

The characteristics of mesoscale convective system rainfall over Europe

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Key Points:

- MCS substantially contribute to precipitation totals and dominate event-based rainfall extremes over Europe.
- MCS's diurnal cycle displays a large variability over the coasts and may exhibit nocturnal peaks over continental areas.
- The yearly cycle of MCS rainfall is understood with the yearly cycle of surface temperature, convective instability, and frontal activity.

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Abstract

Mesoscale Convective Systems (MCS) are common over Europe and can produce severe weather, including extreme precipitation, which can lead to flash floods. The few studies analyzing the climatological characteristics of MCS over Europe are either based on only few years of data or focus on limited sub-areas. Using the recent Integrated Multi-satellitE Retrievals for Global Precipitation Measurement (IMERG) satellite precipitation climatology, we identify and track MCS for 16 years over Europe. We devise a spatial filter and track cells according to the overlap of filtered rain patches between consecutive time steps. By fitting an ellipse to these patches, we determine their overall shape and orientation. To distinguish convective rain patches we condition on lightning data, thus reducing potential identification errors. We analyze this new European MCS climatology to characterize MCS rainfall properties: MCS overall occur most frequently over the Mediterranean and Atlantic during fall and winter, whereas during summer, they concentrate over the continent. Typically, more than half of seasonal precipitation can be attributed to MCS, and their contribution to extreme precipitation is even greater, often exceeding 70%. MCS over the continent display a clear diurnal cycle peaking during the afternoon, and some continental areas even show a second, nocturnal peak. The MCS diurnal cycle for coastal and oceanic regions is more variable. Selecting sub-areas, we find that the spatio-temporal distribution of MCS precipitation throughout the year can be well explained by the spatio-temporal distribution of specific environmental variables, namely (sea) surface temperature, fronts occurrence and convective instability.

Plain Language Summary

Extreme rainfall events leading to flash floods have major socio-economical impacts over Europe. These events are often created by large and long-lived clusters of clouds called Mesoscale Convective Systems (MCS). Although these MCS are well known by the climate community, their rainfall characteristics over Europe are not fully documented. This is the purpose of this study. Here, we identify MCS by using satellite images (detecting rainfall) and lightning strikes for 16 years over Europe. We also develop a tracking algorithm, enabling us to follow each MCS in time and space. The recognition of individual MCS is based on the overlap of rainfall patches between two consecutive satellite images. We find that MCS overall occur most frequently over the Mediterranean and Atlantic during fall and winter, whereas during summer, they concentrate over the continent. We show that they substantially contribute to the yearly total rainfall over Europe. More remarkably, MCS is the most frequent cloud organization form responsible for extreme rainfall events over Europe. Thus, while the present study gives some general explanations on their main behavior, it is of critical importance to further understand European MCS and their potential changes in a warming climate.

1 Introduction

Mesoscale Convective Systems (MCS) are aggregates of cumulonimbus clouds spanning a few hundreds of kilometers horizontally (R. A. Houze, 2018). These organized weather systems are abundant over the tropics where they contribute to more than half of the total rainfall (Laing & Fritsch, 1997; Nesbitt et al., 2006; Liu & Zipser, 2015; Tan et al., 2015; Schumacher & Rasmussen, 2020; Feng et al., 2021). Despite the frequent occurrence of stratiform rainfall from extra-tropical cyclones in mid-latitudes, MCS are also a significant contributor to mid-latitude precipitation (Haberlie & Ashley, 2019; Feng et al., 2021), in particular during summer when thunderstorm activity is most pronounced (Taszarek et al., 2019) In addition to their significant impact on the hydrological cycle, MCS are often associated with severe weather such as heavy rainfall, large hail, strong winds, or tornadoes (Jirak et al., 2003; Mathias et al., 2017; Luo et al., 2020; Schumacher & Rasmussen, 2020; Fowler et al., 2021). In fact, MCS areas and rain intensities tend

65 to be larger in mid-latitudes than in the tropics, possibly due to larger wind shear (Schumacher
66 & Rasmussen, 2020). It is therefore important to understand the characteristics of mid-
67 latitude MCS and how these may change with global change.

68 Several studies have focused on the climatological properties of MCS around the
69 globe. In the USA, MCS preferentially occur in the Midwest during the warm season and
70 in the mid-south during the cold season (Cui et al., 2020; Haberlie & Ashley, 2019). In
71 the warm season, they were found to emerge along the eastern flank of the Rocky Moun-
72 tains (Cheeks et al., 2020) in the late afternoon and subsequently propagate eastward,
73 peaking at night in the central great plains (Geerts et al., 2017). It was suggested that
74 the nocturnal MCS precipitation peak might be related to the peak in the Low Level Jet
75 (LLJ, Pitchford and London (1962)) as well as both gravity waves (Parker, 2008) or po-
76 tential vorticity anomalies (Jirak & Cotton, 2007) generated and advected away from
77 the Rockies. A nocturnal peak in MCS precipitation was also observed in eastern China
78 (Li et al., 2020) and Argentina (Salio et al., 2007). Both these regions have a mountain
79 range in their western parts (Tibetan Plateau and Andes, respectively) and thus feature
80 similar topographic characteristics as the midwest USA. Conversely, the varied European
81 topography with several mountain ranges oriented along different directions might make
82 for a more complex picture of the MCS diurnal cycle.

83 Focusing on a restricted part of Europe (García-Herrera et al., 2005; Punkka & Bis-
84 ter, 2015; Rigo et al., 2019; Surowiecki & Taszarek, 2020), investigating only one season
85 (Morel & Senesi, 2002; Kolios & Feidas, 2010), or using a limited time record to assess
86 climatological properties (Morel & Senesi, 2002; García-Herrera et al., 2005; Kolios &
87 Feidas, 2010), several studies have examined MCS over Europe. Using five years of infra-
88 red (IR) satellite data, Morel and Senesi (2002) found that summer MCS (April-September)
89 are more common over land than sea and are triggered near mountainous areas (Pyre-
90 nees, Alps, Carpathians) during the afternoon, a general characteristic also found for the
91 USA.

92 The present study composes a comprehensive MCS rainfall climatology over Eu-
93 rope from 16 years of the Integrated Multi-satellitE Retrievals for GPM (IMERG) com-
94 bined with EUropean Cooperation for LIghtning Detection (EUCLID) lightning data.
95 MCS were often identified as large contiguous areas of low IR radiation emitted from cold
96 convective anvils. While this approach is successful over the tropics, it may not be ap-
97 propriate over mid-latitudes which are also subject to large frontal non-MCS systems
98 that come with similarly low brightness temperatures. This is why more robust meth-
99 ods were recently developed for identifying MCS in the mid-latitudes (Feng et al., 2021),
100 making use of the precipitation field to distinguish between convective and non convec-
101 tive systems, since convective cells generally produce more extreme rainfall rates than
102 stratiform-type systems. However, since our objective is to investigate the relation be-
103 tween MCS and precipitation intensity, we adopt yet another, precipitation rate-independent,
104 approach, which instead resorts to lightning strikes.

105 The present study thus aims at characterizing and understanding the hydrologi-
106 cal "footprint" and the diurnal cycle of MCS precipitation over Europe. In Sec. 2, we
107 describe the data sets exploited and how they are used to detect and track MCS. The
108 contribution of MCS to both extreme and mean precipitation over Europe, as well as the
109 MCS diurnal cycle, are characterized in Sec. 3. We then investigate the causes explain-
110 ing the regional and seasonal differences of MCS precipitation (Sec. 4). Finally, we dis-
111 cuss our results and conclude (Sec. 5).

2 Data and tracking algorithm

Our method shares aspects with Feng et al. (2021) but primarily defines patches with the precipitation field instead of cloud top brightness temperatures and uses lightning data to distinguish convective patches.

2.1 Data

2.1.1 Integrated Multi-Satellite Retrievals (IMERG)

We identify precipitating features (PF) using the IMERG precipitation product, version V06B, from the Global Precipitation Measurement (GPM) project (Huffman et al., 2019). This product merges measurements from a constellation of satellites, carrying passive microwave (PM) and/or infrared (IR) sensors. While the PM sensors are generally more precise since they are directly measuring the signal alteration by precipitation droplets, their spatio-temporal coverage is limited. In contrast, IR sensors measure precipitation indirectly through cloud top brightness temperatures, but have a higher spatio-temporal resolution. The precipitation estimates from every satellite are inter-calibrated and combined to produce a half-hourly estimate of precipitation at 0.1° of horizontal resolution which is monthly calibrated by the Global Precipitation Climatology Project (GPCP) satellite-gauge product (Adler et al., 2018).

2.1.2 European Cooperation for Lightning Detection (EUCLID)

To differentiate convective from stratiform weather systems, we employ the EUCLID lightning dataset (Schulz et al., 2016; Poelman et al., 2016). Only cloud to ground lightning strikes (CG) are used since they display spatio-temporal homogeneity from 2005 to 2020. The original dataset provides the number of CG in 30-minute time windows and on a $0.045^\circ \times 0.064^\circ$ grid covering most of Europe. We linearly interpolated the original lightning dataset to the IMERG grid ($0.1^\circ \times 0.1^\circ$) to achieve spatial coherence between both datasets.

2.1.3 General Bathymetric Chart of the Oceans (GEBCO)

Since mountain ranges were found to play an important role in the genesis of MCS in mid-latitudes (Morel & Senesi, 2002; Cheeks et al., 2020), we also make use of the GEBCO topography dataset.

2.1.4 ERA5

Several variables (SST; 2-m and 600 hPa temperatures; 600 hPa zonal and meridional wind speed; Convective Available Potential Energy (CAPE)) from the ERA5 global reanalysis product (Hersbach et al., 2020) are used to provide insights on the processes involved explaining the spatio-temporal distribution of MCS over Europe (in section 4).

2.2 MCS tracking algorithm

Detecting precipitation features and tracks. Similar to Feng et al. (2021), we first apply a spatial filter of 0.3° to IMERG precipitation (Fig. 1ab), in order to define coherent PF that are not simply an artifact resulting from noise, and allow for "gaps" of a few tens of km to in the precipitation pattern of a PF. The PF are defined as contiguous patterns (when considering the four nearest neighbors on the regular longitude-latitude IMERG grid) of filtered precipitation above 2 mm.h^{-1} (red contours in Fig. 1b). Other thresholds (0.5 mm.h^{-1} , 1 mm.h^{-1} , 3 mm.h^{-1} and 4 mm.h^{-1}) were tested and 2 mm.h^{-1} was found to give the best compromise in order to discard many weak and sporadic sys-

155 tems that increase computational cost while preserving the main spatial patterns of the
 156 most significant systems.

157 All PFs are labeled at each time step as follows: when a PF spatially overlaps with
 158 another PF at the previous time step, it receives the same identification number (IN).
 159 Under strong wind conditions, it might occur that the area covered by one precipitation
 160 system does not overlap with the area covered by the same precipitation system 30 min-
 161 utes earlier (especially for small systems). To limit identification errors related to these
 162 occurrences, we adopt the iterative strategy of Moseley et al. (2013) computing the mean
 163 displacement of all neighboring PFs within a 1000 km radius around a non-overlapping
 164 PF, then translating the non-overlapping PF backward in time with the resulted displace-
 165 ment vector, and searching for overlap in the corresponding new position. We perform
 166 this procedure for every non overlapping PFs and iterate until not any new overlap is
 167 found and not any new neighboring PF is found.

168 If a PF (e.g. Fig. 1d) spatially overlaps with several PFs at the previous time step
 169 (e.g. Fig. 1e), the IN of the PF that has the largest overlap is chosen for the new PF (merg-
 170 ing case). A PF receives a new IN when it does not overlap with any PF at the previ-
 171 ous time step. Conversely, if two new PFs (e.g. Fig. 1e) overlap with the same PF at the
 172 previous time step (e.g. Fig. 1d), the new PF that has the largest overlap with the old
 173 PF keeps its IN while the other new PF gets a new IN (splitting case). These choices
 174 correspond to the case of $\theta = 1$ in the method proposed by Moseley et al. (2019) to ad-
 175 dress splitting and merging cases.

176 In order to define shape properties, such as diameter, orientation, and eccentric-
 177 ity, we then fit an ellipse to each PF and at each time step. The fitting algorithm min-
 178 imizes the sum of the distances between the contours of the PF and the ellipse in a least
 179 square sense (see Fig. 1c). In this algorithm, the area of the ellipse is set to be equal to
 180 the area of the PF and the center of the ellipse is fixed to the geometric center of the
 181 PF (red point in Fig. 1bc). The goodness of the ellipse fit (G) is defined as follows:

$$G = 1 - \frac{A_{ell,out} + A_{PF,out}}{A_{ell} + A_{PF}} = 1 - \frac{A_{ell,out}}{A_{PF}}, \quad (1)$$

182 where $A_{PF} = A_{ell}$ is the areas of the PF (defined as the sum of the pixel areas belong-
 183 ing to the PF) and ellipse, $A_{ell,out}$ is the ellipse area outside of the PF, and $A_{PF,out}$ the
 184 PF area outside of the ellipse. The probability density function (PDF) of G is displayed
 185 in Figure S1a. It shows that most of the PFs are well fitted by the ellipse with G val-
 186 ues mostly ranging from 0.6 and 1 (99.5% of the PFs). The maximum of G occurrence
 187 is at around 0.95, which corresponds to the average value of G obtained for the ellipse
 188 fitting of small area PFs containing few pixels (Fig. S1b) and which are also the most
 189 frequent. The lowest values of G correspond to large area and complex PFs whose shapes
 190 can not be well represented by an ellipse.

191 **Defining convective precipitation features and MCS.** We now define convective
 192 and stratiform PFs by using the EUCLID lightning dataset regridded to match the IMERG
 193 grid. At any time of its "life cycle", a PF for which at least one CG was detected inside
 194 or in the vicinity (at a distance of less than 5 km) of its ellipse during the correspond-
 195 ing IMERG 30-minutes time window is defined as an "isolated convective PF". In this
 196 study, an MCS is a PF which experiences a diameter of at least 100 km for at least four
 197 consecutive hours during which at least one CG was detected at a distance of less than
 198 5 km from its ellipse. Another approach, which makes use of ERA5 CAPE instead of light-
 199 ning data (described in supplementary materials), was tested to define convective PFs
 200 and produced similar results for MCS (Figs S2, S3), showing that the MCS identifica-
 201 tion is robust. Here we choose to keep using the EUCLID lightning dataset as we be-
 202 lieve that it provides a more direct detection of convective occurrence. Figure 2a is a snap-
 203 shot of IMERG precipitation, EUCLID lightning strikes, and the objects detected by our
 204 algorithm on 9 June 2014 at 23h45 CEST, where intense MCS associated with severe

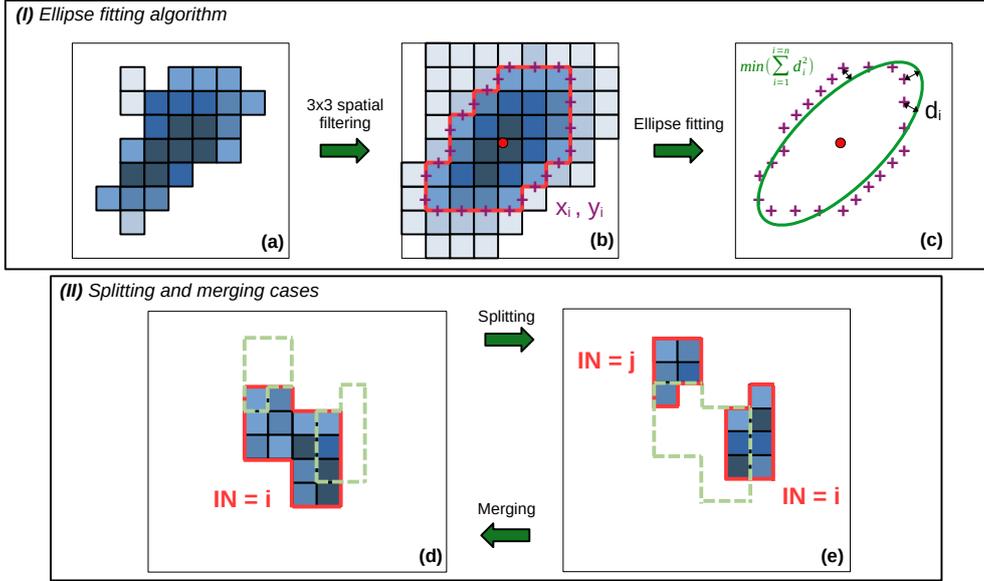


Figure 1. Scheme describing the PF identification (a,b), the ellipse fitting algorithm (c) and the treatment of splitting and merging (d,e) by our algorithm. First, the IMERG precipitation field (represented by blue pixels, with darker blue colors standing for more intense precipitation) is spatially filtered (a,b). Second, contours of filtered precipitation above 2 mm.h^{-1} are drawn (in red) to define PFs (b). The centers of the edges of the pixel contours (purple crosses) are used to fit an ellipse (in green) to each PF by minimizing the distance between the PF contours and the ellipse (c). The snapshots d and e represent two consecutive time steps for which the PF contours of the previous/next time step are reminded in light green dashed lines for an easier identification of the overlaps.

205 weather were observed in western Europe (Mathias et al., 2017). It shows a general good
 206 correspondence between the lightning strikes and the precipitating cells emerging from
 207 two different datasets, as well as fairly consistent ellipse fits to these objects. One can
 208 see that with the threshold approach, only the largest precipitating cells are detected by
 209 the algorithm.

210 For the analysis in the current work we retain unfiltered precipitation from the origi-
 211 nal IMERG grid. Since the PFs are defined using the spatial average of IMERG precipi-
 212 tation from 3x3 grid points, all of these unfiltered IMERG precipitation grid points
 213 contributing to the spatially filtered precipitation field of a particular PF are retained
 214 for this PF. This procedure may result in precipitation grid boxes belonging to two (or
 215 more) PF at the same moment. We have checked the PDFs with and without these re-
 216 peated pixels and found that the differences are minor (not shown) and therefore retained
 217 this approach.

218 3 MCS climatology over Europe

219 3.1 Overall characteristics — MCS are more than a sum of stratiform 220 and convective cells

221 With the algorithm described above, we were able to detect a total of 11,092 MCS
 222 from 2005 to 2020 (on average 693 per year) in our European domain (-13°W to 38°E ,
 223 30°N to 59°N ; Fig. 3). To give an overview, Figure 2b shows the PDF of the duration

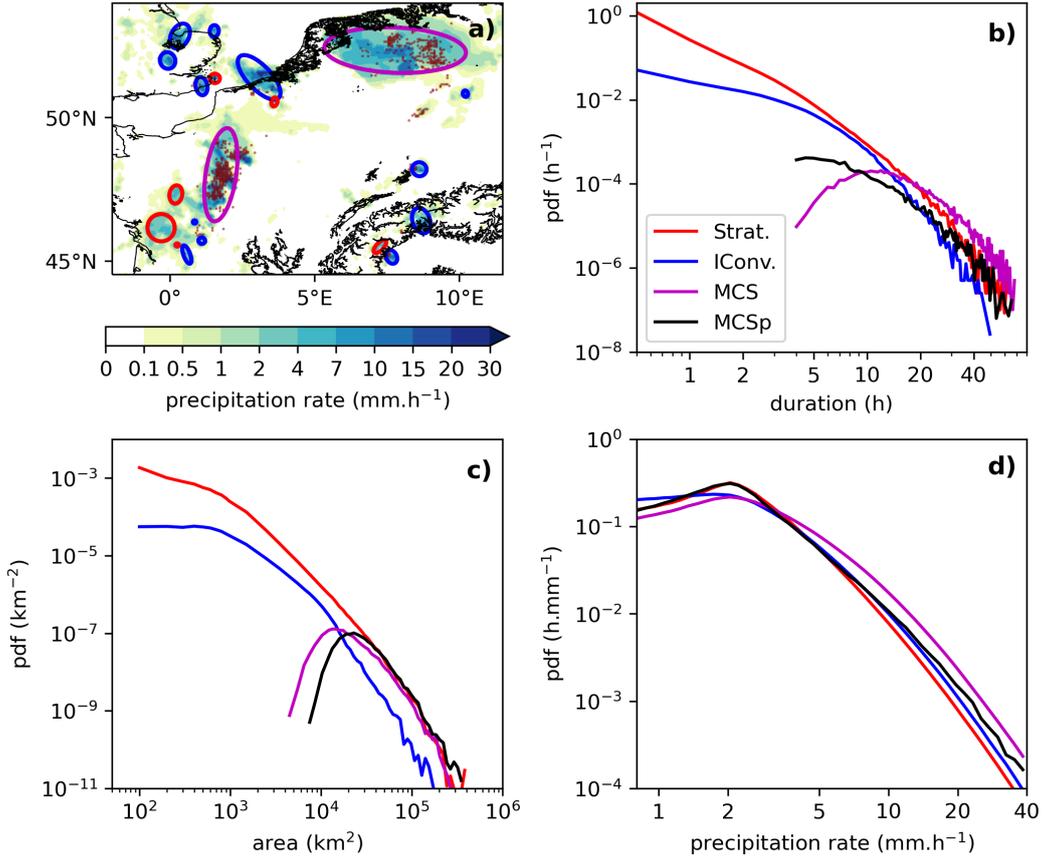


Figure 2. Snapshot of IMERG precipitation (shadings; in mm.h⁻¹) and EUCLID lightning strikes (dark red points) on 9th June 2014 at 23h45 CEST in western Europe (a). The ellipses represent the detected PF according to our algorithm presented in section 2: red for stratiform PF, blue for isolated convective PF, and magenta for MCS PF. Probability density functions (PDF) of precipitation features (PF) duration (b; in h), mean area (c; in km²), and precipitation (d; in mm.h⁻¹) for stratiform ("Strat.", red), isolated convective ("IConv.", blue), MCS PF (magenta), and for MCS periods ("MCSp", black). MCSp was built by selecting only instants for which a MCS PF has MCS attributes (see section 3a). The PDF of duration and area were normalized by the total number of PF while the PDF of precipitation were normalized by the number of instants of PF of the corresponding type (stratiform, isolated convective, MCS, or MCS periods).

224 of detected PF for the different types (stratiform, isolated convective, MCS). Since MCS
 225 are sometimes embedded in fronts, the duration of MCS PF can reach several days whereas
 226 the actual MCS activity may only last for few hours. To account for this potential dif-
 227 ference, we also plot the PDF of MCS periods, defined as instants which are part of a
 228 four consecutive hours with diameter exceeding 100 km and for which a lightning strike
 229 was detected within these same 4 consecutive hours. For stratiform and isolated convec-
 230 tive precipitation, the PDF monotonically decreases with PF duration. The isolated convec-
 231 tive PFs display a more selective range of life duration than the stratiform, as seen
 232 by the stronger curvature of the blue curve compared to the red, in agreement with the
 233 previously reported data by (Berg & Haerter, 2013) but for local rain durations in Ger-
 234 many. We find typical MCS lifetimes to be around 10 hours when accounting for inac-

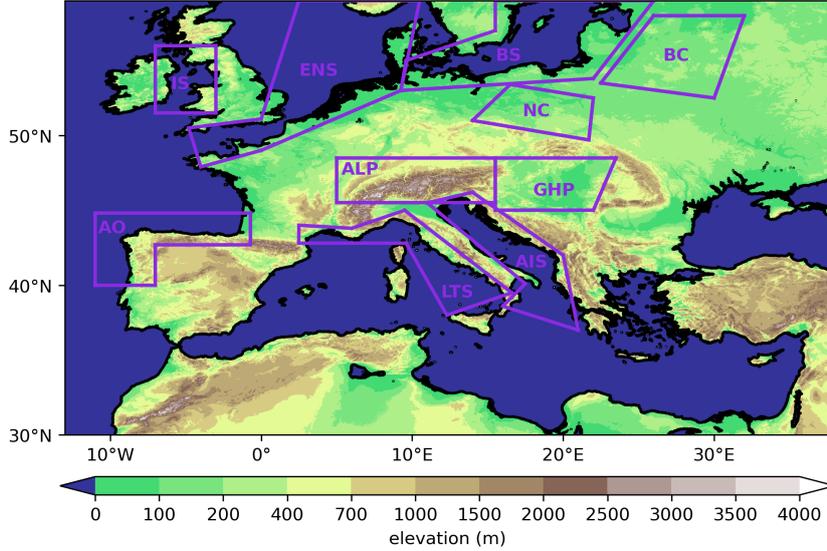


Figure 3. Study domain highlighting sub-regions: AO for Atlantic Ocean, IS for Irish Sea, ENS for English channel and North Sea, LTS for Ligurian and Tyrrhenian Seas, ALP for Alps, BS for Baltic Sea, AIS for Adriatic and Ionian Seas, NC for north Carpathian, GHP for Great Hungarian Plains and BC for Baltic Continent. The shadings represent the elevation (in m).

235 tive periods, whereas the duration of the active MCS periods are shorter by about a half
 236 of the total MCS life time. The area distribution (Fig. 2c) closely mirrors that of dura-
 237 tion. In detail, mean MCS areas are even more selective, their occurrence frequency peak-
 238 ing for areas around 10^4 km^2 , which is partly influenced by our detection method enforc-
 239 ing a size threshold of 100 km of diameter. The PDF of mean precipitation (Fig. 2d) shows
 240 that high precipitation intensities, $> 10 \text{ mm.h}^{-1}$, are approximately three times more fre-
 241 quent within MCS than for isolated convective PFs, and isolated convective cases are
 242 overall more intense than stratiform ones. The maximum around 2 mm.h^{-1} can be at-
 243 tributed to our detection threshold.

244 Given the intensity distributions (Fig. 2d), MCS can not only be seen as a collec-
 245 tion of stratiform and convective precipitation patches but there is a systematic precip-
 246 itation enhancement. This may result from the merging of convective cells, possibly re-
 247 lated to dynamical (cold pools and/or mesoscale circulation; e.g. Haerter and Schlem-
 248 mer (2018)) and/or microphysical effects (reduced entrainment and/or rain evaporation;
 249 e.g. Da Silva et al. (2021)).

250 **3.2 MCS dominate in southern coastal regions in winter and continen-** 251 **tal regions in summer**

252 As noted (Taszarek et al., 2019), mid-latitude convection is strongly dependent on
 253 season, a feature we examine further by examining the MCS occurrence for the differ-
 254 ent months (Fig. 4). As might be expected from the overall precipitation climatology in
 255 Europe (Fig. S4), MCS are generally more frequent in the coastal regions of southern
 256 Europe in winter, whereas they dominate in summer for the North. It is however worth
 257 pointing out that longitudinal differences exist: e.g., along the Eastern Adriatic the over-
 258 all highest MCS frequency (approximately six per month) is reached in November, whereas
 259 the remaining Mediterranean or the continental regions at similar latitude, show a fac-
 260 tor 2—3 less. Similar variations are seen in northwestern Spain or the Italian west coast

261 during fall, where frequencies are again much higher than for similar latitudes. As op-
 262 posed to the strong activity during fall, the transitional period during spring shows gen-
 263 erally weak MCS activity. This lack of symmetry regarding MCS during the transitional
 264 periods, where continental temperatures are fairly similar, points to a strong influence
 265 of the large water bodies, with their large heat capacities, thus memory, on MCS. Sum-
 266 mertime MCS, e.g., from June to August, are most frequent over the Alps, reaching about
 267 five per month in August. To a lesser extent this effect also holds for the Carpathians,
 268 highlighting the role of topography in triggering/enhancing deep convection (J. Houze
 269 & Robert, 2012). Perhaps more surprisingly, the continental regions near the East of south-
 270 ern Baltic Sea experience an important peak of MCS occurrence during the month of
 271 July, with around 3.5 MCS in this month on average. Another remarkable feature is the
 272 high number (exceeding 4 on average) of MCS in both southern Baltic Sea and south-
 273 ern North Sea (especially in the southeastern side) during August, while the surround-
 274 ing continental areas experience comparably fewer MCS. The spatial peak of MCS oc-
 275 currence over these regions extends to the fall months. Finally, one may notice that north-
 276 ern Germany experiences fewer MCS than its surrounding regions between June to Septem-
 277 ber. This may be due to the Alps acting as a barrier to some of the MCS, which mostly
 278 travel in southwesterly flows (not shown).

279 Similarities between the spatial distribution of MCS occurrence in our current study
 280 and previous studies exist for the summer months. Yet, there are some noticeable dif-
 281 ferences compared to the previous climatologies of summer MCS (Morel & Senesi, 2002;
 282 Kolios & Feidas, 2010). While some of the difference might be explained by the longer
 283 averaging time used by the present study, an important difference lies in our method of
 284 identifying MCS by precipitation and lightning, whereas both Morel and Senesi (2002)
 285 and Kolios and Feidas (2010) used a method based on cloud top brightness temperature.
 286 In particular, we found a peak of MCS occurrence in both the North Sea and the Baltic
 287 Sea during August and a generally higher MCS occurrence in northern Europe during
 288 the warm season compared to Morel and Senesi (2002). Similarly, while the peak of MCS
 289 frequency in fall over the eastern Adriatic is expected (Feng et al., 2021; Taszarek et al.,
 290 2019), the peak over northwestern Spain is more surprising and was not found in pre-
 291 vious studies based on cloud top brightness temperature for MCS identification (García-
 292 Herrera et al., 2005; Feng et al., 2021). We believe that the MCS over the North Sea and
 293 the Baltic Sea in late summer, and those over northwestern Spain during the cold sea-
 294 son, are due to less deep convective systems that do not satisfy the IR criteria but have
 295 a large area and still produce some lightning.

296 Thus, MCS affect many regions over Europe throughout the year, and, due to their
 297 convective nature and their large spatial extent, MCS often generate large amounts of
 298 precipitation both in time and in space (e.g., Schumacher and Johnson (2005)). In the
 299 following, we quantify their contribution to total and extreme precipitation for each sea-
 300 sons (DJF, MAM, JJA, SON).

301 **3.3 Substantial MCS contributions to rainfall totals**

302 Again distinguishing seasons, MCS account for large precipitation amounts exceed-
 303 ing 100 mm in a single season over large areas (Fig. 5), which often corresponds to more
 304 than an half of the total rainfall in this season (Fig. 6). Overall, MCS precipitation dom-
 305 inate convective precipitation (Fig. S5) and its spatial patterns are generally commen-
 306 surate with those of MCS frequency in the previous section (Fig. 4) and those of the mean
 307 precipitation climatology (Fig. S4). There are however smaller scale differences that can
 308 be attributed to the average spatial distribution of precipitation within individual MCS.
 309 In winter and to a lesser extent in fall, precipitation totals stemming from MCS tend to
 310 peak offshore along the coasts, a pattern that is even more pronounced for isolated con-
 311 vection (Fig. S6) and suggesting a role of the land-sea contrasts for MCS triggering in
 312 these seasons. The regions most affected by MCS precipitation are eastern Adriatic, west-

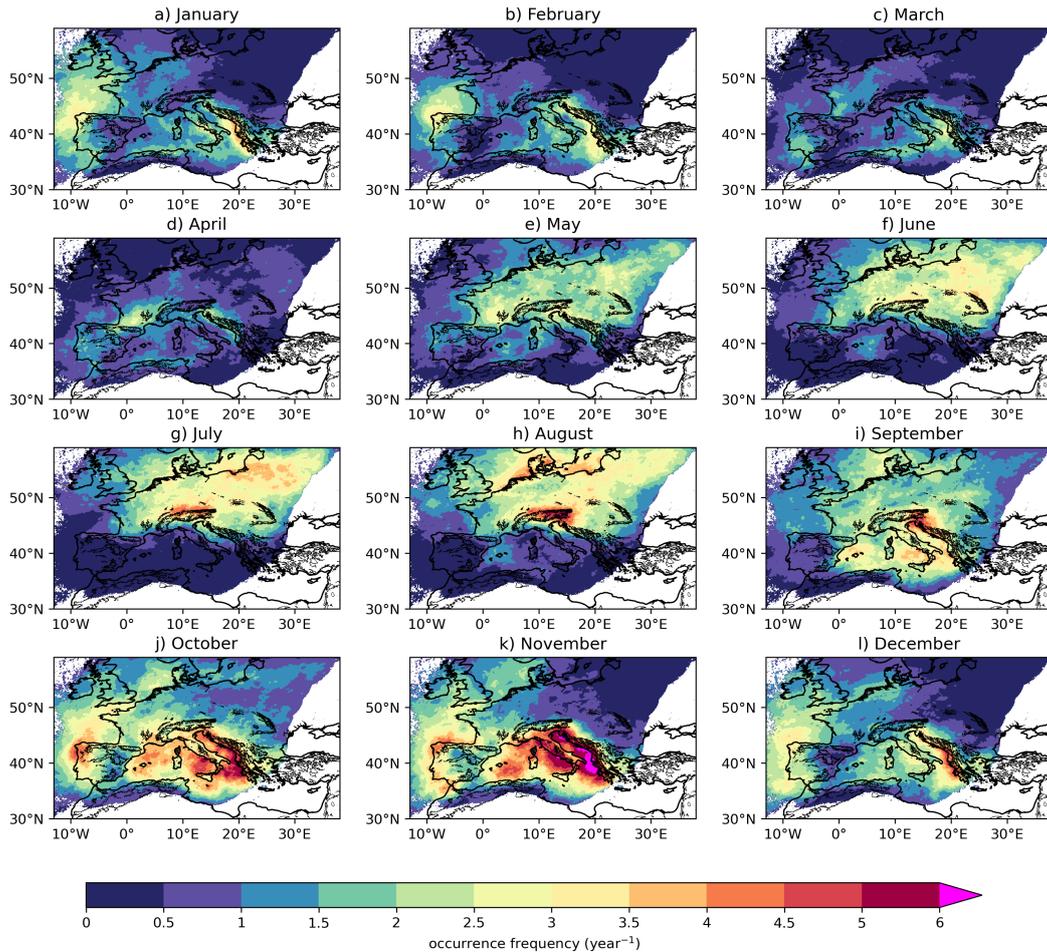


Figure 4. Averaged number of MCS per year by month (a-i). White areas represent missing values, defined as points with means of less than one lightning strike per year.

ern Italy, and south eastern France during fall, with MCS rainfall contributions exceeding 300 mm on average, which corresponds to 60% to 80% of the total precipitation. Northwestern Spain also exhibits a pronounced peak exceeding 200 mm in both fall and winter, although the contribution to total precipitation is somewhat lower with 40-50%. This region, and more generally most of northern Europe is also significantly impacted by stratiform precipitation stemming from Atlantic low pressure systems (Fig. S7), explaining relatively low MCS contributions to total precipitation, there. The MCS contribution to total precipitation is comparatively higher in southern Portugal in all seasons although the number of MCS affecting northwestern Spain is higher.

In spring, MCS precipitation amounts are more homogeneous between continents and seas, reaching about 30-50 mm over large areas, which corresponds to 30-40% of total precipitation. The summer MCS precipitation peaks at about 200 mm over the mountain ranges and the northern Seas of Europe, corresponding to about half of the seasonal total precipitation in these areas.

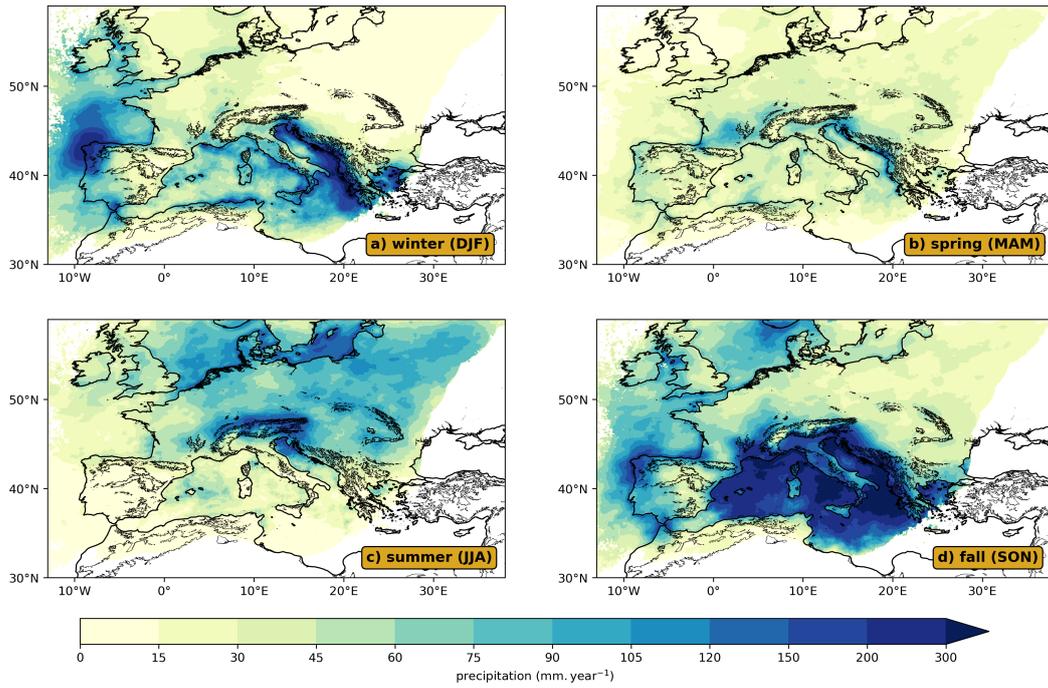


Figure 5. Total precipitation per year (in mm.year⁻¹) from MCS over Europe in winter (DJF, a), spring (MAM, b), summer (JJA, c) and fall (SON, d).

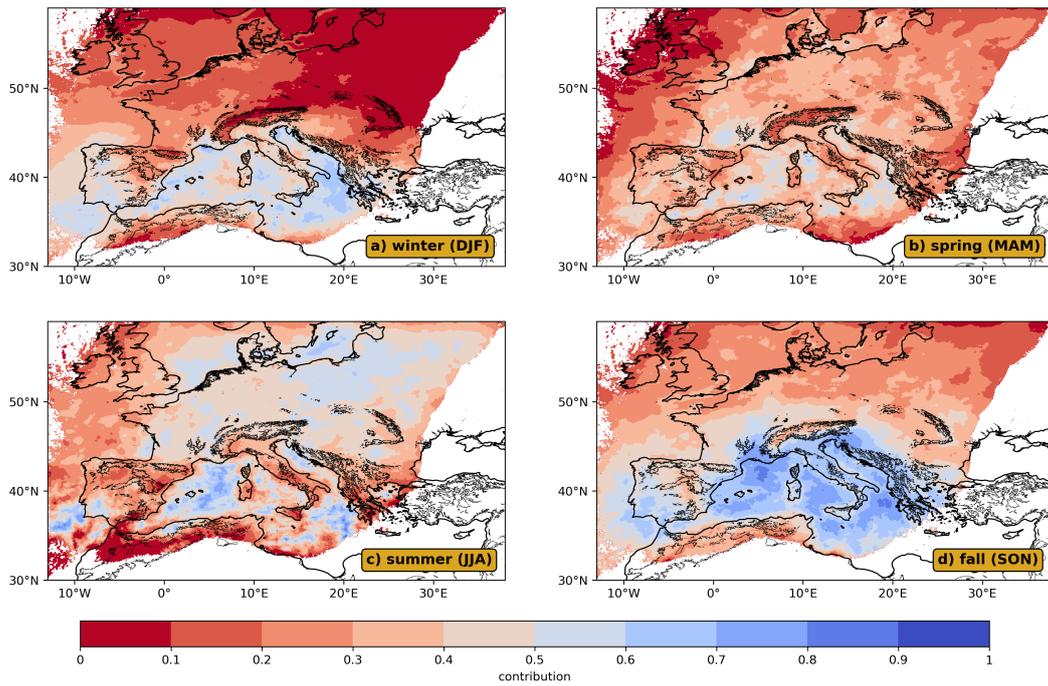


Figure 6. Contribution of MCS to total precipitation over Europe in winter (DJF, a), spring (MAM, b), summer (JJA, c) and fall (SON, d).

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3.4 Extreme precipitation dominated by MCS

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One of the most common hazards resulting from MCS is their tendency to generate intense precipitation accumulations over extended regions. To quantify the MCS contribution to extreme precipitation accumulations we first derive the 90th percentile of event-based precipitation accumulations from individual PFs (both MCS and non-MCS PFs) for each pixel (displayed in Fig. 7). We select areas where the amplitude of the confidence interval (at 95% of confidence level) on the 90th percentile of precipitation accumulations does not exceed 10 percents to ensure a reasonable definition of the 90th percentile. One can see that the PFs tend to produce heavy rain accumulations over the Mediterranean in all seasons but especially during fall and winter where the 90th percentile of precipitation accumulation due to individual PFs exceeds 40 mm along the coasts. Most of the coastal areas exhibit maxima in extreme precipitation accumulations, as noticed for both isolated convective and MCS precipitation totals (Fig. 5, S6). By compositing over events over several of the coasts in December (Fig. S8, S9), we found that their maxima are often associated with enhanced low-level winds from sea to land, suggesting enhanced convergence of moisture by the reduction of wind speed when propagating inland, e.g., due to increased surface roughness or/and the presence of topography. We find this to be a characteristic of coastal isolated convective events and most coastal MCS.

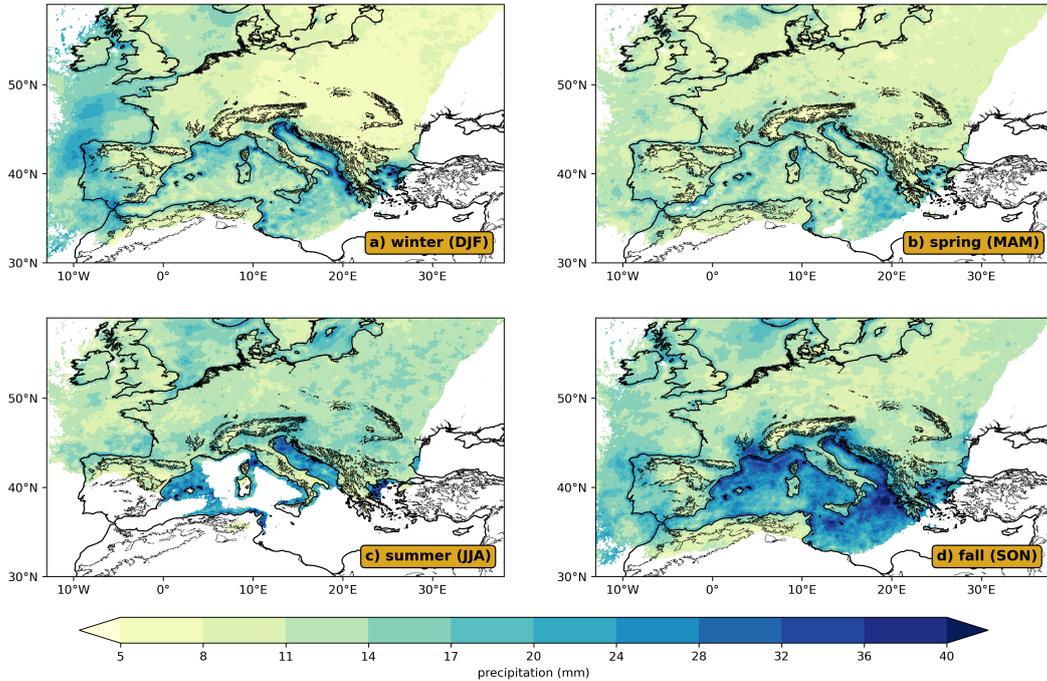


Figure 7. 90th percentile of individual PF precipitation accumulations (in mm) over Europe in winter (DJF, a), spring (MAM, b), summer (JJA, c) and fall (SON, d). White areas are missing data, i.e. points with an insufficient number of PFs (section 3.4) or with means of less than one lightning strike per year.

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For each pixel we then select all PFs that produce rainfall exceeding the local 90th percentile of precipitation accumulation. By determining the fractional contribution by MCS (Figure 8) we show that MCS contribute more strongly to extreme precipitation events than to the mean. In some parts of the Mediterranean and the southern Iberian Peninsula, this contribution reaches a peak during fall approaching 100% and remains

351 high ($> 70\%$) during winter. In summer, more than 70% of rainfall accumulation extremes
 352 in continental Europe are due to MCS while the remaining 30% are mainly due to iso-
 353 lated convective events (Fig. S10). Although MCS are not particularly frequent in spring,
 354 their contribution to extreme precipitation accumulation is significant, exceeding 50%
 355 in most of Europe (except UK) and in the Mediterranean area. In this season, the re-
 356 mainder of extreme rainfall events is due isolated convective and stratiform rainfall (Fig. S11),
 357 with a similar share between these two (around 25%).

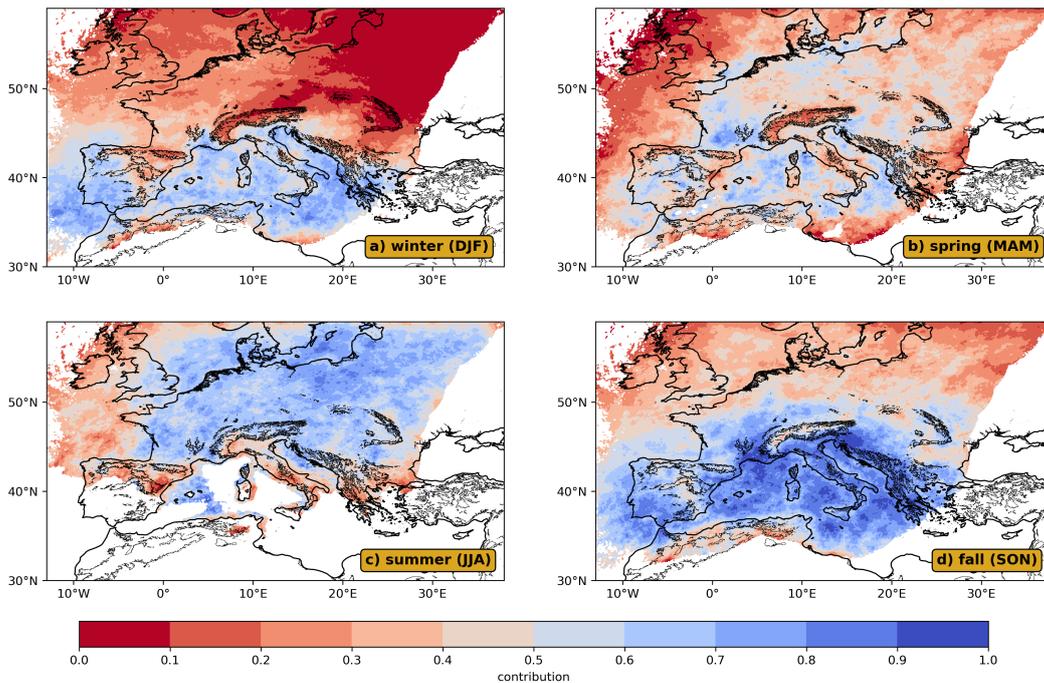


Figure 8. Contribution of MCS to the precipitation features producing the 10% most extreme precipitation accumulations (as defined in section 3.4) over Europe in winter (DJF, a), spring (MAM, b), summer (JJA, c) and fall (SON, d).

358 Summing up, MCS generally dominate precipitation accumulation extremes over
 359 most of Europe, with only northern Europe during winter constituting an exception.

360 **3.5 Diurnal cycle — large contrasts between coasts and continents**

361 Often poorly represented by numerical models (Brockhaus et al., 2008), the diurnal
 362 cycle of precipitation is of key mechanistic and practical relevance. For each of the
 363 sub-regions (Fig. 3) and each month, we compute the diurnal cycle of the expected value
 364 of MCS precipitation given the occurrence of a MCS in the sub-region at any time of the
 365 day. In detail, we collect the MCS precipitation intersecting the sub-region, average over
 366 the sub-region, and stratify by local solar time (LST) 1-h bins. For each MCS affecting
 367 the sub-region, to ensure an equal number of samples per LST bins and thus a fair es-
 368 timation of the MCS precipitation conditional probability, we complete each bins by ze-
 369 ros. For each bin, we finally calculate the MCS averaged precipitation and select the months
 370 of peak MCS activity according to the monthly number distribution shown in Fig. 4.

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3.5.1 Large inter-month and inter-regional variability in coastal regions.

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For the coastal sub-regions (BS, ENS, AO, IS, LTS and AIS) the diurnal cycle of MCS precipitation varies strongly between sub-regions and seasons. Some sub-regions (BS in June, July, October; ENS in November; AO in February; IS in October, November, and December) exhibit afternoon peaks of MCS precipitation, which are likely associated with continental convection. We however note that the amplitude of these peaks is not commensurate with the amplitude of the solar diurnal cycle, e.g., IS experiences the strongest afternoon peak of MCS precipitation during the month with the least diurnal variation in solar irradiance of the year (December). A number of sub-regions (BS in October; ENS from September to December; AO in December and January; IS in October and November; LTS in September, October and December; AIS in February) exhibit a nocturnal/early morning peak, reminiscent of the total precipitation diurnal cycle over most sea areas (Dai, 2001; Bowman et al., 2005; Tan et al., 2019; Watters & Battaglia, 2019). We note that this peak is not systematic and depends on the region, the month and type of precipitation (Figs S12, S13, S14).

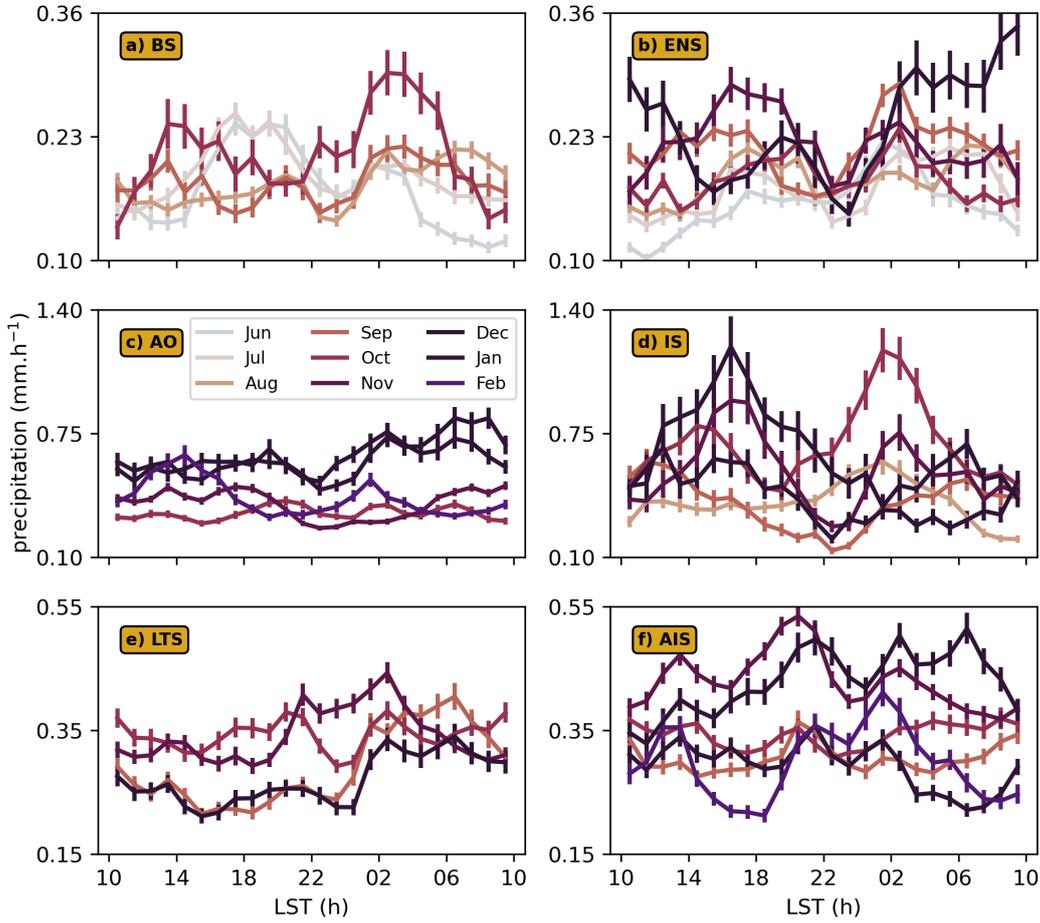


Figure 9. Monthly expected values of MCS precipitation (in $\text{mm}\cdot\text{h}^{-1}$) conditioned on MCS occurrence within the coastal sub-regions as a function of LST (in h): BS (a), ENS (b), AO (c), IS (d), LTS (e) and AIS (f) (see Fig. 3). Results are given for months with the main MCS activity according to Fig. 4. For each LST bin the standard error is calculated to estimate the uncertainty in the mean and represented by error bars.

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3.5.2 Nocturnal peaks in continental regions

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The diurnal cycle analysis was repeated for the continental sub-regions for May to October (Fig. 10). There, a generally more pronounced MCS diurnal cycle is found, exhibiting reduced inter-month variability compared to the coastal areas. In the four continental sub-regions there is a strong late-afternoon peak of MCS precipitation from May to August. This peak is most pronounced during July over ALP and BC, whereas it is more marked in May in GHP and NC. We note that this peak tends to occur later (around 20 LST) in the lee of the Alps (in GHP) and the lee of the Carpathians (in NC), compared to the Alps and the Baltic plains (BC; around 18 LST). This characteristic may be explained by propagating systems from the mountains to the plains occurring later in the evening. Similarly, convective precipitation tends to peak earlier in the afternoon than MCS (Fig. S17), consistent with the time required for the upscale growth of MCS. Generally weaker diurnal ranges of MCS precipitation are observed during September and October (as observed for total precipitation in Mandapaka et al. (2013); Alber et al. (2015)).

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Interestingly, for the GHP sub-region, the diurnal cycle of MCS precipitation exhibits another systematic peak (at around 3 LST). This nocturnal peak becomes more and more pronounced when moving from May to October, as opposed to the late afternoon peak, which diminishes in the course of this seasonal period. A secondary nocturnal peak also appears for the other continental sub-regions, even though it is less pronounced and systematic. One could argue that the nocturnal MCS precipitation peak in GHP might be related to the Adriatic Sea diurnal cycle, "leaking" into GHP at nighttime as a result of a southwesterly flow. However, as seen in Fig. 9g and Fig. S12g, there is no evidence for a clear evening or nocturnal peak in both MCS and isolated convective precipitation for AIS during these months, suggesting a local enhancement/development of MCS precipitation during the night in GHP. We further note that the nocturnal peak is generally less pronounced or does not appear in isolated convective precipitation, as well as for lightning (Fig. S15, S16 and S17). Levizzani et al. (2010) evidenced a slight nocturnal peak of cold cloud frequency in August over similar longitudes, mentioning a potential role of the Carpathians in enhancing precipitating systems. Twardosz (2007) analyzed the diurnal cycle of precipitation over southern Poland conditional on different circulation types and noted a nocturnal/early morning peak of precipitation associated with warm fronts in southerly/southwesterly flows. It is however uncertain whether nocturnal MCS in this region are regularly embedded within a warm front, when warm fronts are usually associated to less convectively unstable environments (as noted in Twardosz (2010)). The precise origin of MCS nocturnal precipitation peaks over continental areas remains thus uncertain and requires further studies.

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4 Understanding the spatio-temporal distribution of European MCS

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It was found that MCS often develop near frontal boundaries which provide dynamical lifting over large scales (e.g. Maddox (1983)). Here, we estimate the frontal activity by using the method of Parfitt et al. (2017) to identify fronts in the middle troposphere (600 hPa; to avoid the detection of low level breeze fronts), and define fronts as contiguous frontal pixels with a horizontal extent of at least 300 km. To only select synoptic fronts from low pressure systems, we discard every fronts containing less than 4 ERA5 pixels with a low pressure and a low geopotential height at 500 hPa (defined as a negative anomaly from a 2000-2020 climatology). By calculating the frequency of frontal pixels as a function of the distance from a PF at the time of their largest extent (Fig. S18), we find that MCS are more tightly connected to the presence of a frontal boundary at few hundreds of km from their center than for isolated convective and stratiform PFs. Among these fronts, the contribution of cold fronts is the most important by a factor of two compared to warm fronts (not shown).

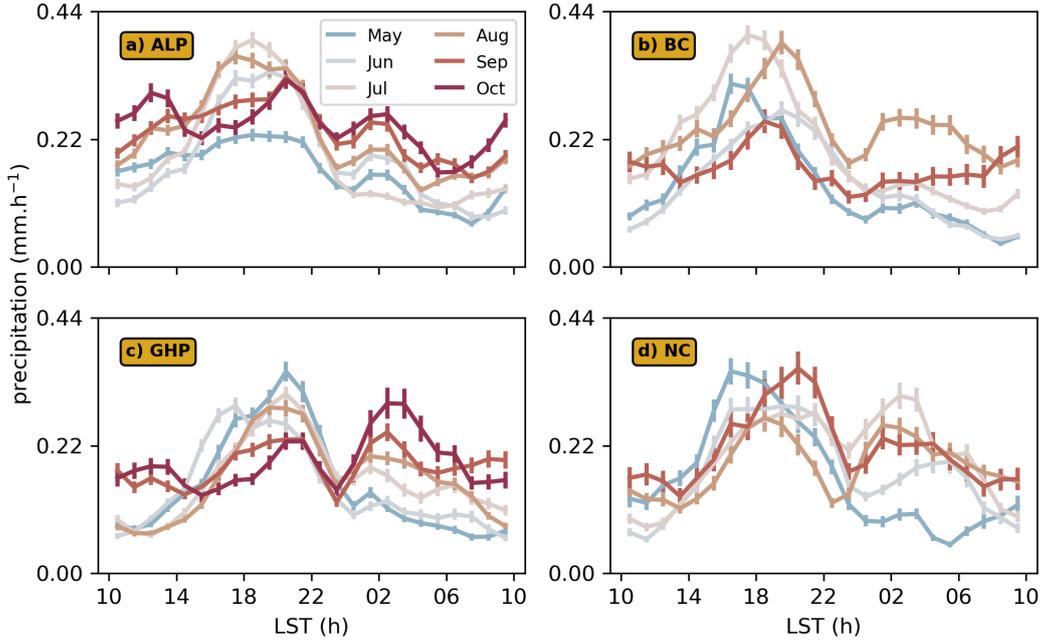


Figure 10. Similar as Fig. 9 but for the continental sub-regions: ALP (a), BC (b), GHP (c) and NC (d) (see Fig. 3).

437 In the remainder of this section, we analyze the MCS precipitation annual cycle
 438 for the different sub-regions (Fig. 3) in relation to the SST (or land 2-m temperatures
 439 for continental sub-regions), the frequency of significant CAPE, and frontal occurrence.
 440 CAPE is considered as significant when it exceeds a threshold of 100 J.kg^{-1} (consistently
 441 with fig. S2). We evaluate frontal occurrence as follows: for each pixel within each sub-
 442 region we count the number of times a front occurred over each month. If a pixel is part
 443 of two fronts that are separated within less than a three-hour interval, it is assumed that
 444 it is the same front. This front occurrence frequency is then averaged over the box and
 445 the 16 years.

446 **4.1 Coastal drivers: dynamics.**

447 In all coastal locations, SSTs generally peak in August, as does CAPE. For the north-
 448 ern coasts of Europe, BS and ENS, these peaks coincide with that of MCS precipitation,
 449 suggesting that convective instability might play a determining role in MCS precipita-
 450 tion there. This applies particularly to BS, where the rapid SST decrease after August
 451 is accompanied by a rapid decay of CAPE. For ENS the drop in SSTs is more gradual,
 452 limiting the decay of CAPE in fall. This, associated with increased frontal activity, may
 453 extend the MCS precipitation peak until November in ENS. For all remaining coastal
 454 regions the MCS precipitation peak is delayed relative to the August SST and CAPE
 455 peaks: November for the Mediterranean coasts (LTS and AIS), October for IS and Dec-
 456 ember for AO. Unlike BS and ENS, these regions experience higher SSTs in August that
 457 decrease progressively during fall, hence these regions might be less limited by CAPE
 458 availability in fall. Rather, despite the larger summertime CAPE, the lack of triggering
 459 and organizing large scale patterns, such as fronts, may be limiting factors in these re-
 460 gions during summer. Across sub-regions, we attribute the decrease in MCS activity in
 461 winter or early spring to CAPE limitations.

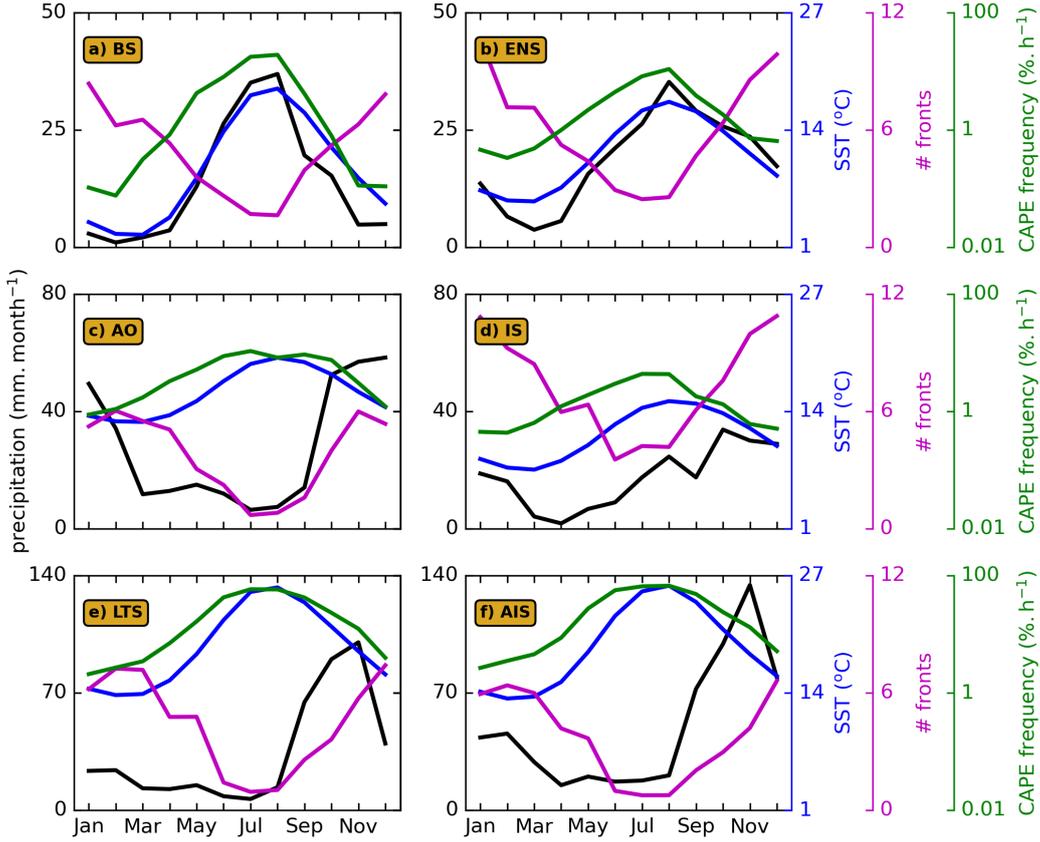


Figure 11. Averaged monthly time series of IMERG MCS precipitation amounts (in $\text{mm}\cdot\text{month}^{-1}$, black), ERA-5 Sea Surface Temperature (SST, in degrees, blue), number of fronts (magenta), and Convective Available Potential Energy (CAPE) frequency (defined in section 4; in $\%\cdot\text{h}^{-1}$, green; note the logarithmic scale) for the coastal sub-regions: BS (a), ENS (b), AO (c), IS (d), LTS (e) and AIS (f) (see Fig. 3).

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4.2 Continental drivers: thermodynamics.

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In contrast to the coastal regions, for land regions MCS precipitation peaks generally coincide with the peaks in surface temperature, i.e., July for BC and NC and August for ALP and GHP, despite a relatively low front frequency, suggesting a more thermodynamic control. We interpret this as resulting from land surfaces often constituting topographic boundaries that force large-scale convection without the need for an air mass boundary. We note that CAPE frequency maxima generally occurs slightly earlier in the year (typically in July). ALP and GHP show a long tail in the fall months despite thermodynamic and instability conditions deteriorating. These might be related to Mediterranean unstable air masses that are advected towards the Alps and Balkans, and eventually leading to MCS formation by topographic lifting or MCS advection.

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5 Conclusions

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We have characterized mesoscale convective systems (MCS) over Europe by building a long-term MCS climatology (16 years) at high spatial resolution (0.1°). MCS are identified by detecting and tracking precipitation features using the recent IMERG satellite-

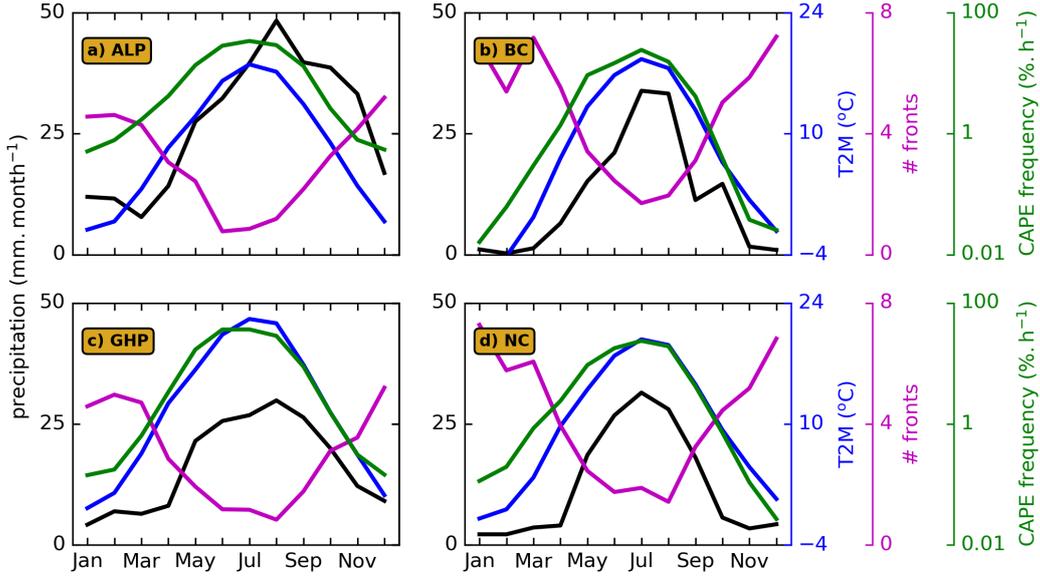


Figure 12. Similar as Fig. 11 but for the continental sub-regions: ALP (a), BC (b), GHP (c) and NC (d) (see Fig. 3).

477 based dataset and conditioning on lightning data from the EUCLID dataset. MCS are
 478 abundant and responsible for substantial precipitation totals in all seasons. In fall and
 479 winter, MCS are mainly concentrated over the Mediterranean and the Atlantic coasts,
 480 whereas in summer, MCS mainly affect continental Europe, especially mountainous re-
 481 gions, and the northern seas. Spring is transitional, with MCS activity moving inland
 482 and pole-ward.

483 The contribution of MCS to total rainfall peaks over the Mediterranean during fall,
 484 exceeding 70% over large areas. While many other regions are also significantly affected
 485 by stratiform precipitation from extratropical cyclones, the MCS contribution often reaches
 486 similar amplitudes over the hotspot regions. Concerning extremes, MCS contribute even
 487 more strongly, exceeding 90% in the Mediterranean in fall and 70% over northern Eu-
 488 rope in summer.

489 The diurnal cycle of MCS precipitation over coastal areas exhibits large inter-month
 490 and inter-regional variability, far from a systematic nocturnal/early morning maximum
 491 expected from the climatology (Watters & Battaglia, 2019), and suggesting that local
 492 mechanisms are involved. The MCS precipitation diurnal cycle over the selected conti-
 493 nental sub-regions shows a more pronounced and systematic diurnal cycle during the warmest
 494 months of the year. For these months we find a late afternoon/evening peak for MCS,
 495 following the afternoon peak of isolated convective. In some of the locations (particu-
 496 larly in the Great Hungarian Plains in early fall), we find an additional nocturnal max-
 497 imum, despite reduced convective instability. The exact origin of this striking feature re-
 498 mains unclear and begs for further investigation, such as through high-resolution sim-
 499 ulation case studies.

500 We then analyze the MCS annual cycle and associated variables, finding that, across
 501 sub-regions, convective instability peaks in summer whereas frontal activity, for which
 502 we found an overall strong involvement in MCS activity, peaks in the winter. Two main
 503 features stick out:

- 504 • In sub-regions where convective instability is a limiting factor and decreases rapidly
505 from summer to fall, MCS precipitation peaks concomitantly with the peak of con-
506 vective instability and surface temperature. This is the case for the continental
507 regions and the Baltic and North Seas.
- 508 • In sub-regions where the convective instability has a more gradual decrease or re-
509 mains significant in fall, MCS precipitation tends to peak in fall. We further at-
510 tribute this delay to more favorable dynamical conditions, namely more pronounced
511 frontal activity and larger boundary layer lapse rates. This is the case of the large
512 water bodies of high-heat capacity, for which the decrease of SSTs during fall is
513 slower. Whereas MCS do occasionally occur in these regions, the lack of dynam-
514 ical forcing appears as a limiting factor during summer compared to fall.

515 In summary, this study highlights the significant role of MCS in driving total, and
516 in particular extreme, rainfall in Europe. We advocate studies unveiling the mechanisms
517 leading to extreme MCS rainfall and their local characteristics, such as the nocturnal MCS
518 rainfall enhancement over eastern Europe, diurnal cycle variability in coastal regions, and
519 the role of the topography, microphysics, and radiation. Such studies could combine higher
520 resolution precipitation datasets, e.g., radar, with numerical simulations to explore lo-
521 cal effects. Such endeavors may ultimately lead to a better causal understanding and thus
522 improved forecasting of mid-latitude MCS rainfall extremes.

523 6 Open Research

524 ERA5 reanalysis data were downloaded from <https://doi.org/10.24381/cds.bd0915c6>
525 and <https://doi.org/10.24381/cds.adbb2d47>. The IMERG precipitation product was
526 downloaded from <https://doi.org/10.5067/GPM/IMERG/3B-HH/06> (Huffman et al., 2019).
527 The surface synoptic observation (SYNOP; O'Brien (2008)) was downloaded from [https://](https://catalogue.ceda.ac.uk/uuid/9f80d42106ba708f92ada730ba321831)
528 catalogue.ceda.ac.uk/uuid/9f80d42106ba708f92ada730ba321831. The EUCLID data
529 are available upon request from <https://www.euclid.org/#>. Topography data were sup-
530 plied by the GEBCO Compilation Group (2022) GEBCO_2022 Grid (doi:10.5285/e0f0bb80-
531 ab44-2739-e053-6c86abc0289c).

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