*, 630, 977–991, <https://doi.org/10.1016/j.scitotenv.2018.02.241>, 2018.
- 665 Browning, K., Blyth, A., Clark, P., Corsmeier, U., Morcrette, C., Agnew, J., Bamber, D., Barthlott, C., Bennett, L., Beswick, K., Bitter,
666 M., Bozier, K., Brooks, B., Collier, C., Cook, C., Davies, F., Deny, B., Feuerle, T., Forbes, R., Gaffard, C., Gray, M., Rolf Hankers, R.,
667 Hewison, T., Kalthoff, N., Khodayar, S., Kohler, M., Kottmeier, C., Kraut, S., Kunz, M., Ladd, D., Lenfant, J., Marsham, J., McGregor,
668 J., Nicol, J., Norton, E., Parker, D., Perry, F., Ramatschi, M., Ricketts, H., Roberts, N., Russell, A., Schulz, H., Slack, E., Vaughan, G.,
669 Waight, J., Watson, R., Webb, A., and Wieser, A.: The Convective Storms Initiation Project, *Bull. Am. Meteorol. Soc.*, 88, 1939–1955,
670 <https://doi.org/10.1175/BAMS-88-12-1939>, 2007.
- 671 Corfidi, S. F.: Cold pools and MCS propagation: Forecasting the motion of downwind-developing MCSs, *Weather Forecast.*, 18, 997–1017,
672 [https://doi.org/10.1175/1520-0434\(2003\)018<0997:CPAMPF>2.0.CO;2](https://doi.org/10.1175/1520-0434(2003)018<0997:CPAMPF>2.0.CO;2), 2003.
- 673 Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P.,
674 Bechtold, P., Beljaars, A. C. M., Van De Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger,
675 L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, I., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Mor-
676 crette, J. J., Park, B. K., Peubey, C., De Rosnay, P., Tavolato, C., Thépaut, J. N., and Vitart, F.: The ERA-Interim reanalysis: Configuration
677 and performance of the data assimilation system, *Q. J. R. Meteorol. Soc.*, 137, 553–597, <https://doi.org/10.1002/qj.828>, 2011.
- 678 Dennis, E. J. and Kumjian, M. R.: The impact of vertical wind shear on hail growth in simulated supercells, *J. Atmos. Sci.*, 74, 641–663,
679 <https://doi.org/10.1175/JAS-D-16-0066.1>, 2017.
- 680 Dole, R. M. and Gordon, N. D.: Persistent anomalies of the extratropical Northern Hemisphere wintertime circulation: Geo-
681 graphical distribution and regional persistence characteristics, *Mon. Weather Rev.*, 111, 1567–1586, [https://doi.org/10.1175/1520-0493\(1983\)111<1567:PAOTEN>2.0.CO;2](https://doi.org/10.1175/1520-0493(1983)111<1567:PAOTEN>2.0.CO;2), 1983.
- 683 Doswell, C. A. and Evans, J. S.: Proximity sounding analysis for derechos and supercells: An assessment of similarities and differences,
684 *Atmos. Res.*, 67, 117–133, [https://doi.org/10.1016/S0169-8095\(03\)00047-4](https://doi.org/10.1016/S0169-8095(03)00047-4), 2003.
- 685 Doswell, C. A., Brooks, H. E., and Maddox, R. A.: Flash flood forecasting: An ingredients-based methodology, *Weather Forecast.*, 11,
686 560–581, [https://doi.org/10.1175/1520-0434\(1996\)011<0560:FFFAIB>2.0.CO;2](https://doi.org/10.1175/1520-0434(1996)011<0560:FFFAIB>2.0.CO;2), 1996.

687 Dotzek, N., Groenemeijer, P., Feuerstein, B., and Holzer, A. M.: Overview of ESSL's severe convective storms research using the European
688 Severe Weather Database ESWD, *Atmos. Res.*, 93, 575–586, <https://doi.org/10.1016/j.atmosres.2008.10.020>, 2009.

689 Drüe, C., Hauf, T., Finke, U., Keyn, S., and Kreyer, O.: Comparison of a SAFIR lightning detection network in northern Germany to the
690 operational BLIDS network, *J. Geophys. Res. Atmos.*, 112, D18 114, <https://doi.org/10.1029/2006JD007680>, 2007.

691 Durre, I., Vose, R. S., and Wuertz, D. B.: Overview of the integrated global radiosonde archive, *J. Climate*, 1151, 53–68,
692 <https://doi.org/10.1175/JCLI3594.1>, 2006.

693 DWD: Schadensrückblick des Deutschen Wetterdienstes: Gefährliche Wetterereignisse und Wetterschä-
694 den in Deutschland 2018, Deutscher Wetterdienst (DWD), Offenbach, Germany. Available from:
695 https://www.dwd.de/DE/presse/pressemitteilungen/DE/2018/20181213_schadensrueckblick2018_news.html (Accessed 6 March 2020),
696 2018a.

697 DWD: REGNIE: Regionalisierte Niederschläge Verfahrensbeschreibung und Nutzeranleitung, Deutscher Wetterdienst (DWD), Abteilung
698 Hydrometeorologie, Offenbach, Germany. Available from: <https://www.dwd.de/DE/leistungen/regnie/regnie.html?nn=353366> (Accessed
699 13 December 2019), 2018b.

700 DWD: RADOLAN/RADVOR: Hoch aufgelöste Niederschlagsanalyse und -vorhersage auf der Basis quantitativer Radar- und Om-
701 brometerdaten für grenzüberschreitende Fluss-Einzugsgebiete von Deutschland im Echtzeitbetrieb – Beschreibung des Kompositfor-
702 mats Version 2.5, Tech. rep., Deutscher Wetterdienst (DWD): Abteilung Hydrometeorologie, Offenbach, Germany. Available from:
703 <https://www.dwd.de/DE/leistungen/radolan/radolan.html> (Accessed 6 March 2020), 2019.

704 Ehmele, F. and Kunz, M.: Flood-related extreme precipitation in Southwestern Germany: Development of a two-dimensional stochastic
705 precipitation model, *Hydrol. Earth Syst. Sci.*, 23, 1083–1102, <https://doi.org/10.5194/hess-23-1083-2019>, 2019.

706 Enno, S.-E., Sugier, J., Alber, R., and Seltzer, M.: Lightning flash density in Europe based on 10 years of ATDnet data, *Atmos. Res.*, 235,
707 104 769, <https://doi.org/10.1016/j.atmosres.2019.104769>, 2020.

708 ESSL: ESWD Event reporting criteria, Last revision: May 10, 2014, European Severe Storms Laboratory e.V., Munich, Germany. Available
709 from: https://www.eswd.eu/docs/ESWD_criteria_en.pdf (Accessed 13 December 2019), 2014.

710 Ferranti, L., Corti, S., and Janousek, M.: Flow-dependent verification of the ECMWF ensemble over the Euro-Atlantic sector, *Q. J. R.*
711 *Meteorol. Soc.*, 141, 916–924, <https://doi.org/10.1002/qj.2411>, 2015.

712 Galway, J. G.: The lifted index as a predictor of latent instability, *Bull. Am. Meteorol. Soc.*, 37, 528–529, [https://doi.org/10.1175/1520-0477-](https://doi.org/10.1175/1520-0477-37.10.528)
713 [37.10.528](https://doi.org/10.1175/1520-0477-37.10.528), 1956.

714 Grams, C. M., Binder, H., Pfahl, S., Piaget, N., and Wernli, H.: Atmospheric processes triggering the central European floods in June 2013,
715 *Nat. Hazards Earth Syst. Sci.*, 14, 1691–1702, <https://doi.org/10.5194/nhess-14-1691-2014>, 2014.

716 Grams, C. M., Beerli, R., Pfenninger, S., Staffell, I., and Wernli, H.: Balancing Europe's wind-power output through spatial deployment
717 informed by weather regimes, *Nat. Clim. Change*, 7, 557–562, <https://doi.org/10.1038/nclimate3338>, 2017.

718 Grams, C. M., Magnusson, L., and Madonna, E.: An atmospheric dynamics perspective on the amplification and propagation of forecast error
719 in numerical weather prediction models: A case study, *Q. J. R. Meteorol. Soc.*, 144, 2577–2591, <https://doi.org/10.1002/qj.3353>, 2018.

720 Groenemeijer, P., Půčik, T., Holzer, A. M., Antonescu, B., Riemann-Campe, K., Schultz, D. M., Kühne, T., Feuerstein, B., Brooks, H. E.,
721 Doswell, C. A., Koppert, H.-J., and Sausen, R.: Severe convective storms in Europe: Ten years of research at the European Severe Storms
722 Laboratory, *Bull. Am. Meteorol. Soc.*, 98, 2641–2651, <https://doi.org/10.1175/BAMS-D-16-0067.1>, 2017.

723 Gumbel, E. J.: *Statistics of Extremes*, Columbia University Press, New York, USA, 1958.

724 Haklander, A. J. and van Delden, A.: Thunderstorm predictors and their forecast skill for the Netherlands, *Atmos. Res.*, 67–68, 273–299,
725 [https://doi.org/10.1016/S0169-8095\(03\)00056-5](https://doi.org/10.1016/S0169-8095(03)00056-5), 2003.

726 Handwerker, J.: Cell tracking with TRACE3D — A new algorithm, *Atmos. Res.*, 61, 15–34, [https://doi.org/10.1016/S0169-8095\(01\)00100-4](https://doi.org/10.1016/S0169-8095(01)00100-4),
727 2002.

728 Hoskins, B. J., McIntyre, M. E., and Robertson, A. W.: On the use and significance of isentropic potential vorticity maps, *Q. J. R. Meteorol.*
729 *Soc.*, 111, 877–946, <https://doi.org/10.1002/qj.49711147002>, 1985.

730 Houston, A. L. and Wilhelmson, R. B.: The impact of airmass boundaries on the propagation of deep convection: A modeling-based study
731 in a high-CAPE, low-shear environment, *Mon. Weather Rev.*, 140, 167–183, <https://doi.org/doi:10.1175/MWR-D-10-05033.1>, 2012.

732 Huntrieser, H., Schiesser, H. H., Schmid, W., and Waldvogel, A.: Comparison of traditional and newly developed thunderstorm indices for
733 Switzerland, *Weather Forecast.*, 12, 108–125, [https://doi.org/10.1175/1520-0434\(1997\)012<0108:COTAND>2.0.CO;2](https://doi.org/10.1175/1520-0434(1997)012<0108:COTAND>2.0.CO;2), 1997.

734 Johns, R. H. and Doswell, C. A.: Severe local storms forecasting, *Weather Forecast.*, 7, 588–612, [https://doi.org/10.1175/1520-0434\(1992\)007<0588:SLSF>2.0.CO;2](https://doi.org/10.1175/1520-0434(1992)007<0588:SLSF>2.0.CO;2), 1992.

736 Kapsch, M. L., Kunz, M., Vitolo, R., and Economou, T.: Long-term trends of hail-related weather types in an ensemble of regional climate
737 models using a Bayesian approach, *J. Geophys. Res.*, 117, D15 107, <https://doi.org/10.1029/2011JD017185>, 2012.

738 Klein Tank, A. M. G., Wijngaard, J. B., Können, G. P., Böhm, R., Demarée, G., Gocheva, A., Mileta, M., Pashiardis, S., Hejkrlik, L.,
739 Kern-Hansen, C., Heino, R., Bessemoulin, P., Müller-Westermeier, G., Tzanakou, M., Szalai, S., Pálsdóttir, T., Fitzgerald, D., Rubin, S.,
740 Capaldo, M., Maugeri, M., Leitass, A., Bukantis, A., Aberfeld, R., van Engelen, A. F. V., Forland, E., Miletus, M., Coelho, F., Mares,
741 C., Razuvaev, V., Nieplova, E., Cegnar, T., Antonio López, J. A., Dahlström, B., Moberg, A., Kirchhofer, W., Ceylan, A., Pachaliuk, O.,
742 Alexander, L. V., and Petrovic, P.: Daily dataset of 20th-century surface air temperature and precipitation series for the European climate
743 assessment, *Int. J. Climatol.*, 22, 1441–1453, <https://doi.org/10.1002/joc.773>, 2002.

744 Kunz, M.: The skill of convective parameters and indices to predict isolated and severe thunderstorms, *Nat. Hazards Earth Syst. Sci.*, 7,
745 327–342, <https://doi.org/10.5194/nhess-7-327-2007>, 2007.

746 Kunz, M., Wandel, J., Fluck, E., Baumstark, S., Mohr, S., and Schemm, S.: Ambient conditions prevailing during hail events in central
747 Europe, *Nat. Hazards Earth Syst. Sci. Discuss.* (accepted), <https://doi.org/10.5194/nhess-2019-412>, 2020.

748 Lenggenhager, S. and Martius, O.: Atmospheric blocks modulate the odds of heavy precipitation events in Europe, *Clim. Dynam.*, 53,
749 4155–4171, <https://doi.org/10.1007/s00382-019-04779-0>, 2019.

750 Lenggenhager, S., Croci-Maspoli, M., Brönnimann, S., and Martius, O.: On the dynamical coupling between atmospheric blocks and
751 heavy precipitation events: A discussion of the southern Alpine flood in October 2000, *Q. J. R. Meteorol. Soc.*, 145, 530–545,
752 <https://doi.org/10.1002/qj.3449>, 2018.

753 Manzato, A.: A climatology of instability indices derived from Friuli Venezia Giulia soundings, using three different methods, *Atmos. Res.*,
754 67, 417–454, [https://doi.org/10.1016/S0169-8095\(03\)00058-9](https://doi.org/10.1016/S0169-8095(03)00058-9), 2003.

755 Markowski, P. and Richardson, Y.: *Mesoscale meteorology in midlatitudes*, John Wiley & Sons, Chichester, UK, 2010.

756 Martius, O., Sodemann, H., Joos, H., Pfahl, S., Winschall, A., Croci-Maspoli, M., Graf, M., Madonna, E., Mueller, B., Schemm, S., Sedlacek,
757 J., Sprenger, M., and Wernli, H.: The role of upper-level dynamics and surface processes for the Pakistan flood of July 2010, *Q. J. R.*
758 *Meteorol. Soc.*, 139, 1780–1797, <https://doi.org/10.1002/qj.2082>, 2013.

759 Merino, A., Wu, X., Gascón, E., Berthet, C., García-Ortega, E., and Dessens, J.: Hailstorms in southwestern France: Incidence and atmo-
760 spheric characterization, *Atmos. Res.*, 140–141, 61–75, <https://doi.org/10.1016/j.atmosres.2014.01.015>, 2014.

761 Michel, C. and Rivière, G.: The link between Rossby wave breakings and weather regime transitions, *J. Atmos. Sci.*, 68, 1730–1748,
762 <https://doi.org/10.1175/2011JAS3635.1>, 2011.

763 Michelangeli, P.-A., Vautard, R., and Legras, B.: Weather regimes: Recurrence and quasi stationarity, *J. Atmos. Sci.*, 52, 1237–1256,
764 [https://doi.org/10.1175/1520-0469\(1995\)052<1237:WRRASQ>2.0.CO;2](https://doi.org/10.1175/1520-0469(1995)052<1237:WRRASQ>2.0.CO;2), 1995.

765 Mohr, S.: Änderung des Gewitter- und Hagelpotentials im Klimawandel, Ph.D. thesis, *Wiss. Berichte d. Instituts für Meteorologie und Klimaforschung des Karlsruher Instituts für Technologie*, Vol. 58, KIT Scientific Publishing, Karlsruhe, Germany,
766 <https://doi.org/10.5445/KSP/1000033828>, 2013.

768 Mohr, S. and Kunz, M.: Recent trends and variabilities of convective parameters relevant for hail events in Germany and Europe, *Atmos. Res.*, 123, 211–228, <https://doi.org/10.1016/j.atmosres.2012.05.016>, 2013.

770 Mohr, S., Wandel, J., Lenggenhager, S., and Martius, O.: Relationship between atmospheric blocking and warm season thunderstorms over
771 western and central Europe, *Q. J. R. Meteorol. Soc.*, 145, 3040–3056, <https://doi.org/10.1002/qj.3603>, 2019.

772 Morcrette, C., Lean, H., Browning, K., Nicol, J., Roberts, N., Clark, P., Russell, A., and Blyth, A.: Combination of mesoscale and synop-
773 tic mechanisms for triggering an isolated thunderstorm: Observational case study of CSIP IOP 1, *Mon. Weather Rev.*, 135, 3728–3749,
774 <https://doi.org/10.1175/2007MWR2067.1>, 2007.

775 Munich Re: Natural catastrophe statistics online – the new NatCatSERVICE analysis tool, Munich Re, Munich, Germany. Available from:
776 <https://www.munichre.com/en/reinsurance/business/non-life/natcatservice/index.html> (Accessed 13 December 2019), 2019.

777 Nachtnebel, H.-P.: New strategies for flood risk management after the catastrophic flood in 2002 in Europe, in: *Third DPRI-IIASA International Symposium on Integrated Disaster Risk Management: Coping with Regional Vulnerability*, Full Conference Proceedings; 3-5 July
778 2003, Kyoto International Conference Hall, Kyoto, Japan, 2003.

780 Nieto, R., Gimeno, L., Añel, J. A., De la Torre, L., Gallego, D., Barriopedro, D., Gallego, M., Gordillo, A., Redaño, A., and Delgado,
781 G.: Analysis of the precipitation and cloudiness associated with COLs occurrence in the Iberian Peninsula, *Meteorol. Atmos. Phys.*, 96,
782 103–119, <https://doi.org/10.1007/s00703-006-0223-6>, 2007a.

783 Nieto, R., Gimeno, L., De la Torre, L., Ribera, P., Barriopedro, D., García-Herrera, R., Serrano, A., Gordillo, A., Redano, A., and Lorente,
784 J.: Interannual variability of cut-off low systems over the European sector: The role of blocking and the Northern Hemisphere circulation
785 modes, *Meteorol. Atmos. Phys.*, 96, 85–101, <https://doi.org/10.1007/s00703-006-0222-7>, 2007b.

786 Nieto, R., Sprenger, M., Wernli, H., Trigo, R. M., and Gimeno, L.: Identification and climatology of cut-off lows near the tropopause, *Ann. NY Acad. Sci.*, 1146, 256–290, <https://doi.org/10.1196/annals.1446.016>, 2008.

788 Nisi, L., Martius, O., Hering, A., Kunz, M., and Germann, U.: Spatial and temporal distribution of hailstorms in the Alpine region: A
789 long-term, high resolution, radar-based analysis, *Q. J. R. Meteorol. Soc.*, 142, 1590–1604, <https://doi.org/10.1002/qj.2771>, 2016.

790 Ozturk, U., Wendi, D., Crisologo, I., Riemer, A., Agarwal, A., Vogel, K., López-Tarazón, J. A., and Korup, O.: Rare flash floods and debris
791 flows in southern Germany, *Sci. Total Environ.*, 626, 941–952, <https://doi.org/10.1016/j.scitotenv.2018.01.172>, 2018.

792 Pfahl, S. and Wernli, H.: Quantifying the relevance of atmospheric blocking for co-located temperature extremes in the Northern Hemisphere
793 on (sub-)daily time scales, *Geophys. Res. Lett.*, 39, L12 807, <https://doi.org/10.1029/2012GL052261>, 2012a.

794 Pfahl, S. and Wernli, H.: Quantifying the relevance of cyclones for precipitation extremes, *J. Climate*, 25, 6770–6780,
795 <https://doi.org/10.1175/JCLI-D-11-00705.1>, 2012b.

796 Piaget, N., Froidevaux, P., Giannakaki, P., Gierth, F., Martius, O., Riemer, M., Wolf, G., and Grams, C. M.: Dynamics of a local
797 Alpine flooding event in October 2011: Moisture source and large-scale circulation, *Q. J. R. Meteorol. Soc.*, 141, 1922–1937,
798 <https://doi.org/10.1002/qj.2496>, 2015.

799 Piper, D. and Kunz, M.: Spatiotemporal variability of lightning activity in Europe and the relation to the North Atlantic Oscillation telecon-
800 nection pattern, *Nat. Hazards Earth Syst. Sci.*, 17, 1319–1336, <https://doi.org/10.5194/nhess-17-1319-2017>, 2017.

801 Piper, D., Kunz, M., Ehmele, F., Mohr, S., Mühr, B., Kron, A., and Daniell, J.: Exceptional sequence of severe thunderstorms and re-
802 lated flash floods in May and June 2016 in Germany. Part I: Meteorological background, *Nat. Hazards Earth Syst. Sci.*, 16, 2835–2850,
803 <https://doi.org/10.5194/nhess-16-2835-2016>, 2016.

804 Piper, D. A., Kunz, M., Allen, J. T., and Mohr, S.: Investigation of the temporal variability of thunderstorms in Central and Western Europe
805 and the relation to large-scale flow and teleconnection patterns, *Q. J. R. Meteorol. Soc.*, 145, 3644–3666, <https://doi.org/10.1002/qj.3647>,
806 2019.

807 Poelman, D. R., Schulz, W., Diendorfer, G., and Bernardi, M.: The European lightning location system EUCLID – Part 2: Observations, *Nat.*
808 *Hazards Earth Syst. Sci.*, 16, 607–616, <https://doi.org/10.5194/nhess-16-607-2016>, 2016., 2016.

809 Portmann, R., Crezee, B., Quinting, J., and Wernli, H.: The complex life cycles of two long-lived potential vorticity cut-offs over Europe, *Q.*
810 *J. R. Meteorol. Soc.*, 144, 701–719, <https://doi.org/10.1002/qj.3239>, 2018.

811 Puskeiler, M., Kunz, M., and Schmidberger, M.: Hail statistics for Germany derived from single-polarization radar data, *Atmos. Res.*, 178–
812 179, 459–470, <https://doi.org/10.1016/j.atmosres.2016.04.014>, 2016.

813 Quinting, J. F. and Vitart, F.: Representation of synoptic-scale Rossby wave packets and blocking in the S2S Prediction Project Database,
814 *Geophys. Res. Lett.*, 46, 1070–1078, <https://doi.org/10.1029/2018GL081381>, 2019.

815 Rädler, A. T., Groenemeijer, P., Faust, E., and Sausen, R.: Detecting severe weather trends using an Additive Regressive Convective Hazard
816 Model (AR-CHaMo), *J. Appl. Meteorol. Climatol.*, 57, 569–587, <https://doi.org/10.1175/JAMC-D-17-0132.1>, 2018.

817 Rasmussen, P. F. and Gautam, N.: Alternative PWM-estimators of the Gumbel distribution, *J. Hydrol.*, 280, 265–271,
818 [https://doi.org/10.1016/S0022-1694\(03\)00241-5](https://doi.org/10.1016/S0022-1694(03)00241-5), 2003.

819 Rauthe, M., Steiner, H., Riediger, U., A., M., and Gratzki, A.: A Central European precipitation climatology – Part I: Generation and
820 validation of a high-resolution gridded daily data set (HYRAS), *Meteorol. Z.*, 22, 235–256, <https://doi.org/10.1127/0941-2948/2013/0436>,
821 2013.

822 Rex, D. F.: Blocking action in the middle troposphere and its effect upon regional climate: I. An aerological study of blocking action, *Tellus*,
823 2, 196–211, <https://doi.org/10.3402/tellusa.v2i3.8546>, 1950a.

824 Rex, D. F.: Blocking action in the middle troposphere and its effect upon regional climate: II. The climatology of blocking action, *Tellus*, 2,
825 275–301, <https://doi.org/10.3402/tellusa.v2i4.8603>, 1950b.

826 Roberts, N. M.: The relationship between water vapour imagery and thunderstorms, Joint Centre for Mesoscale Meteorology Internal Report
827 No. 110, Met Office, Reading, UK, 2000.

828 Röthlisberger, M. and Martius, O.: Quantifying the local effect of Northern Hemisphere atmospheric blocks on the persistence of summer
829 hot and dry spells, *Geophys. Res. Lett.*, 43, 10 101–10 111, <https://doi.org/10.1029/2019GL083745>, 2019.

830 Röthlisberger, M., Martius, O., and Wernli, H.: Northern Hemisphere Rossby wave initiation events on the extratropical jet – A climatological
831 analysis, *J. Climate*, 31, 743–760, <https://doi.org/10.1175/JCLI-D-17-0346.1>, 2018.

832 Russell, A., Vaughan, G., and Norton, E. G.: Large-scale potential vorticity anomalies and deep convection, *Q. J. R. Meteorol. Soc.*, 138,
833 1627–1639, <https://doi.org/10.1002/qj.1875>, 2012.

834 Sánchez, J. L., Marcos, J. L., Dessens, J., López, L., Bustos, C., and García-Ortega, E.: Assessing sounding-derived parameters as storm
835 predictors in different latitudes, *Atmos. Res.*, 93, 446–456, <https://doi.org/10.1016/j.atmosres.2008.11.006>, 2009.

836 Santos, J. A. and Belo-Pereira, M.: A comprehensive analysis of hail events in Portugal: Climatology and consistency with atmospheric
837 circulation, *Int. J. Climatol.*, 39, 188–205, <https://doi.org/10.1002/joc.5794>, 2019.

838 Schaller, N., Sillmann, J., Anstey, J., Fischer, E. M., Grams, C. M., and Russo, S.: Influence of blocking on Northern European and Western
839 Russian heatwaves in large climate model ensembles, *Environ. Res. Lett.*, 13, 054 015, <https://doi.org/10.1088/1748-9326/aaba55>, 2018.

840 Schmidberger, M.: Hagelgefährdung und Hagelrisiko in Deutschland basierend auf einer Kombination von Radardaten und Versicherungs-
841 daten, Ph.D. thesis, *Wiss. Berichte d. Instituts für Meteorologie und Klimaforschung des Karlsruher Instituts für Technologie*, Vol. 78,
842 KIT Scientific Publishing, Karlsruhe, Germany, <https://doi.org/10.5445/KSP/1000086012>, 2018.

843 Schulz, W., Diendorfer, G., Pedebay, S., and Poelman, D. R.: The European lightning location system EUCLID – Part 1: Performance
844 analysis and validation, *Nat. Hazards Earth Syst. Sci.*, 16, 595–605, <https://doi.org/10.5194/nhess-16-595-2016>, 2016.

845 Sivapalan, M. and Blöschl, G.: Transformation of point rainfall to areal rainfall: Intensity-duration-frequency curves, *J. Hydrol.*, 204, 150–
846 167, [https://doi.org/10.1016/S0022-1694\(03\)00241-5](https://doi.org/10.1016/S0022-1694(03)00241-5), 1998.

847 Sousa, P. M., Trigo, R. M., Barriopedro, D., Soares, P. M. M., Ramos, A. M., and Liberato, M. L. R.: Responses of European precipita-
848 tion distributions and regimes to different blocking locations, *Clim. Dynam.*, 48, 1141–1160, <https://doi.org/10.1007/s00382-016-3132-5>,
849 2017.

850 Sprenger, M. and Wernli, H.: The LAGRANTO Lagrangian analysis tool–version 2.0, *Geosci. Model Dev.*, 8, 2569–2586,
851 <https://doi.org/10.5194/gmd-8-2569-2015>, 2015.

852 Sprenger, M., Frangkoulidis, G., Binder, H., Croci-Maspoli, M., Graf, P., Grams, C. M., Knippertz, P., Madonna, E., Schemm, S., Škerlak,
853 B., and Wernli, H.: Global climatologies of Eulerian and Lagrangian flow features based on ERA-Interim, *Bull. Am. Meteorol. Soc.*, 98,
854 1739–1748, <https://doi.org/10.1175/BAMS-D-15-00299.1>, 2017.

855 Tarabukina, L. D., Antokhina, O. Y., Kononova, N. K., Kozlov, V. I., and Innokentiev, D. E.: Formation of intense thunderstorms in
856 Yakutia in periods of frequent atmospheric blocking in Western Siberia, in: *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 698, p. 044050,
857 <https://doi.org/10.1088/1757-899x/698/4/044050>, 2019.

858 Thompson, R. L., Mead, C. M., and Edwards, R.: Effective storm-relative helicity and bulk shear in supercell thunderstorm environments,
859 *Weather Forecast.*, 22, 102–115, <https://doi.org/10.1175/WAF969.1>, 2007.

860 Tibaldi, S. and Molteni, F.: On the operational predictability of blocking, *Tellus A*, 42, 343–365, <https://doi.org/10.1034/j.1600->
861 [0870.1990.t01-2-00003.x](https://doi.org/10.1034/j.1600-0870.1990.t01-2-00003.x), 1990.

862 Trapp, R. J.: *Mesoscale-convective processes in the atmosphere*, Cambridge University Press, New York, USA, 2013.

863 UCAR/NCAR/CISL/VETS: The NCAR Command Language (Version 6.6.2) [Software], Boulder, Colorado, USA,
864 <https://doi.org/10.5065/D6WD3XH5>, 2019.

865 van Delden, A.: The synoptic setting of thunderstorms in Western Europe, *Atmos. Res.*, 56, 89–110, <https://doi.org/10.1016/S0169->
866 [8095\(00\)00092-2](https://doi.org/10.1016/S0169-8095(00)00092-2), 2001.

867 van den Besselaar, E. J. M., Klein Tank, A. M. G., and Buishand, T. A.: Trends in European precipitation extremes over 1951–2010, *Int. J.*
868 *Climatol.*, 33, 2682–2689, <https://doi.org/10.1002/joc.3619>, 2013.

869 Vautard, R.: Multiple weather regimes over the North Atlantic: Analysis of precursors and successors, *Mon. Weather Rev.*, 118, 2056–2081,
870 [https://doi.org/10.1175/1520-0493\(1990\)118<2056:MWROTN>2.0.CO;2](https://doi.org/10.1175/1520-0493(1990)118<2056:MWROTN>2.0.CO;2), 1990.

871 Wapler, K.: High-resolution climatology of lightning characteristics within Central Europe, *Meteorol. Atmos. Phys.*, 122, 175–184,
872 <https://doi.org/10.1007/s00703-013-0285-1>, 2013.

873 Wapler, K. and James, P.: Thunderstorm occurrence and characteristics in Central Europe under different synoptic conditions, *Atmos. Res.*,
874 158, 231–244, <https://doi.org/10.1016/j.atmosres.2014.07.011>, 2015.

875 Weisman, M. L. and Klemp, J. B.: The dependence of numerically simulated convective storms on vertical wind shear and buoyancy, *Mon.*
876 *Weather Rev.*, 110, 504–520, [https://doi.org/10.1175/1520-0493\(1982\)110<0504:TDonSC>2.0.CO;2](https://doi.org/10.1175/1520-0493(1982)110<0504:TDonSC>2.0.CO;2), 1982.

877 Wernli, H. and Davies, H. C.: A Lagrangian-based analysis of extratropical cyclones. I: The method and some applications, *Q. J. R. Meteorol.*
878 *Soc.*, 123, 467–489, <https://doi.org/10.1002/qj.49712353811>, 1997.

879 Wernli, H. and Sprenger, M.: Identification and ERA-15 climatology of potential vorticity streamers and cutoffs near the extratropical
880 tropopause, *J. Atmos. Sci.*, 64, 1569–1586, <https://doi.org/10.1175/JAS3912.1>, 2007.

881 Westermayer, A. T., Groenemeijer, P., Pistotnik, G., Sausen, R., and Faust, E.: Identification of favorable environments for thunderstorms in
882 reanalysis data, *Meteorol. Z.*, 26, 59–70, <https://doi.org/10.1127/metz/2016/0754>, 2017.

883 WetterOnline: Tornado wütet bei Viersen: Dutzende Häuser stark beschädigt (17.05.2018), WetterOnline Meteorologische Dienstleistungen
884 GmbH, Bonn, Germany. Available from: [https://www.wetteronline.de/extremwetter/tornado-wuetet-bei-viersen-dutzende-haeuser-stark-](https://www.wetteronline.de/extremwetter/tornado-wuetet-bei-viersen-dutzende-haeuser-stark-beschaedigt-2018-05-17-tv)
885 [beschaedigt-2018-05-17-tv](https://www.wetteronline.de/extremwetter/tornado-wuetet-bei-viersen-dutzende-haeuser-stark-beschaedigt-2018-05-17-tv) (Accessed 13 March 2020), 2018a.

886 WetterOnline: Unwetterserie Ende Mai: Ganze Ortschaften verwüstet, WetterOnline Meteorologische Dienstleistungen GmbH, Bonn,
887 Germany. Available from: [https://www.wetteronline.de/extremwetter/unwetterserie-ende-mai-ganze-ortschaften-verwuestet-2018-05-31-](https://www.wetteronline.de/extremwetter/unwetterserie-ende-mai-ganze-ortschaften-verwuestet-2018-05-31-us)
888 [us](https://www.wetteronline.de/extremwetter/unwetterserie-ende-mai-ganze-ortschaften-verwuestet-2018-05-31-us) (Accessed 13 March 2020), 2018b.

889 WetterOnline: Unwetterserie im Juni: Überflutungen und Hagelmassen (14.06.2018), WetterOnline Meteorologische Dienstleistun-
890 gen GmbH, Bonn, Germany. Available from: [https://www.wetteronline.de/extremwetter/unwetterserie-im-juni-ueberflutungen-und-](https://www.wetteronline.de/extremwetter/unwetterserie-im-juni-ueberflutungen-und-hagelmassen-2018-06-14-js)
891 [hagelmassen-2018-06-14-js](https://www.wetteronline.de/extremwetter/unwetterserie-im-juni-ueberflutungen-und-hagelmassen-2018-06-14-js) (Accessed 13 March 2020), 2018c.

892 Wilks, D. S.: *Statistical methods in the atmospheric sciences: An introduction – Second Edition*, Academic Press, Elsevier, Burlington, USA,
893 2006.

894 Wilson, J. W. and Schreiber, W. E.: Initiation of convective storms at radar-observed boundary-layer convergence lines, *Mon. Weather Rev.*,
895 114, 2516–2536, [https://doi.org/10.1175/1520-0493\(1986\)114<2516:IOCSAR>2.0.CO;2](https://doi.org/10.1175/1520-0493(1986)114<2516:IOCSAR>2.0.CO;2), 1986.

896 Woollings, T., Barriopedro, D., Methven, J., Son, S.-W., Martius, O., Harvey, B., Sillmann, J., Lupo, A. R., and Seneviratne, S.: Blocking
897 and its response to climate change, *Curr. Clim. Change Rep.*, 4, 287–300, <https://doi.org/10.1007/s40641-018-0108-z>, 2018.

898 Wussow, G.: Untere Grenzwerte dichter Regenfälle, *Meteorol. Z.*, 39, 173–178, 1922.

Table 1. Top list of 1 h, 3 h, and 24 h rainfall totals (in UTC) within the study domain during the study period (AT = Austria, FR = France, GE = Germany). Note that 24 h value means precipitation between 00 and 00 UTC on the next day. Note that some stations only provide reports for the full 24 hours (e.g. Bruchweiler; Mauth-Finsterau). Further analyses regarding rain duration (RD), track length (in km), and propagation speed (in m s^{-1}) are limited to Germany due to data availability. RD3 means a rain duration with a rain rate $> 3 \text{ mm h}^{-1}$, RD35 $> 35 \text{ mm h}^{-1}$, and RD60 $> 60 \text{ mm h}^{-1}$. Note two tracks for the German events could not be identified by TRACE3D due to the overlapping of several cells, which were relatively quasi-stationary.

Period	Location (Country)	Coordinates	Rainfall	Time	RD3	RD35	RD60	Length	Speed
1 h	Dietenhofen (GE)	49.4°N, 10.7°E	85.7 mm	31 May 19 h	1 h	45 min	35 min		
1 h	Rohr-Dechendorf (GE)	49.3°N, 10.9°E	71.0 mm	09 June 15 h	1 h	40 min	15 min	84	15
1 h	Labécède-Lauragais (FR)	43.4°N, 2.0°E	64.4 mm	10 June 17 h					
1 h	Hohenberg an der Eger (GE)	50.1°N, 12.2°E	61.4 mm	31 May 18 h	1 h	55 min	30 min	30	6.6
1 h	Lenzkirch-Ruhbühl (GE)	47.9°N, 8.2°E	59.8 mm	31 May 20 h	40 min	30 min	20 min		
1 h	Langres (FR)	47.8°N, 5.3°E	59.4 mm	05 June 20 h					
1 h	Castanet-le-Haut (FR)	43.7°N, 3.0°E	56.2 mm	30 May 14 h					
1 h	Erlbach-Eubabrunn (GE)	50.3°N, 12.4°E	55.6 mm	31 May 17 h	1 h	50 min	35 min	25	4.4
1 h	Rouvroy-en-Santerre (FR)	49.8°N, 2.7°E	54.3 mm	28 May 22 h					
3 h	Prades-le-Lez (FR)	43.7°N, 3.9°E	86.8 mm	11 June 15 h					
3 h	Bad Elster-Sohl (GE)	50.3°N, 12.3°E	86.3 mm	24 May 15 h	3 h	25 min	0 min	16.5	4.6
3 h	Puchberg am Schneeberg (AT)	47.8°N, 15.9°E	86.3 mm	12 June 15 h					
3 h	Dietenhofen (GE)	49.4°N, 10.7°E	86.2 mm	31 May 21 h	~ 1 h 25 min	45 min	35 min		
3 h	L'Oudon-Lieury (FR)	49.0°N, 0.0°E	83.8 mm	28 May 15 h					
3 h	Rocroi (FR)	49.9°N, 4.5°E	79.4 mm	27 May 21 h					
3 h	Leutkirch-Herlazhofen (GE)	47.8°N, 10.0°E	79.1 mm	08 June 18 h	~ 2 h 30 min	45 min	20 min	8.7	3.2
3 h	Kleve (GE)	51.8°N, 6.1°E	78.8 mm	29 May 18 h	~ 2 h 45 min	40 min	20 min	14.5	5.4
3 h	Sulzberg (AT)	47.5°N, 9.9°E	78.0 mm	04 June 18 h					
24 h	Mauth-Finsterau (GE)	48.9°N, 13.6°E	166.5 mm	12 June	~ 8 h 0 min	55 min	20 min	9.2	3.4
24 h	Bad Elster-Sohl (GE)	50.3°N, 12.3°E	154.9 mm	24 May	~ 8 h 15 min	20 min	0 min	16.5	4.6
24 h	Bruchweiler (GE)	49.8°N, 7.2°E	145.0 mm	27 May	~ 2 h 30 min	1 h 5 min	50 min	20.5	5.7
24 h	Monein (FR)	43.3°N, 0.5°W	130.0 mm	12 June					
24 h	Ger (FR)	43.2°N, 0.1°W	126.4 mm	12 June					
24 h	Mont Aigoual (FR)	44.1°N, 3.6°E	124.1 mm	28 May					
24 h	Les Botherreaux (FR)	48.9°N, 0.7°E	123.0 mm	04 June					
24 h	Navarrenx (FR)	43.3°N, 0.8°W	117.0 mm	12 June					
24 h	Puchberg am Schneeberg (AT)	47.8°N, 15.9°E	116.3 mm	12 June					

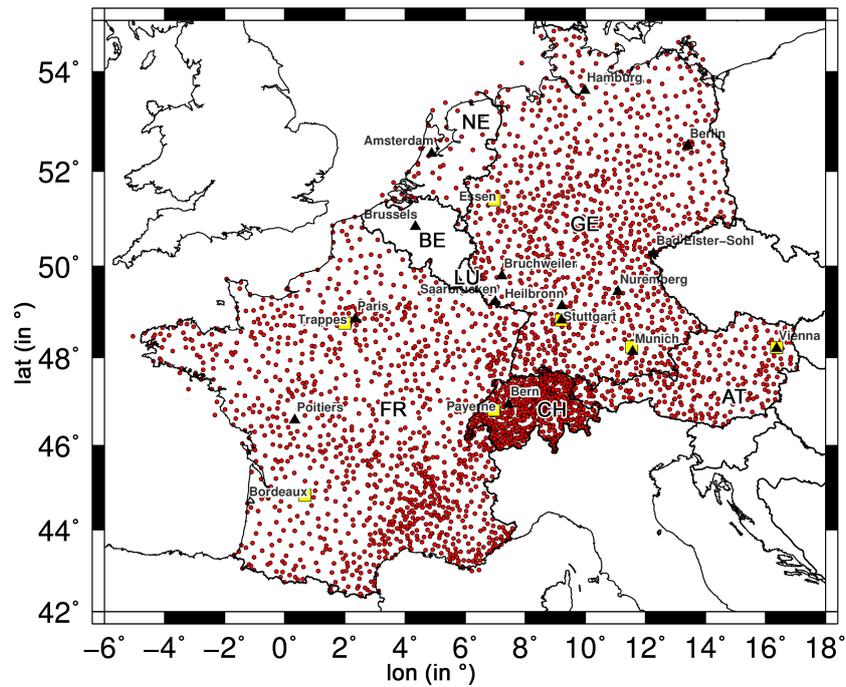


Figure 1. All considered precipitation stations (in red) collected from ECA&D and the three national weather services (France, Germany, Switzerland; see Sect. 2.1.3). In addition, the seven investigated sounding stations are shown (in yellow, see Sect. 2.1.5). Some relevant locations are also presented, which are used in the text. Defined country codes are FR = France, BE = Belgium, NE = Netherlands, LU = Luxembourg (the latter three: Benelux), GE = Germany, CH = Switzerland, AT = Austria.

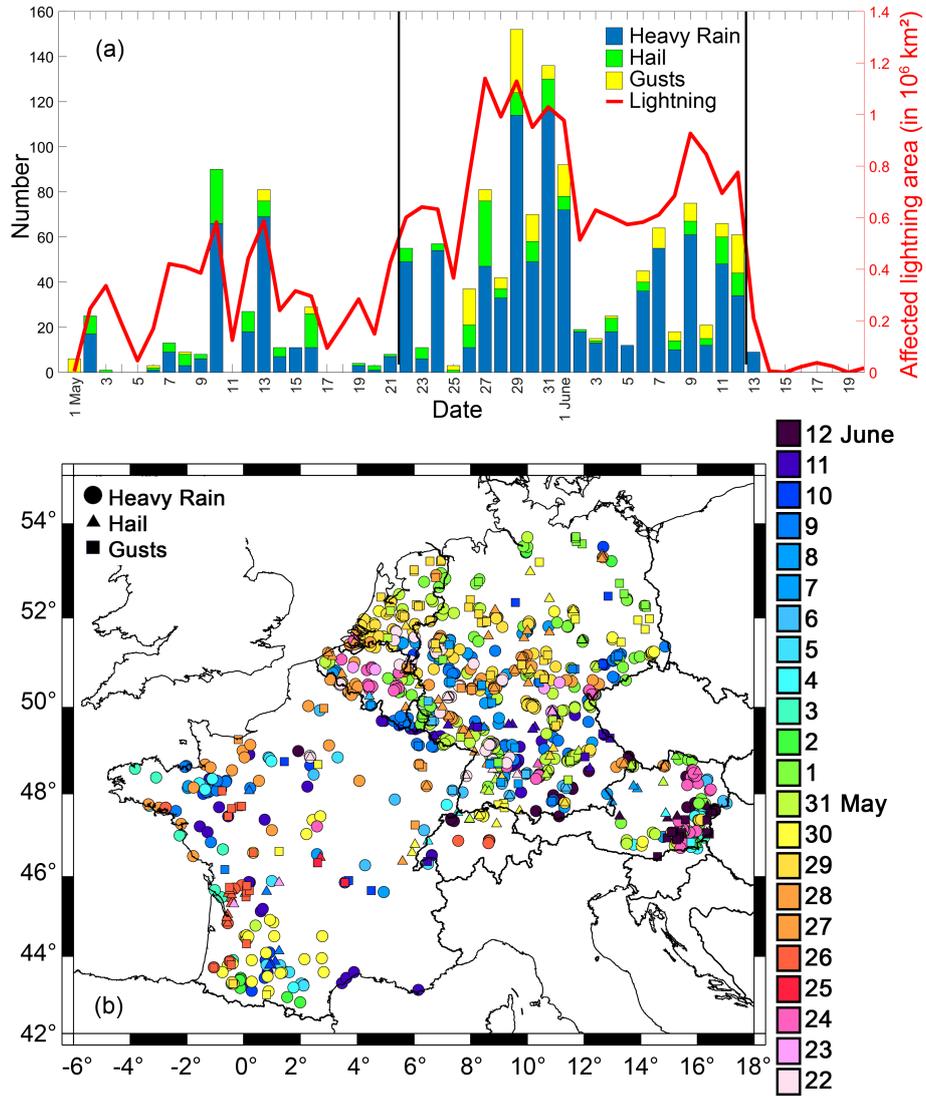


Figure 2. (a) Time series of all recorded ESWD reports (heavy rain in blue, hail in green, convective gusts in yellow) in the study domain during the extended study period (i.e. 1 May to 20 June) including the daily total area affected by lightning in km² (in red). Vertical black lines indicate the study period (22 May to 12 June 2018). (b) Related regional distribution of the different phenomena (heavy rain ●, hail ▲, convective gusts ■) during the study period.

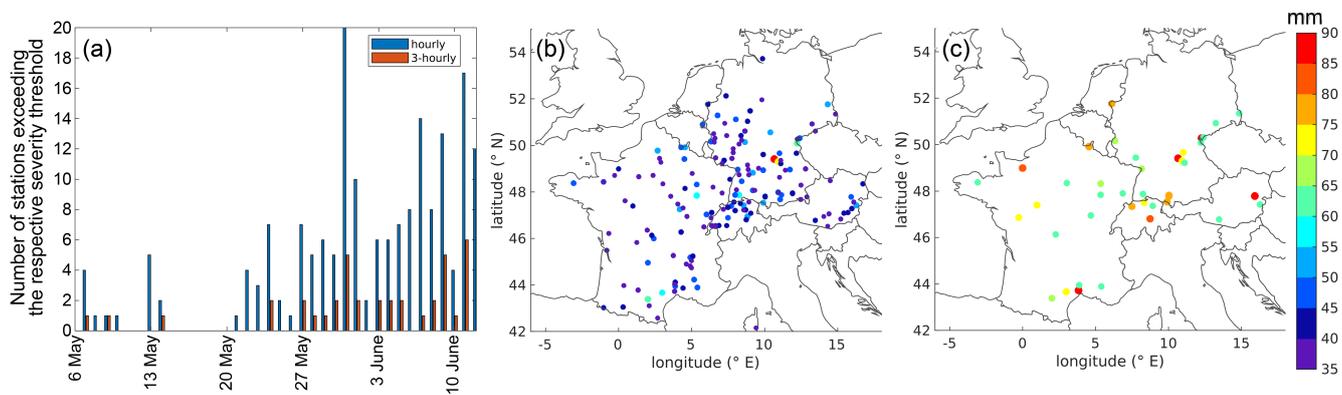


Figure 3. (a) Time series of the number of stations exceeding precipitation thresholds of > 35 mm 1-hour (blue) and > 60 mm over 3-hours (red) including the location and the maximum of (b) 1-hour and (c) 3-hour accumulation of the respective station during the study period (22 May to 12 June).

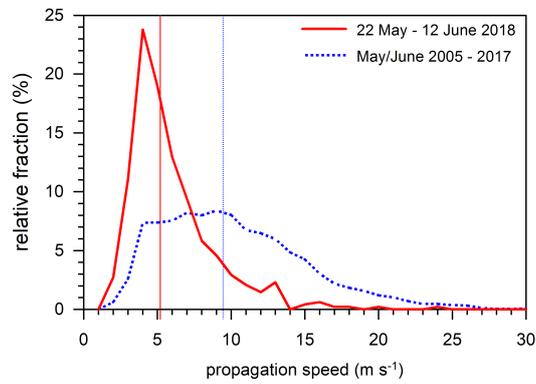


Figure 4. Histogram of the propagation speed of convective cells (increments of 1 m s^{-1}) detected by TRACE3D in Germany during the study period (red) and for all convective cells between 2005 and 2017 (May/June; blue); vertical lines indicate the median of the two samples.

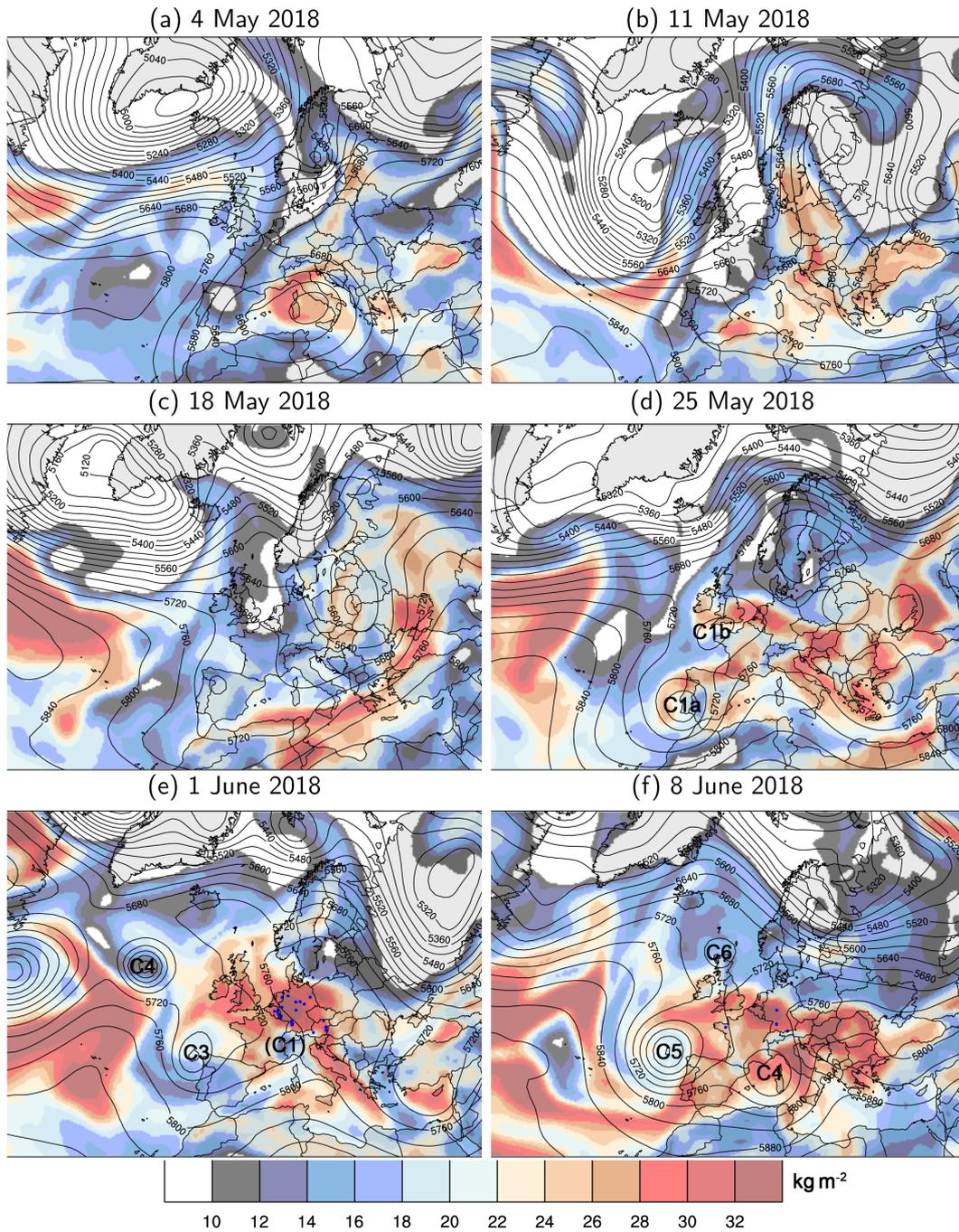


Figure 5. 500 hPa geopotential height (contours every 40 gpm) and vertically integrated water vapor (IWV, shaded in kg m^{-2}) for selected days at 00 UTC during the extended study period: (a) 4 May, (b) 11 May, (c) 18 May, (d) 25 May, (e) 1 June, and (f) 8 June (ERA-Interim). Several cut-off lows during the study period mentioned in the text are indicated with numbers (C1, ..., C6). Small blue dots (in e and f) mark the ESWD reports on heavy rain from Fig. 2. Note that there are no ESWD reports for the first four panels.

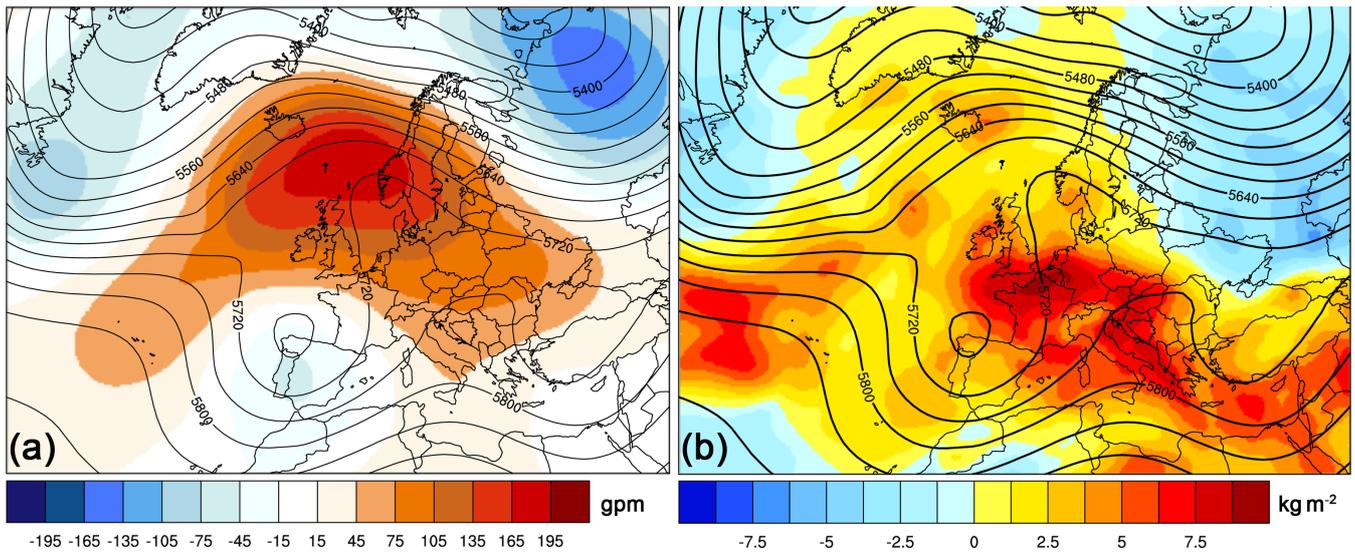


Figure 6. Mean anomalies during May/June 2018 of (a) 500 hPa geopotential height anomaly (shaded in gpm) and (b) integrated water vapour anomaly (IWV; shaded in kg m^{-2}), together with the mean 500 hPa geopotential height (contours every 40 gpm). Anomalies are computed with respect to the climatology (1981–2001; based on ERA-Interim).

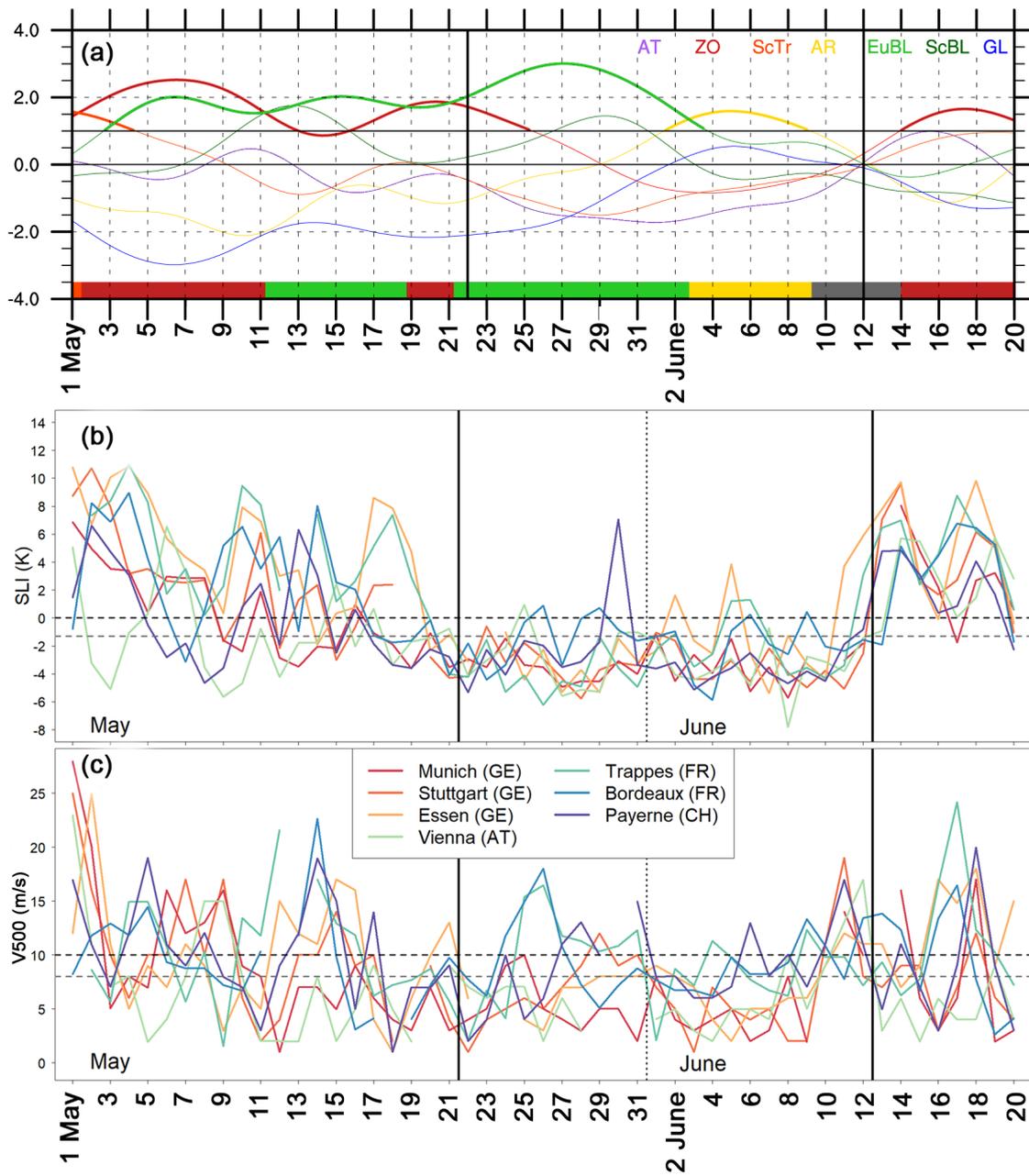


Figure 7. Time series of three different parameters during the extended study period from 1 May to 20 June 2018: (a) Atlantic-European weather regime life cycles based on the normalized projection into all seven regimes (colored curves, based on ECMWF analysis). Active regime life cycles with a projection > 1.0 and persistence of at least 5 days are highlighted in bold curves (cf. Sect. 2.3), the dominant regime (maximum projection and active life cycle) is marked at the bottom. Relevant active regime life cycles are: Zonal regime (ZO, dark red), European Blocking (EuBL, light green), Atlantic Ridge (AR, yellow), no regime (grey). (b) Surface-based Lifted Index (SLI in K) and (c) horizontal wind speed at 500 hPa ($V500$ in m s^{-1}) for the 12 UTC sounding at seven European stations. Horizontal black/gray dashed lines indicate thresholds as defined in PIP16 (Basic criterion: 0 K & 10 m s^{-1} ; Strict criterion: -1.3 K & 8 m s^{-1} ; cf. Sect. 2.6). Vertical black lines indicate the study period.

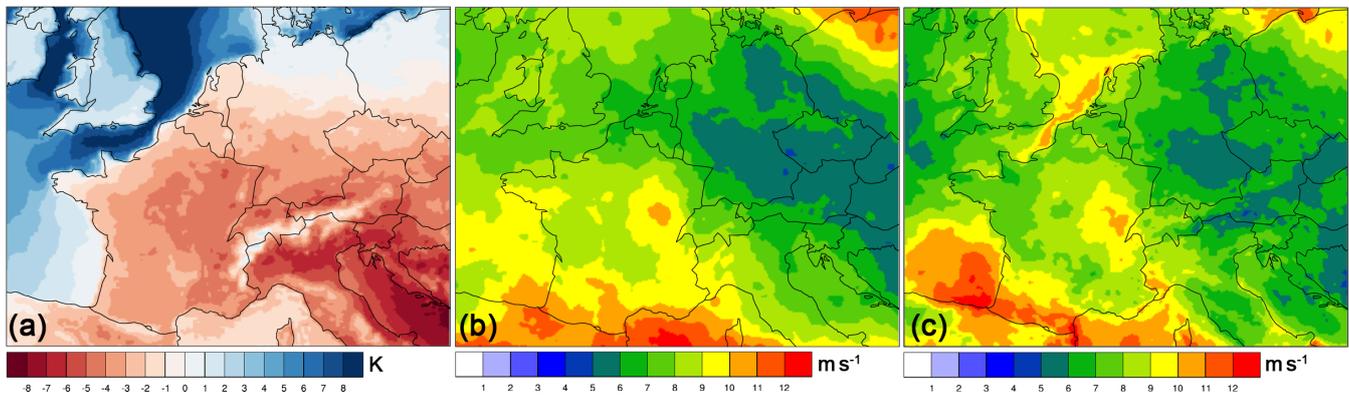


Figure 8. (a) Surface-based Lifted Index (SLI in K), (b) horizontal wind speed at 500 hPa (V_{500} in m s^{-1}), and (c) bulk wind shear between 500 hPa and 10 m (BWS in m s^{-1}) at 12 UTC averaged over the study period from 22 May to 12 June 2018 (ECMWF analysis).

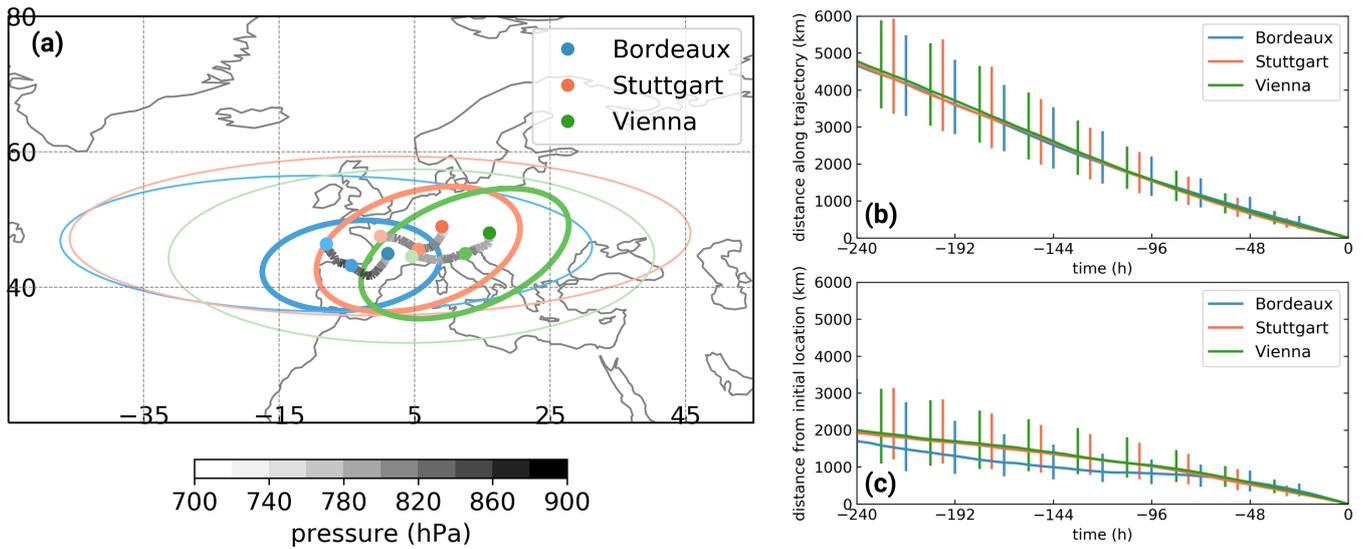


Figure 9. 10-day backward trajectory analysis from 22 May to 12 June 2018. (a) Median backward trajectories coloured by their median pressure (hPa) for three locations given in legend. The ellipses show the dispersion of the trajectories around their median location (dots) at 10 days (thin ellipses) and 5 days (bold ellipses) prior to arriving at the location. The dimensions of the ellipses are given by the eigenvalues of the covariance matrix of all longitude-latitudes at the respective times and the ellipses are rotated such that their semi-major axes align with the largest eigenvector. The length of the semi-major and semi-minor axes are chosen such that the ellipses enclose about 2/3 of the trajectories. (b) Temporal evolution of median distance travelled by the trajectories (km) prior to arriving at one of the locations given in legend. Bars show the interquartile range. (c) As in (b), but for distance from the initial location.

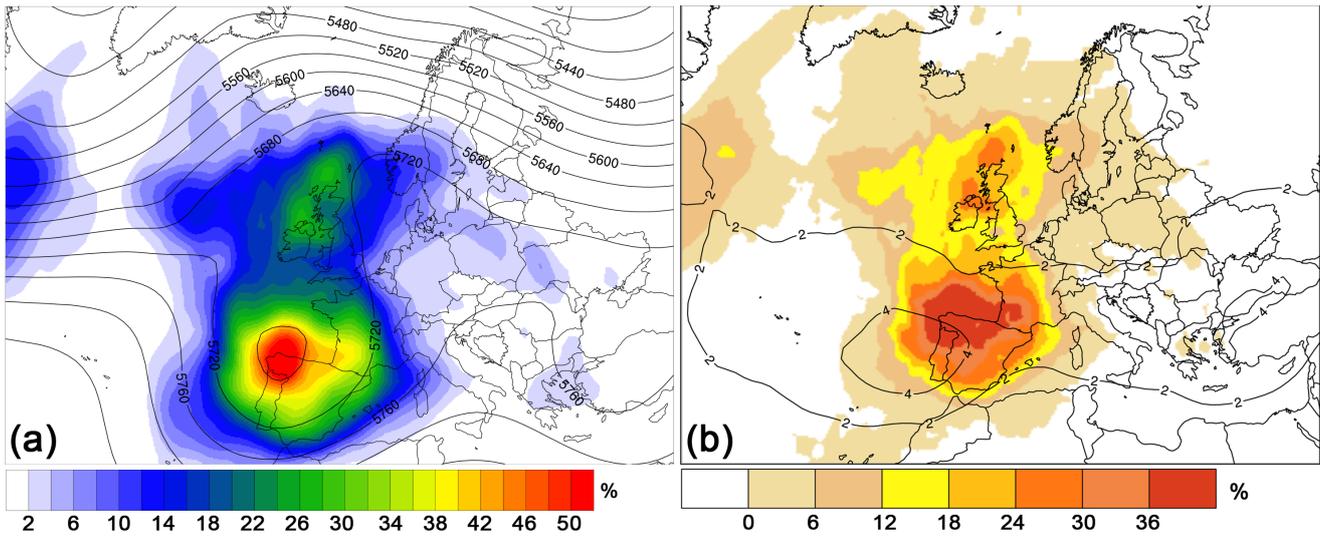


Figure 10. (a) Composite mean of 500 hPa geopotential height (contours every 40 gpm) and cut-off low frequency (color shading in %) during the study period. (b) Climatological mean percentage of days with a cut-off low in May and June (black contours; every 2%; for May and June 1981–2010) and anomaly percentage of days during the study period (shaded in % with reference to mean percentage of days in May and June; both based on ERA-Interim).

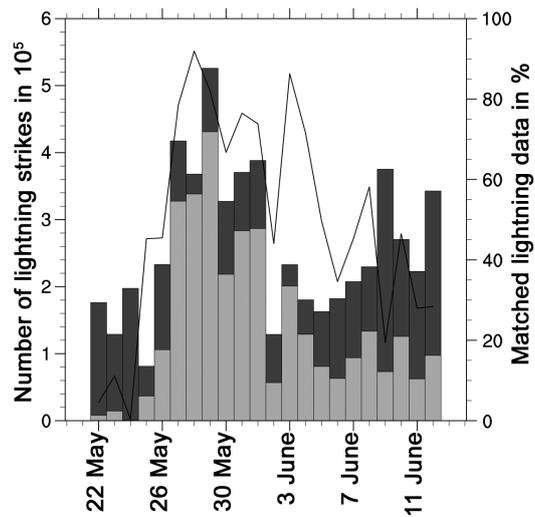


Figure 11. Lightning strikes per day (03 UTC–03 UTC on the next day) during the study period for all thunderstorm events (dark grey bars) and those thunderstorms that can be linked to a cut-off low (light grey bars). The black line shows the percentage of lightning strikes per day that can be attributed to a cut-off low.

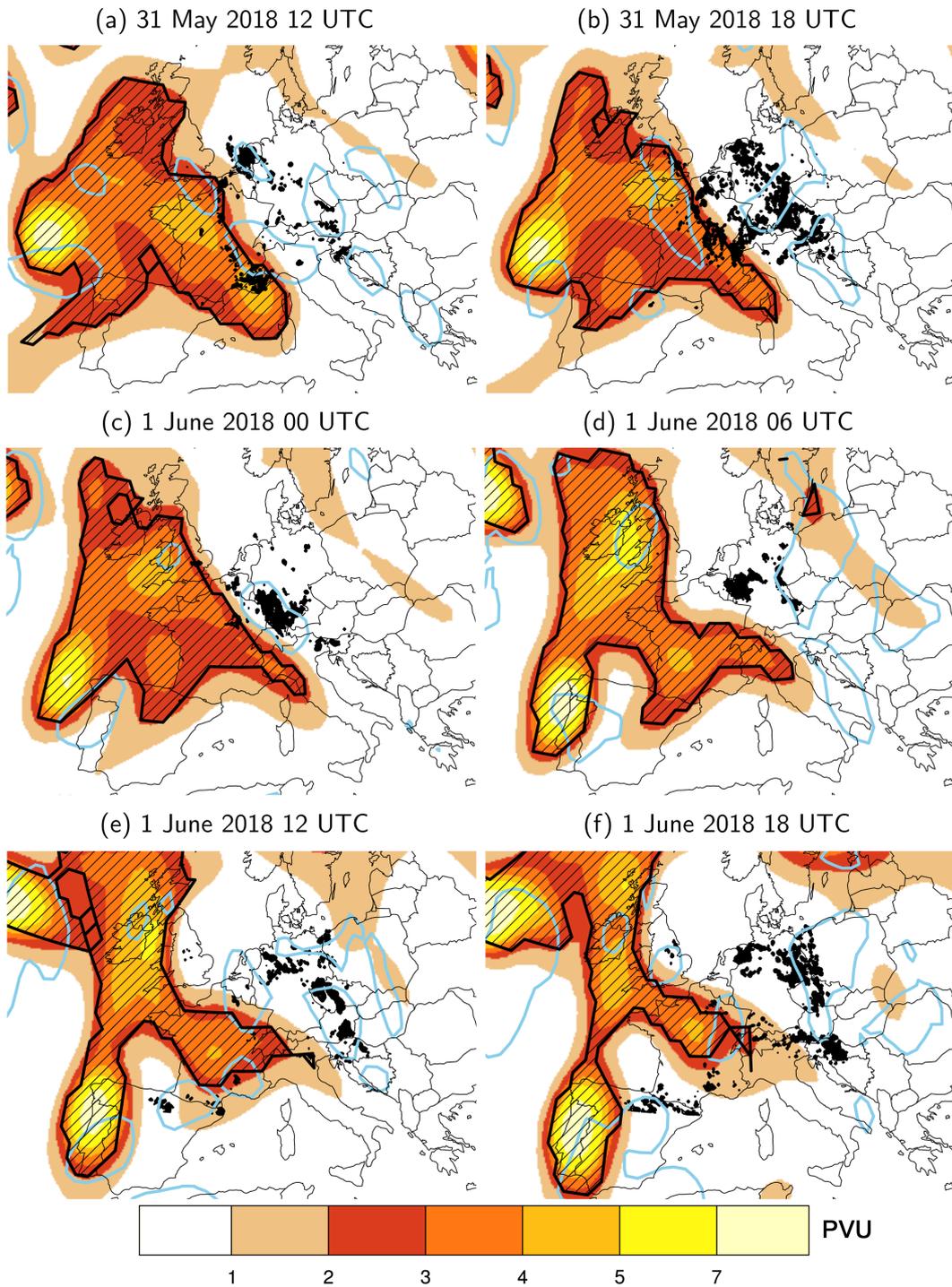


Figure 12. Lightning data (dark black dots) for 6-hour time spans centered around the respective time and PV on the 325 K isentropic surface (shaded in PVU; ERA-Interim). Regions of ascent at 500hPa are indicated by light blue contours ($\omega = -0.1 \text{ Pa s}^{-1}$; ERA-Interim). Hatching indicates masks of objectively identified cut-offs on the 325 K isentropic surface (See Supplementary Fig. 2 including the buffer zone.)

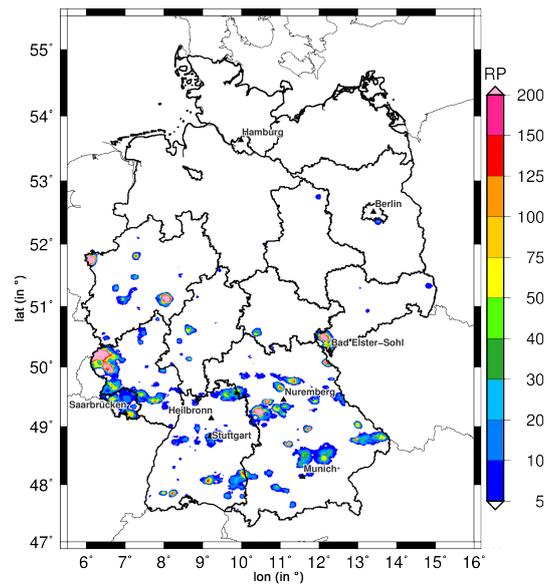


Figure 13. Return period (RP) of the highest 24-hour rainfall totals that occurred during the study period at each grid point (REGNIE precipitation data; reference period: 1951 – 2017, summer half-year).

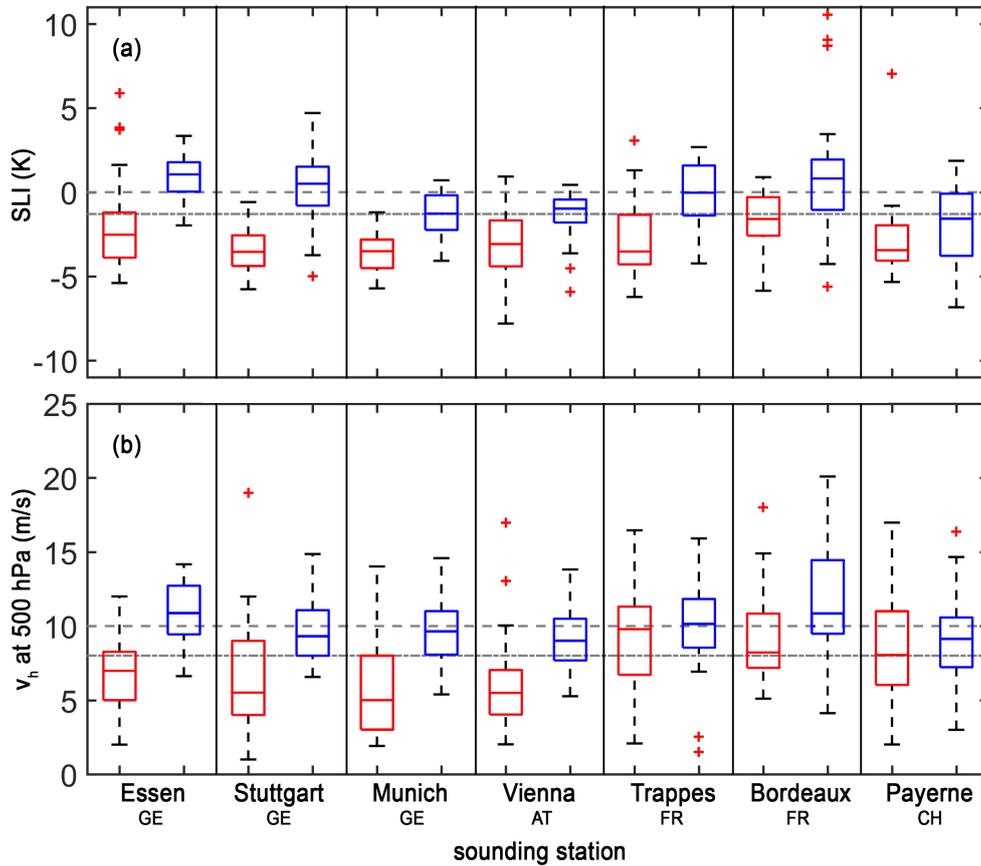


Figure 14. Box-and-whisker plots (median, 1st/3rd quartiles, whisker = $\pm 2.7\sigma$, outliers) for the seven sounding stations. The left box-plots (in red) of each station include all values of (a) SLI and (b) V500 during the study period at 12 UTC, the right box-plots (in blue) include the annual minimum of the running mean (22 days) during May and June between 1981 and 2010. The two gray lines indicate thresholds as defined in PIP16 (Basic criterion: 0 K & 10 m s⁻¹; Strict criterion: -1.3 K & 8 m s⁻¹; cf. Sect. 2.6). Note that the median on the left box-and-whisker plots is calculated identically as all 30 values in the right box-and-whisker plots.

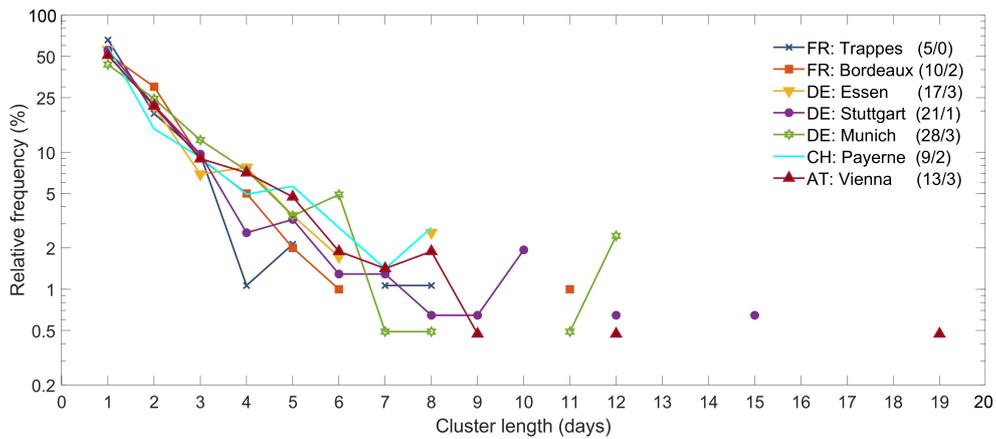


Figure 15. Relative frequency of the length of consecutive days exceeding the basic criterion for concurrent events with low stability ($SLI < 0 \text{ K}$) and weak flow ($V500 < 10 \text{ m s}^{-1}$) at the seven sounding stations (Trappes, Bordeaux, Essen, Stuttgart, Munich, Payerne, Vienna) during 1981 – 2017 (May/June). Maximum days with event persistence n (including skip days m) during the extended study period in 2018 (May/June) are shown in the legend (n/m).