~~More frequent flash flood events and extreme precipitation favouring atmospheric~~ Atmospheric conditions favouring extreme precipitation and flash floods in temperate regions of Europe

Commented [JM1]: Adjust when leaving out the first hypothesis

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Abstract: In recent years, flash floods repeatedly occurred in temperate regions of central western Europe. Unlike in Mediterranean catchments, this flooding behaviour is unusual. In the past, and especially in the 1990s, floods were characterized by predictable, slowly rising water levels during winter and driven by westerly atmospheric fluxes ~~(Pfister et al., 2004)~~. ~~The intention of this~~Here, we explore potential links and causes between ~~study is to link~~ the recent occurrence of flash floods in central western Europe to extreme precipitation and specific atmospheric conditions ~~to identify the cause for this apparent shift~~. ~~Therefore, w~~We hypothesise that a change in atmospheric conditions led to more frequent extreme precipitation events that subsequently ~~led~~ triggered ~~to more~~ flash flood events in central western Europe. To test this hypothesis, we compiled data on flash floods in central western Europe and selected precipitation events above 40 mm h^{-1} from radar data (RADOLAN, DWD). Moreover, we identified proxy parameters representative for ~~flash flood~~extreme precipitation favouring atmospheric conditions from the ERA5 reanalysis dataset. High specific humidity in the lower troposphere ($q \geq 0.004$ kg kg^{-1}), sufficient latent instability (CAPE ≥ ~~100~~ 327 J kg^{-1}) and weak ~~deep-layer wind shear~~wind speeds (~~DLS~~$WS_{10m-500hPa}$ ≤ ~~10~~6 m s^{-1}) proved to be characteristic for ~~long-lasting~~ intense rainfall that can potentially trigger flash floods. We relied on linear models for analysing 40 years-worth (1981-2020) of~~These~~ atmospheric parameters, as well as ~~the flash flood and~~ related precipitation events ~~were then analysed using linear models~~. ~~Thereby w~~We found significant increases in atmospheric moisture contents and increases in atmospheric instability. Parameters representing the motion and organisation of convective systems remained largely unchanged in the considered ~~time~~ period ~~from~~ (1981-2020). ~~Moreover, a trend in the more frequent occurrence of flash floods was confirmed.~~ However, t~~T~~he number of precipitation events, their maximum 5-minute intensities as well as their hourly sums were ~~however~~ characterized by large inter-annual variations and no trends could be identified between 2002-2020. ~~This~~ Our study ~~therefore~~ shows that there is no single mechanistic path leading ~~link~~ from atmospheric conditions ~~leading~~ to extreme precipitation and subsequently to flash floods ~~cannot be traced down in an isolated way~~. The ~~complexity of~~ interactions between the processes involved are so intricate that more~~is likely higher and future~~ analyses ~~should~~

~~include other~~are required, ~~including~~considering other potentially relevant factors such as intra-annual precipitation patterns or catchment specific parameters.

1 Introduction

Flash floods mostly originate from deep moist convection and rank among the most destructive hazards~~ originating from deep moist convection~~, leading to economic losses, damage to infrastructure, and high mortality rates (Gaume et al., 2009; Hall, 1981; Llasat et al., 2014; WMO, 2017). They are often accompanied by massive erosion and other geomorphologic processes, such as landslides (Bucała-Hrabia et al., 2020; Vogel et al., 2017). While flash floods remain rather exceptional, their occurrence has more than doubled in Europe since the beginning of the 21st century in comparison to the late 1980s (Marchi et al., 2010; Owen et al., 2018).~~ In Europe, flash floods have to be categorized according to local climate characteristics: Mediterranean Flash Floods (typically occurring in the Mediterranean – including Catalonia, Crete, Southern France, Italy, Slovenia) and Continental Flash Floods (limited to the inland, or continental regions – including Austria, Romania, and Slovakia) (Marchi et al., 2010).~~

~~Flash flood events in the Mediterranean region, such as the Cévennes, Gard or Aude floods (Alfieri et al., 2011; Nuissier et al., 2008; Séchet, 2019), are usually characterised by warm and very moist air masses being advected from the Mediterranean Sea (Van Delden, 2001; Ducrocq et al., 2008; Marchi et al., 2010; Nuissier et al., 2008). When these air masses encounter orographic lift by geographic barriers such as the Pyrenees, the Massif Central or the Alps, they can cause exceptional amounts of precipitation – potentially covering several 100 km^2 (Marchi et al., 2010). Within hours, these precipitation events can account for more than 20 % of the annual local precipitation and considerably affect the annual water balance (Marchi et al., 2010). Additionally, when soils are dried-out following dry spells at the end of the summer, infiltration capacities are low and rapidly lead to surface runoff and subsequent flash floods (Borga et al., 2007; Marchi et al., 2010).~~

~~In comparison to Mediterranean events, severe convective storms leading to continental f~~Flash floods in central western Europe typically affect ~~much smaller~~relatively small areas (a few to 100 km^2) and generally last less than seven hours (Marchi et al., 2010). Caused by conditionally unstable atmospheric conditions mainly between May and July, they do not substantially affect the annual water balance. High pre-event soil moisture – caused by rainy weather in the preceding days – may lead to a rapid saturation of soils and a swift onset of extreme runoff response (Marchi et al., 2010). Examples of ~~continental~~ flash floods in recent years relate to Luxembourg around June 2018 (Pfister et al., 2020) and July 2016 (Pfister et al., 2018), to Braunsbach (Germany) in May 2016 (Bronstert et al., 2017, 2018) or the Starzel river flood in June 2008 (Ruiz-Villanueva et al., 2012). While large scale winter inundations were the most common flood type in western Europe until the 1990s (Pfister et al., 2004), flash flood events have increasingly occurred over the last 15 years (Göppert, 2018; Marchi et al., 2010). This raises the question about the origin of this change in flooding type (Bertola et al., 2020, 2021). In this study, we conjecture that changes in the average atmospheric conditions may lead more often to flash flood prone meteorological conditions~~ more frequently~~.

Commented [JM2]: EC: define what a flash flood is in this study

The definitions of flash floods are manifold and sometimes even equivocal in literature. In this study we focus on pluvial floods triggered by intense (convective) rainfall during summer – typically lasting for a few hours. The response times to peak discharge lie within a similar range. The flood characteristics refer to a comprehensive set of extreme and small-scale floods with rapidly rising and falling limbs of the hydrograph and a high impact in terms of damage to infrastructure and/or casualties in the worst case. The largest floods in our data base involved catchments (Ernz Blanche, Starzel river) with a size just over 100 km^2, the smallest events have affected hillslopes of a few 100 meters, where major surface runoff had been reported. We prefer to keep the definition simple and not precisely quantify or limit it to specific processes, as little is understood about the underlying processes.

~~While in western Europe large scale winter inundations were the most common flood type until the 1990s (Pfister et al., 2004), (continental) flash flood events have increasingly occurred over the last 15 years (Göppert, 2018; Marchi et al., 2010). This raises the question about the origin of this change in flooding type (Bertola et al., 2020, 2021). In this study, we conjecture that changes in the average atmospheric conditions may lead to flash flood prone meteorological conditions more frequently.~~

Precipitation events potentially causing flash floods are characterized by high rainfall amounts over~~in~~ a ~~short~~sufficient period ~~of time~~. This ~~is accomplished~~condition is met by high rainfall intensities, which typically last between 30 minutes and a few hours ~~also last over a longer period of time~~ (Doswell et al., 1996; Markowski and Richardson, 2010). ~~That~~ This is mostly the case during rainfall events of convective origin. In particular, slow-moving or quasi-stationary multicellular storms can combine both, high rainfall intensities and a sufficiently long duration.~~ Therein, c~~ Combined effects of several physical processes can cause the most severe rainfall, eventually initiating flash floods. One of these effects consists of storm training~~, i.e~~. The propagation of the 'first' storm away from the area may be cancelled out by the advection of the new, following convective cells~~,~~. Similar to the waggons of a freight train, the storm cells move consecutively ~~which then consecutively move~~ over the same area, which may then ~~may~~ cause high precipitation totals. ~~This effect is especially pronounced in the case of rear propagation or~~Another~~,~~ comparable effect leading to abundant precipitation or a prolonged event duration is the so-called effect of back building with the forward movement being ~~neglected~~ halted by a backward development of a new cell, leading in the end to slow ground relative speeds of the whole ~~region of~~ precipitation area. During the flash flood events in Luxembourg in 2016 and 2018, upscale growth also had a distinctive impact on the precipitation processes (Mathias, 2019, 2021). As a result of this~~Another effect consists of the~~ merging of two or more individual convective cells to form a multicell storm,~~ –~~ the initial~~Varying~~ raindrop sizes and dynamics of merging cells are often varied, which then in turn can cause downdrafts producing extremely high precipitation intensities (Doswell et al., 1996; Markowski and Richardson, 2010).~~ This was the case during the flash flood events in Luxembourg in 2016 and 2018 (Mathias, 2019, 2021).~~

Commented [JM3]: RC3: Lines 59–62: There are some contradictions in these lines as to how you refer to precipitation events that trigger floods. In line 59, you state that they are characterized by high rainfall amounts over a short period of time, while in the next few lines, you say that the rainfall also lasts over longer periods of time. What do you mean here? Please be clear if these are short or long duration rainfall events. Perhaps providing typical durations could be helpful here.

Commented [JM4]: RC3: Lines 67–70: I am not sure I understand what you are saying here–which processes are you referring to? Do you mean the upscale growth of convective cells into organized convection, like a mesoscale convection system? Please be more specific.

Atmospheric conditions associated with excessive convective rainfall have three major characteristics: (1) sufficient latent instability, (2) high moisture content and (3) a slow storm motion (Van Delden, 2001; Doswell et al., 1996; Markowski and Richardson, 2010; Taszarek et al., 2021a). For deep moist convection to occur, first, the tropospheric lapse rates need to be sufficiently steep and a lifting mechanism is required (Van Delden, 2001). Second, the moisture content in the boundary layer needs to be abundant in order to supply water vapour for condensation during the lifting process. High to moderate values of relative humidity in the lower to mid troposphere can further nurture convective cells through limiting water vapour losses due to evaporation and entraining dry air around convective cell boundaries (Doswell et al., 1996; Markowski and Richardson, 2010; Púčik et al., 2015). The same effect – limiting the diminishment of specific humidity by entrainment – is realized by a wide updraft. Additionally, high freezing levels and low cloud base heights enhance the warm cloud depth and thus allow~~ing~~ the warm rain process of collision and coalescence to be more dominant. This leads to a higher precipitation efficiency and is associated with higher rainfall rates (Doswell et al., 1996; Markowski and Richardson, 2010; Schroeder et al., 2016). In continental Europe, high values of total column water vapour are often related to the advection of warm Mediterranean air masses (Van Delden, 2001) or air masses from the subtropical region of the North Atlantic (Mathias, 2021; Mohr et al., 2020). Lastly, to ensure a sufficient duration of the rainfall event, a large rainfall system or slow storm motion is needed (Van Delden, 2001). This generally occurs in case of very weak pressure or ~~/~~geopotential gradients when the mean wind speed and the bulk shear between the surface and the lower to mid troposphere are weak. This process is often enhanced by orography, that influences the near-surface wind field channelling convergence zones (Whiteman, 2000). Moreover, a decoupled flow (rapid vertical shift of prevailing wind directions by at least 90 degrees) between the lower and mid troposphere can significantly reduce storm motion in some cases, as analysed by Mathias (2019).

Proxy parameters from climate reanalysis data are regularly used to identify the atmospheric conditions described above during convective events (Brooks, 2009; Groenemeijer and van Delden, 2007; Púčik et al., 2015; Taszarek et al., 2017; Westermayer et al., 2017). The main parameters used in these studies are the bulk wind shear to estimate the thunderstorm cell organisation and precipitation efficiency, and convective available potential energy (CAPE), to identify atmospheric instability. Púčik et al. (2015) and ~~(~~Westermayer et al.~~,~~ (2017)~~)~~ found heavy precipitation to occur across a wide range of deep-layer wind shear (DLS; bulk shear between the surface and 6 km height). ~~This was confirmed by Westermayer et al. (2017) who specifically identified high and low values of DLS to favour deep moist convection. Weak DLS is generally present during weakly organized and slow-moving storms. In case of stronger DLS, cells are better organized and training/back-building multicell storms are possible. Both cases can lead to high precipitation efficiencies (Fankhauser, 1988). Low-level wind shear (LLS; bulk shear between the surface and 1 km height) shows similar patterns (Westermayer et al., 2017), but is not indicating the severity of a rainfall event (Púčik et al., 2015).~~ CAPE, as a proxy for latent instability, needs to be reasonably high for thunderstorms to develop (Púčik et al., 2015; Westermayer et al., 2017)~~, with values varying between 200-400 J kg^{-1} already being sufficient (Westermayer et al., 2017)~~. ~~In conditions with higher CAPE, thunderstorms are more likely to develop (Púčik et al., 2015). Westermayer et al. (2017) identified environments of CAPE > 400 J kg^{-1} and convective inhibition (CIN) > -50 J kg^{-1} to be the most supportive for thunderstorms. Since abundant CIN can prevent the formation of thunderstorms even in presence of sufficient CAPE, it must be considered in this study.~~ When focussing on heavy precipitation events within the range of thunderstorms, high specific or relative humidity are parameters to identify moisture content at different atmospheric levels (Púčik et al., 2015; Westermayer et al., 2017). ~~Púčik et al. (2015) identified high absolute humidity levels in the boundary layer and high relative humidity values at low and mid tropospheric levels to be characteristic during heavy precipitation events. Moreover, Westermayer et al. (2017) found that dry mid-level air (relative humidity < 50 %) can suppress formation~~

Commented [JM5]: RC3: I would also cite Schroeder et al. (2016) regarding a larger warm cloud depth leading to higher precipitation efficiency → really suitable source!

Commented [JM6]: RC3: Lines 83–84: Large rainfall systems can also result in long duration storms (Doswell et al. 1996).

Commented [JM7]: RC2: Lines 84 – 86 "This generally occurs in case of very weak pressure/geopotential gradients when the mean wind speed and the bulk shear between the surface and the lower to mid troposphere are weak.": True, but what about orography enhancing this?

Commented [JM8]: RC2: Lines 88 – 109: I think this paragraph can be shortened. The authors give an extensive overview of proxy parameters used in literature. This is appreciated, but it is, in my opinion, a bit too long and distracting from the main message in the introduction. Perhaps give a couple of examples and then come to the main point of the paragraph.

Commented [JM9]: RC1: By examining the trend in individual component of the comprehensive conditions as the authors did here offer limited insights into the real changes in flood potential

Commented [JM10]: RC3: Lines 91–93: The results of this study seem to contradict your previous sentence stating that bulk wind shear can be used to estimate precipitation efficiency if heavy precipitation occurs over a variety of DSL values. How do you reconcile this conflict?

~~of convective storms.~~ So far, studies only included the wind speed in the form of wind shear as a proxy parameter for the potential organisation of convective systems, which is important for hail, severe gusts, and tornadoes. However, the development of flash floods relies on longer-lasting, extreme precipitation. Therefore, the storm motion must be slow, which is dependent on a weak flow in the lower to mid troposphere. Hence, we consider the wind speed as a relevant parameter when assessing the flash flood hazard via a slow storm motion.

The identified atmospheric parameters can be ~~Using the identified atmospheric parameters, it is possible to~~ analysed ~~parameters~~ over a longer period ~~and look~~ for trends or oscillations. Therein, especially trends in atmospheric instability are debated. While several studies find increasing CAPE in reanalysis data, recent studies by Rasmussen et al., 2020, Chen et al. (2020) and Taszarek et al. (2021) point out~~,~~ that CAPE is opposed by increasing convective inhibition (CIN). ~~This is observed even to the point where CIN likely supresses the formation of thunderstorms in seemingly more unstable conditions in terms of higher CAPE (Taszarek et al., 2021a) and may even lead to an effective reduction in the overall number of thunderstorms and light of weak to moderate thunderstorms (Chen et al., 2020; Rasmussen et al., 2017).~~ However, strongly increased CAPE triggers more intense thunderstorms despite high CIN levels (Chen et al., 2020; Rasmussen et al., 2017). In ~~addition~~contrast, decreasing relative humidity levels ~~decrease~~ at low levels of the atmosphere, connected to rising temperatures, ~~which also~~ could potentially reduce~~s~~ the number of thunderstorms (Taszarek et al., 2021a). ~~In contrast and without considering the effects of CIN, Rädler et al. (2018) found, that the increase in instability (CAPE) is high enough to not be suppressed by decreases in relative humidity.~~ Absolute humidity is however expected to increase in warmer conditions and can potentially release higher precipitation totals (Lenderink and Van Meijgaard, 2008; Martinkova and Kysely, 2020; Mishra et al., 2012). Changes in wind shear were found to be minor (Rädler et al., 2018). Rädler et al. (2018) concluded, that the frequency of thunderstorms did not increase significantly over the past 40 years in central western Europe, but that they are more likely to produce severe weather.

So far, most studies have focussed on thunderstorm conditions in general or convective hazards related to lightning, hail, tornadoes, or wind gusts. Here, we focus on the thunderstorm events that cause extreme precipitation and especially flash flood events. Forecasting potential heavy precipitation based on atmospheric conditions remains a major challenge, as different atmospheric constellations (e.g. back-building multicells, chaotic cell clustering, atmospheric rivers) can cause heavy precipitation events, while large hail, for example, is mostly associated with supercells, and therefore less challenging to identify (Púčik et al., 2015).

In view of these recent findings, we hypothesise that a change in atmospheric conditions led to more frequent extreme precipitation events that subsequently ~~led to more~~triggered flash flood events in central western Europe~~.~~. Prior to hypothesis testing, we have compiled a comprehensive set of 20-40 years-worth hydro-climatological observation series – including extreme precipitation events, related atmospheric conditions, and documented flash flood occurrences. We then leveraged this dataset for investigating a potential increase in extreme precipitation events ~~and flash floods~~ in central western Europe. Secondly, we relied on proxy parameters, such as ~~the K-Index~~ CAPE, specific humidity, and wind speed, for identifying the atmospheric conditions that had prevailed during extreme precipitation and related flash flood events. Third, we applied a trend analysis to the identified set of atmospheric parameters using the ERA5 reanalysis data (Hersbach et al., 2020) for the past

Commented [JM11]: Citation added

Commented [JM12]: RC2: Lines 116 – 118 "In addition, relative humidity levels decrease at low levels of the atmosphere, connected to rising temperatures, which also reduces the number of thunderstorms (Taszarek et al., 2021a).": Although I am not an expert on this topic, I can image that with higher temperatures evapotranspiration also increases, which leads to higher moisture contents again (besides the fact that the air can contain more moisture at higher temperatures). As said, I am not an expert on this, but I think the statement at least calls for more references.

(1981-2020). The overarching goal of our study is to contribute to a better apprehension of climate change effects, as expressed through modifications in the frequency and severity of extreme precipitation ~~and flash flood~~ events in a temperate climate – more specifically in an area where flash floods used to be an extremely rare phenomenon until recently.

2 Data and Methods

2.1 Study area and period

Our study area comprises central western Europe (50.5° N, 10° E, 47.5° S, 5° W) including Luxembourg, south-western Germany, and north-eastern France (Figure 1 a-c). The study period spans the summer months from May to August, that exhibit the most favourable conditions for thunderstorms and the onset of flash floods (Van Delden, 2001; Rauber et al., 2008), between 1981 and 2020.

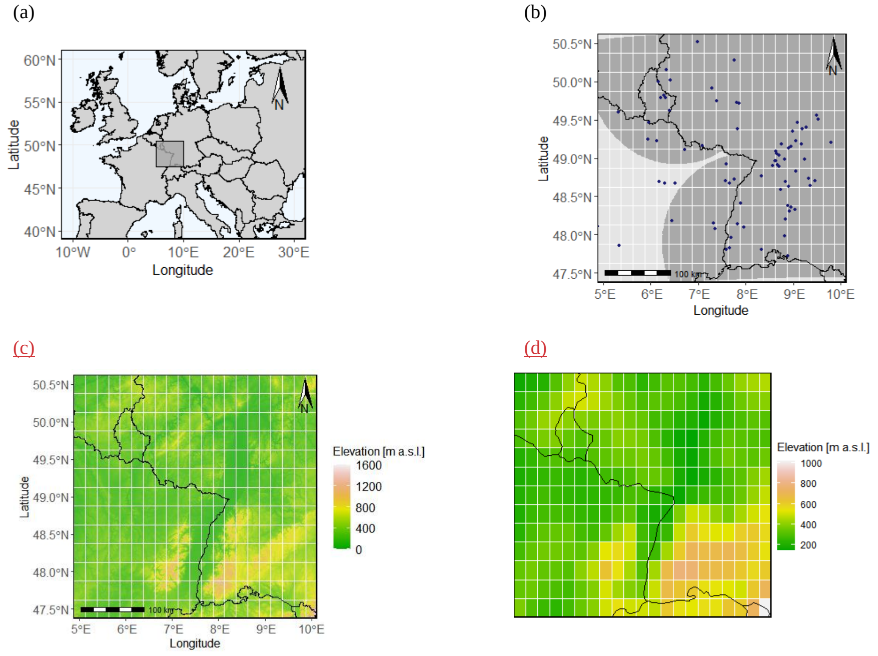

Figure 1: (a) Location of the study area (dark grey square) within Europe. (b) Map of the study area including data points of occurred flash floods and the range of the DWD-RADOLAN precipitation radar data in dark grey. The white grids show the grid width of the ERA5 reanalysis dataset. (c) Model-topography within the study area based on the ERA5 surface geopotential.

2.2 Database

We downloaded the ERA5 *atmospheric reanalysis data* from the Copernicus' Climate Data Store (CDS) on single levels (Hersbach et al., 2018b) and on different pressure levels (Hersbach et al., 2018a). In addition, we downloaded land data from ERA5 (Muñoz Sabater, 2019) to analyse the pre-event wetness state of soils in catchments. Within the summer months from May to August for the period 1981 to 2020, selected parameters (cf. Sect. 2.3) were retrieved at a 1-hourly timestep. The horizontal grid spacing of the atmospheric data is 0.25° x 0.25° and of the land data is 0.1° x 0.1°.

The *extreme precipitation event database* was created based on the Radar-based Precipitation Climatology (RADKLIM) dataset from the German Weather service (Version 2017.002 – ~~(~~Winterrath et al., 2018~~)~~). This is a processed version of the operational RADOLAN radar dataset from the German Weather Service (Weigl et al., 2004; Weigl and Winterrath, 2009; Winterrath et al., 2017). Data are available from 2001-2020 and were considered from May to August. The ~~RADOLAN~~ dataset has a 1 km x 1 km grid size and a temporal resolution of 5 minutes. Unfortunately, the south-western part of the study area is not covered by the RADOLAN data. Although the original RADOLAN product is already quality checked and corrected and consequently reaching high quality, we applied some additional quality control and correction when needed. This included – next to a thorough visual check of the data – the detection and correction of possible anomalous propagation (anaprop) echoes, further ground clutter detection and removal as well as an extended rain gauge adjustment with supplementary local rain gauges. The last operation was done to achieve a further densification of the measuring network (in comparison to the original product), which is especially important when dealing with flash floods, which often exhibit large spatial precipitation sum gradients. To ensure a comparable standard, we used the same methodology for the rain gauge adjustment as used for the generation of the original RADOLAN/RADKLIM dataset, that is the best combination of the multiplicative and the additive adjustment (Bartels et al., 2004; Wilson and Brandes, 1979; Wood et al., 2000). The adjustment interval was one hour. The extra stations used, were – in Luxembourg – mainly the stations of the ASTA network (Administration des services techniques de l'agriculture) (ranging from 7 to 40 extra stations), and – in Germany – the stations of the agricultural-meteorological network of the state of Rhineland-Palatinate (ranging from 10 to 50 extra stations). The additional rain gauge data was quality controlled based on ~~(~~Sevruk~~,~~ (1985)~~)~~ and ~~(~~Michaelides~~,~~ (2008~~); Sevruk, 1985).~~ ~~Furthermore, the radar data were checked visually.~~ We extracted the precipitation events (P events) for the database from the radar database by identifying 1 km x 1 km grid cells with precipitation amounts ≥ 40 mm h^{-1}. Connected grid cells with maximum one cell in between two or more cells exceeding the threshold were clustered to account for one P event (Figure 2)~~.~~. The~~This~~ threshold of 40 mm h^{-1} was used according to the definition of extreme precipitation events by the German Weather Service (DWD, 2021). For every ~~hour~~ P event~~in which a grid cell exceeded the threshold~~, we extracted the maximum hourly precipitation ~~sum~~ intensity as well as the maximum 5-minute precipitation intensity. Moreover, the temporal (time of the first threshold exceedance in one of the grid cells of the P event to the time of the last exceedance) and spatial (area of the number of grid cells that are part of a P event) distribution of the events were identified.~~We selected an ERA5 grid cell as precipitation event if one or more high-resolution~~

Commented [JM13]: RC2: Lines 160 – 161 "an extended rain gauge adjustment with supplementary local rain gauges": How many rain gauges were used, what time step was used and what kind of adjustment have the authors applied?

~~radar grid cells within the bigger, low-resolution ERA5 grid cell exceeded the hourly precipitation threshold~~ Atmospheric conditions during P events were identified at the beginning of a P event, as atmospheric conditions should be the most characteristic at the onset of a P event. To receive a spatially representative value the mean was calculated of each atmospheric ERA5 grid cell of the P event itself as well as a buffer zone around according to the schematic representation in Figure 2. A more detailed description of this procedure and its special cases are documented in the Supplement S3. ~~The final precipitation event database is therefore at the resolution of the ERA5 dataset including all events that were detected in the radar dataset.~~

The *flash flood database* was compiled via a search through case studies in scientific literature (Brauer et al., 2011; Bronstert et al., 2018; Van Campenhout et al., 2015; Eden et al., 2018; Göppert, 2018; Ruiz-Villanueva et al., 2012), water agency reports (Johst et al., 2018; Pfister et al., 2018, 2020), reinsurance data (Caisse Centrale de Réassurance (CCR), 2021), personal communication (engineering consultants Wald + Corbe) and news archives (Franceinfo, 2021; Luxemburger Wort, 2021). We included ~~all~~ floods in streams, fields or on streets that ~~directly followed~~are spatially (max. 30 km) and temporally (same day) linked to an extreme ~~convective precipitation~~P event exceeding the threshold of 40 mm h^{-1}. Despite a careful and comprehensive query, the database is likely non-exhaustive. A list of the events spanning the period from 1981 to 2020 can be found in the Supplement S1 of this manuscript. To extract atmospheric parameters during flash flood events, we identified the triggering~~analysed hourly precipitation~~ P event within a 30 km range ~~within the ERA5 grid cell of a specific event and its neighbouring grid cells on the day of the flash flood~~and proceeded according to the approach for P events as shown in Figure 2. ~~The maximum hourly precipitation value was considered the trigger for the flash flood and atmospheric parameters were extracted from the identified grid cell and time. For flash floods outside the temporal and spatial extent of the RADOLAN precipitation dataset, the exact timing of the flash flood event is unknown. Therefore, an occurrence time of 6 pm UTC was taken, as we assume thunderstorms to occur most often in the evening hours (Van Delden, 2001).~~

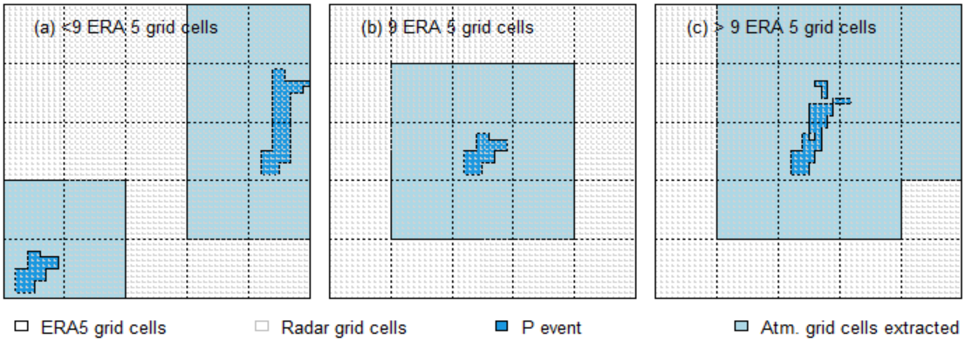

Figure 2: Schematic representation of the ERA5 grid cells (0.25° x 0.25°, ~25 km x 25 km) that were averaged to calculate representative atmospheric conditions during P events (grid width 1 km x 1 km). Panel (b) shows the standard case of a buffer zone

Commented [JM14]: RC3: Line 175–176: Are this 8 neighboring grid cells centered around the precipitation event grid cell? What if the precipitation event takes up multiple grid cells?

Commented [JM15]: RC2: Lines 177 – 178: "The maximum hourly precipitation value was considered the trigger for the flash flood and atmospheric parameters were extracted from the identified grid cell and time.": What about the cells around this grid cell, as their parameters may also have influenced the rainfall that fell there?

Commented [JM16R15]: In the new approach, neighbouring grid cells were considered to get a more representative value of the atmospheric conditions within the area.

Commented [JM17]: RC2: Lines 178 – 180: How did you find the flash floods here and the rainfall intensities, as this is outside the RADOLAN data coverage? In addition, do you have time series of the catchments, which could already indicate the presence and timing of a flash flood?

Commented [JM18R17]: Flash floods outside the RADOLAN coverage were not anymore considered in the new approach.

of a one ERA5 grid cell P event, while panel (a) shows some possible exceptions at the boundary of the study area and panel (c) shows the procedure for larger P events covering multiple ERA5 grid cells.

2.3 Identification of atmospheric parameters favouring extreme precipitation and flash floods

Referring to work done by Van Delden 2001; Westermayer et al. 2017; Taszarek, Brooks, and Czernecki 2017; Púčik et al. 2015, we selected relevant atmospheric parameters to represent (1) instability, (2) the moisture content, and (3) the storm motion. Additionally, we extracted (4) soil moisture content from the ERA5 dataset to get an indication for the wetness state of the catchment before the onset of an extreme precipitation event (Table 1).

(1) As proxy parameters for atmospheric instability, we used the convective available potential energy (CAPE) [J kg^{-1}], which is provided within the ERA5 single level datasets. In addition, we also considered convective inhibition (CIN) [J kg^{-1}]. Given its recognised potential as flash flood proxy, we used the K-Index [°C] that is provided within the ERA5 dataset. The K-Index (George, 1960) is defined via Eq. (1) where T is the air temperature at differing pressure levels and Td the dew point temperature in °C.

$$K\text{-}Index = (T_{850\,hPa} - T_{500\,hPa}) + Td_{850\,hPa} - (T_{700\,hPa} - Td_{700\,hPa}) \qquad (1)$$

The K-Index is a stability index, based on the vertical extent of low-level moisture and the vertical temperature lapse rate of the lower and mid-troposphere. While the operational use of stability indices alone is limited (Doswell and Schultz, 2006), indices can provide additional value when assessing severe weather potential. The K-Index was originally developed to assess potential air mass thunderstorms, or thunderstorms without a dynamic triggering mechanism (George, 1960). Most importantly, it shows some special skill in forecasting the potential of thunderstorms related to heavy precipitation (Funk, 1991; Junker et al., 1999). Regarding the potential for heavy precipitation, it can be generally stated that the higher the K-Index value, the greater the potential for heavy rain. Originally, K-Index values above 20°C indicate thunderstorms, while there is no thunderstorm potential for values below 20. K-Index values are further subcategorized into isolated thunderstorms (20°C - 25°C), widely scattered thunderstorms (25°C - 30°C), scattered thunderstorms (31°C - 35°C) and numerous thunderstorms (> 35°C). Note that the highest category with K-Index values above 35°C is however extremely rare in central western Europe (< 0.5%).

Commented [JM19]: RC2: Line 203 “extremely rare in Central Europe”: just out of interest (and perhaps worth mentioning), how rare is it (quantified)?

(2) To reach a sufficiently high rainfall rate causing heavy precipitation and consequent flash floods, the atmosphere’s moisture content is pivotal. We opted for the total column water vapour (TCWV) [kg m^{-2}] as well as specific humidity (q) [kg kg^{-1}] and relative humidity (RH) [%] at the pressure level of 700~~-~~ hPa as atmospheric moisture content proxies. The pressure level at 700 hPa was chosen, because it is approximately the middle of the lower, weather relevant part of the atmosphere between the surface and 500 hPa.

Commented [JM20]: RC2: Line 206 “700 hPa”: Why have the authors chosen to pick the 700 hPa level?

(3) To assess the storm motion, we computed the wind speed (WS) from the square root of the squared northward direction wind vector u [m s^{-1}] and the squared eastward direction wind vector v [m s^{-1}] at the pressure level of 700~~-~~ hPa. In addition, the mean of the wind speed between 10 m above the ground level and the pressure level of 500

hPa was calculated. Low-level wind shear (LLS) [m s^{-1}] was likewise computed based on the square root of the differences of the vectors u and v ~~at pressure levels at ground (1000 hPa)~~near the ground and at about 1.5 km height levels (850 hPa). Accordingly, we calculated the deep-layer wind shear (DLS) [m s^{-1}] as the difference of the wind vectors ~~at~~ near the ground ~~(1000 hPa)~~ and in about 6 km height levels (500 hPa). The wind shear allows an assessment of the organisational mode of deep moist convection.

(4) We considered soil moisture parameters for assessing the pre-event wetness state of a catchment. Therefore, we extracted soil moisture (Swvl) [m^3 m^{-3}] at depths of 0-7 cm, 7-28 cm, and 28-100 cm from ERA5, 24 hours before identified events.

Table 1: Selected proxy parameters for the assessment of convection relevant atmospheric conditions from the ERA5 dataset.

Proxy for	**Parameter**	**Abbr.**	**Unit**	**Level**	**Source**
Instability	Convective available potential energy	CAPE	J kg^{-1}	s~~S~~ingle	Hersbach et al., 2018b
	Convective inhibition	CIN	J kg^{-1}	single	Hersbach et al., 2018b
	K-Index	Kx	°C	single	Hersbach et al., 2018b
Moisture	Total column water vapour	TCWV	kg m^{-2}	single	Hersbach et al., 2018b
	Specific humidity	q	kg kg^{-1}	700 hPa	Hersbach et al., 2018a
	Relative humidity	RH	%	700 hPa	Hersbach et al., 2018a
Storm motion and organisation	U-component of wind	u	m s^{-1}	10 m,	Hersbach et al., 2018a
	V-component of wind	v	m s^{-1}	500 hPa & ~~700 hPa~~ 700 hPa	Hersbach et al., 2018a
Catchment wetness state	Volumetric soil water layer 1	Swvl1	m^3 m^{-3}	0-7 cm	Muñoz Sabater, 2019
	Volumetric soil water layer 2	Swvl2	m^3 m^{-3}	7-28 cm	Muñoz Sabater, 2019
	Volumetric soil water layer 3	Swvl3	m^3 m^{-3}	28-100 cm	Muñoz Sabater, 2019

To identify extreme precipitation and flash flood relevant proxy parameters, we extracted their respective values from the ERA5 atmospheric dataset at the time step and grid cell of initially identified events. Next, we created thresholds for every proxy parameter, that make the occurrence of precipitation events possible. Therefore, we chose the 75th or the 25th percentile as the upper or the lower boundaries including either the lower or the upper three quartiles of all values~~75 %~~ of extreme events. These percentiles were chosen as statistical standard as also used in ~~(~~Schroeder et al.~~,~~ (2016~~)~~). This analysis leads to the determination of the thresholds in Table 2, Sect. 3.3, to classify atmospheric conditions as extreme precipitation and potentially flash flood favouring. We used these thresholds, as well as the three parameters identified the most suitable from the groups of moisture, instability, and storm motion and organisation to eventually conduct trend analyses.

Commented [JM21]: RC2: Lines 222 – 223 “Therefore, we chose upper or lower boundaries including 75 % of extreme events.”: Do the authors mean the events IQR of the extreme events or did I understand it incorrectly?

2.4 Trend analyses

We carried out linear trend analyses to ~~prove~~ test the different parts of our working hypothesis – linking a potential increase in atmospheric conditions triggering extreme precipitation events to a rise in the occurrence of ~~flash flood~~extreme precipitation events in central western Europe. We applied the linear models to our ~~flash flood~~precipitation event database, as well as to the occurrence frequency, precipitation amount and ~~maximum 5-minute~~ intensity of identified extreme precipitation events. Likewise, we applied linear models to the flash flood relevant parameter ranges of the identified set of ERA5 atmospheric parameters, as well as to the simultaneous occurrences of the three most relevant parameters.

3 Results

3.1 ~~More frequent~~F ~~f~~lash flood occurrences

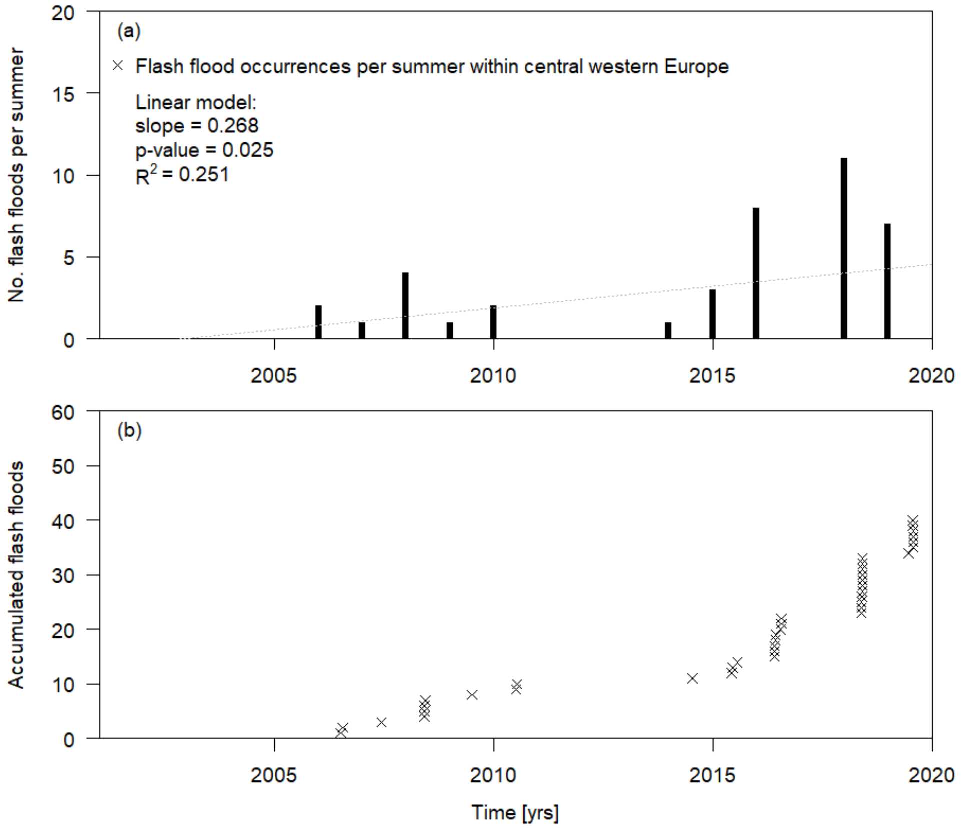

Figure 3~~2~~: Occurrence of flash flood events within central western Europe between ~~1981~~ 2001 and 2020. Panel (a) shows the number of flash flood occurrences per ~~year~~summer, panel (b) maintains the exact occurrence date of the flash flood event.

Figure 3 shows~~The patterns of~~ flash flood occurrences in central western Europe~~ have substantially changed between 1981 and 2020 (Figure 2 (a)). A simple linear model applied to the number of annual flash floods shows an increasing trend of 0.382 events per year (p-value 0.039)~~. While barely any events were reported before 2006, two remarkable ~~years~~ summers are 2016 and 2018, when flash floods occurred particularly often in the study area (~~23~~ 8 and ~~20~~ 11 occurrences respectively). As the temporal inconsistencies in the dataset do not allow drawing conclusions on any robust trends, this flash flood data compilation cannot support the conjectured increase in frequency of flash floods. Yet, tendencies seem to point in that direction. ~~Possibly, there might be a breakpoint in the time series before 2016. This can however not be demonstrated statistically as the time series after 2016 is still too short.~~ Note that often several events occurred within a few days (Figure 3 b) ~~(Figure 1 (b))~~ under the same meso-scale atmospheric constellation, in the same area or even in neighbouring catchments, and are, therefore, not completely independent from one another. Two flash floods in 2008 (Rangendingen, Jungingen, ~~(~~Ruiz-Villanueva et al., 2012~~)~~) and four floods in 2018 (Rhineland-Palatine, ~~(~~Johst et al., 2018~~)~~) occurred during the same large-scale P event.

3.2 ~~Unchanged occurrence of e~~Extreme precipitation event characteristics

Within our study area, we extracted extreme ~~precipitation~~ P events with precipitation ~~sums~~ intensities ≥ 40 mm h^{-1} from the DWD-radar-dataset. Between 2001 and 2020, we observed a slight, but insignificant increase in the number of events per ~~year~~ summer (Figure 4~~Figure 3~~a). Note that interannual variance is very high and that this increase includes two extreme years, 2006 and 2018, when precipitation events ≥ 40 mm h^{-1} occurred particularly often. Similar to the flash flood occurrences, many of the extreme precipitation events happened on the same days over a wider region. This is particularly the case for 2008 and 2018 ~~(Figure 3b)~~ – with the multiple rainfall events from 2018 overlapping with a high number of flash floods. For the precipitation amounts we could not ~~find~~ identify significant trends in the 2001-2020 period for both the maximum 5-minute precipitation intensities~~y~~ (Figure 4~~Figure 3c~~b) and the maximum hourly ~~precipitation sums~~ intensities per event (Figure 4~~Figure 3~~d). P events that eventually led to flash floods (Figure 4c, e) do not differ in the range of precipitation intensities from P events that did not cause flash floods. The event duration of P events that caused flash floods is however slightly longer compared to the other extreme P events (Figure 4 f, g). The largest difference between P events causing flash floods and other P events is, however, the temporal and spatial extent. P events that cause flash floods are often longer-lasting and larger in comparison to extreme P events that did not lead to flooding (Figure 4 h, i). Neither the temporal nor the spatial extent of the P events shows trends over the study period of 20 years (Figure 4f, h).

Commented [JM22]: RC2: Line 248 “Between 2001 and 2020, we observed a slight increase in the number of events per year (Figure 3a).”: But not a significant one, right?

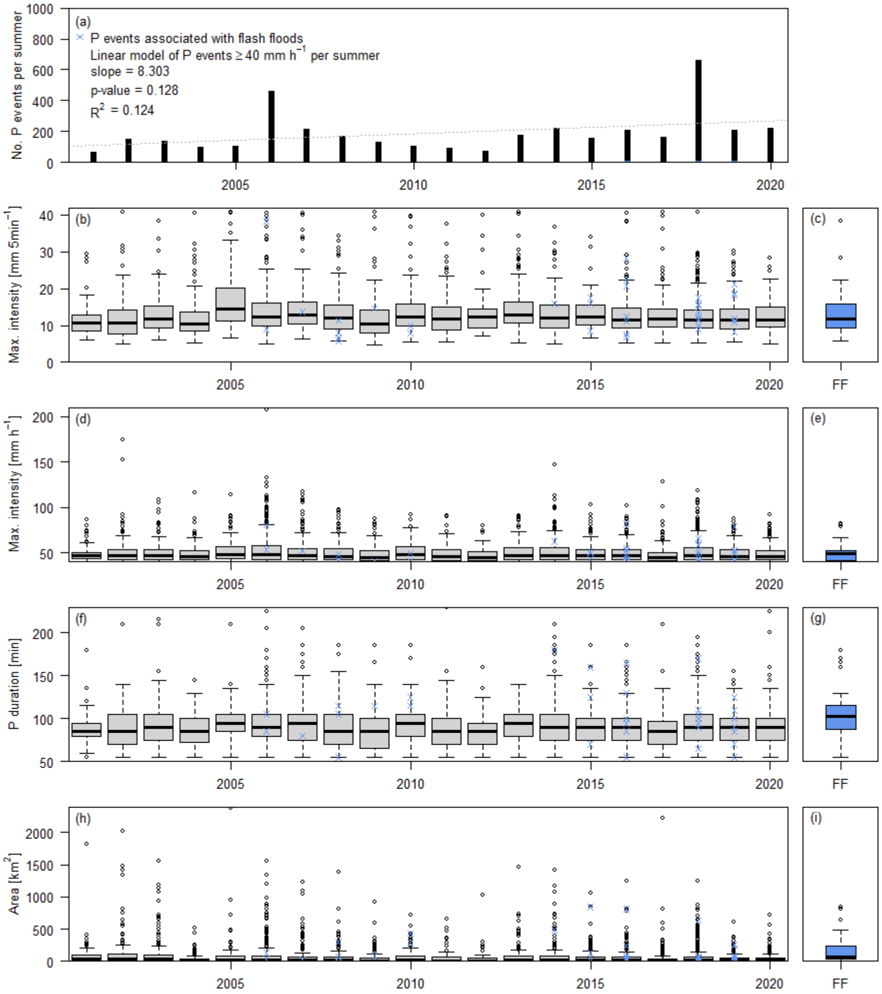

Figure 4~~3~~: Occurrence of extreme precipitation events (≥ 40 mm h^{-1}) within central western Europe. The panels in the left column show the precipitation event characteristics per summer between 2001-2020. The blue crosses and the right column (c, e, g, i) show the precipitation characteristics of the events, that are associated with a flash flood. Panel (a) shows the number of precipitation events per summer. The panels (b) and (c) show the P events' maximum precipitation intensity in 5 minutes per event, and per hour (d) and (e). The panels (f) and (g) show the temporal and (h) and (i) the spatial extent of the identified events.

3.3 Identification of atmospheric parameters favouring extreme precipitation and flash flood events

To identify parameter ranges that favour flash floods, we considered all hourly values of the parameters between May and August irrespective of any identified events, as events could only be identified within the last 20 years of the study period. Moreover, ~~as well as~~ we extracted the parameters present during the time of extreme ~~precipitation~~ P events and the selection of ~~precipitation~~ P events that led to flash flood occurrences (Figure 5~~Figure 4~~). The data emphasise the occurrence of extreme events under conditionally unstable atmospheric conditions. Most extreme precipitation and flash flood events occurred within the upper quartile of CAPE values (Figure 5~~Figure 4~~a). ~~High~~Sufficient values of CAPE are often accompanied by ~~low~~ moderate values of CIN. ~~While~~ Both extreme precipitation and flash flood events occurred over a wide range of CIN, ~~CIN is mostly limited to values below 100 J kg^{-1} during flash flood events~~with a slightly higher median value at the onset of an event compared to the general values (Figure 5~~Figure 4~~b). However, both CAPE and CIN appear to be widely scattered within the ~~upper and respectively lower~~ spectrum of their possible ranges. The K-Index, in contrast, proves to be a reliable index and more than 80% of all extreme precipitation and flash flood events occur within the thunderstorm relevant categories of the index above 28~~0~~°C (Figure 5~~Figure 4~~c). Moisture conditions during extreme precipitation and flash flood events were found to be mostly within the upper percentiles of the overall simulated values. Especially the specific humidity (q) and total column water vapour (TCWV) ~~during events~~ range~~s~~ clearly within the upper quartile of all values during events (Figure 5~~Figure 4~~d, e). ~~Total column water vapour (TCWV) and r~~Relative humidity (RH) also proves to always be high during extreme events (Figure 5f). All moisture parameters, and especially RH tend to be even higher during flash flood events compared to general extreme precipitation events (Figure 5~~Figure 4~~d-f). The wind related parameters considered to analyse storm motion and organisation are generally low during extreme precipitation and flash flood events. Especially the WS$_{10m-500hPa}$~~wind speed~~ (Figure 5~~Figure 4g~~h) ~~and DLS (Figure 4i)~~ stands out, with most of the values observed during extreme events being in the lower quartile of the full range of occurrences. Tendencies regarding WS$_{700hPa}$, DLS and LLS (Figure 5~~Figure 4k~~g, i, j) are less clear but show the same pattern. In addition to atmospheric parameters, soil moisture conditions were evaluated 24 h before identified events. Often, soil moisture within the upper and lower soil layer (Swvl1$_{0\text{-}7\ cm}$, Swvl3$_{7\text{-}100\ cm}$) is higher during flash flood events compared to general extreme ~~precipitation~~ P events (Figure 5~~Figure 4j, l~~k, m). The mid-level soil layer (Swvl2$_{7\text{-}28\ cm}$) ~~does not show major differences~~shows lower soil moisture before flash flood events (Figure 5~~Figure 4k~~l).

Commented [JM23]: RC3: Line 258: what does "all hourly values" refer to? Is it the time of the precipitation event and the flood event combined or something else? This needs to be described in more detail.

Commented [JM24]: RC3: Lines 261–262: Half of the distribution is above 100 J Kg-1 of CIN, which is moderate CIN, so I do not believe saying high values of CAPE are often accompanied by low values of CIN is entirely accurate.

Commented [JM25]: RC2: Lines 269 – 270 "All moisture parameters, and especially RH tend to be even higher during flash flood events compared to general extreme precipitation events (Figure 4d-f).": As clearly not all heavy rainfall events lead to flash flood events, can you also give some event statistics (earlier in the manuscript) between the two groups? What were average rainfall intensities in both groups, does the duration differ, does the size of the rainfall storms differ, etc.? This will give an idea why we see differences between the two groups. Lines 274 – 277: This also says a lot about the initial catchment wetness prior to a flash flood event. As stated earlier by the authors, the wetter, the quicker a flash flood can occur. Now, from these results, I do not directly see a significant difference between the three groups. Only the 'P' group has somewhat lower initial soil moisture values, which gives the impression that heavy, convective rainfall does more often occur during drier periods. Something which corresponds a bit to the summer weather patterns in Northwest Europe. It also suggests that initial soil moisture conditions were on average not different from other days in the studied periods, so the flash floods are mostly a result of the weather system and not initial conditions here.
In addition, perhaps it is interesting to show the soil moisture as a relative scale (so % of the capacity).

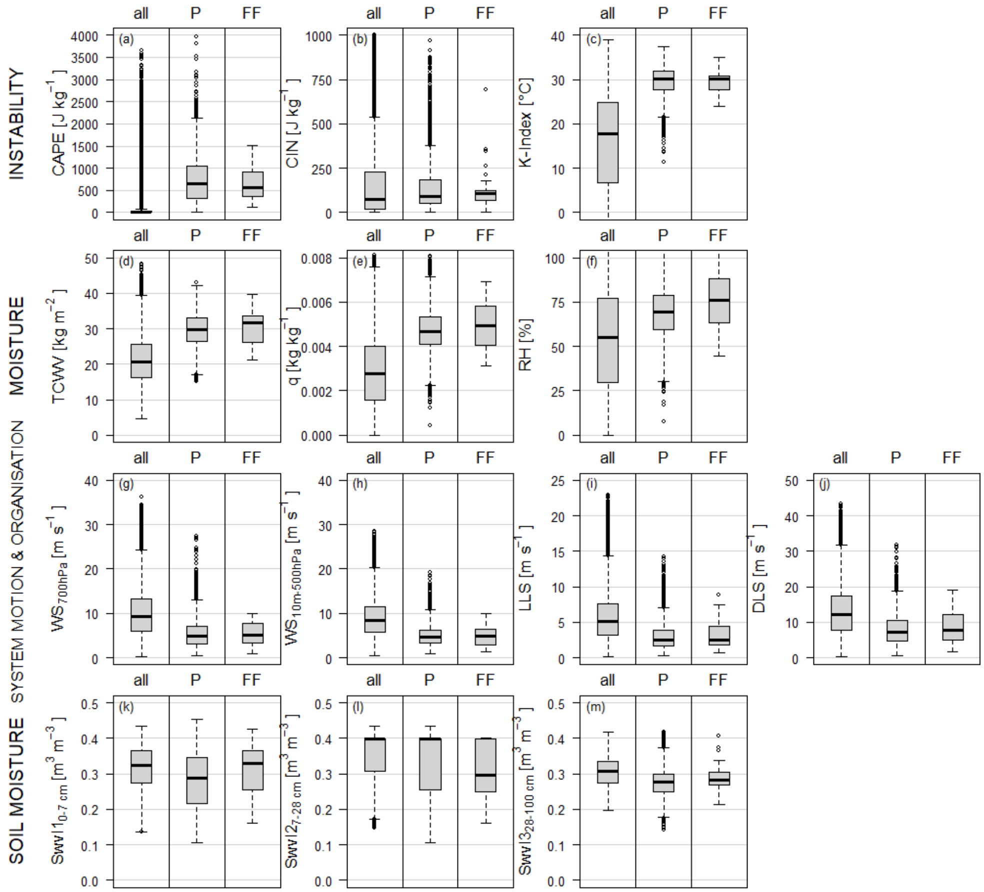

Figure 5~~4~~: All hourly values of the proxy parameters (a-~~i~~j) during the entire time period (all), ~~during~~ before extreme precipitation events (P) and before flash flood events (FF). Soil moisture (~~j-l~~k-m) was extracted 24 hours before identified P or FF events.

This analysis leads to the determination of the thresholds in ~~Table 1~~ Table 2 to classify atmospheric conditions as extreme precipitation and potentially flash flood favouring. Moreover, ~~high~~ sufficient CAPE, high q and weak ~~DLS~~ $WS_{10m-500hPa}$ were identified as the most clearly distinguishing parameters per category to characterize extreme precipitation events, including 75 % of all extreme precipitation events and excluding around 75% of all generally occurring parameters values.

Table 2: Threshold values determined as flash flood favouring based on the lower/upper quartile of their range of occurrence during extreme precipitation events.

Instability			Moisture			Storm motion & organisation			
CAPE	CIN	Kx	TCWV	q	RH	$WS_{700\ hPa}$	$WS_{10m\text{-}500hPa}$	LLS	DLS
≥ 326.9~~100~~	≤ 183.5~~180~~	≥ 27.8~~22~~	≥ 26.5~~20~~	≥ ~~0.004~~0.004	≥ 59.4~~50~~	≤ 7.1~~7~~	≤ ~~3~~6.2	≤ 3.8	≤ ~~10~~10.4
J kg^{-1}	J kg^{-1}	°C	kg m^{-2}	kg kg^{-1}	%	m s^{-1}	m s^{-1}	m s^{-1}	m s^{-1}

3.4 Changes of atmospheric parameters between 1981-2020

Instability, as shown representatively by CAPE above ~~100~~ 326.9 J kg^{-1}, has increased between 1981 and 2020. The number of hours with high enough instabilities to support the occurrence of thunderstorms increased by up to five hours per ~~year~~ summer (Figure 6~~Figure 5~~a). These findings were particularly significant for the northern part of the study area (Figure 6~~Figure 5~~b). There are ~~however no clear~~moreover significant increasing trends regarding the actual values of CAPE above 326.9 ~~100~~ J kg^{-1} in the north-western and mid-southern part of the study area (Figure 6~~Figure 5~~c, d).

The observed increase in high atmospheric moisture content, represented by specific humidity above 0. 004~~004~~ kg kg^{-1} (Figure 6~~Figure 5~~e, g), is highly significant over the entire study area (Figure 6~~Figure 5~~f, h). Conditions with high moisture content became up to 8 hours per ~~year~~ summer more frequent, especially over south-western Germany. The absolute increase of very high moisture content is however small (Figure 6~~Figure 5~~g).

The storm motion potentially decreases with weak ~~DLS~~ $WS_{10m\text{-}500hPa}$ that tends to occur more often ~~over most parts of~~in the study area (Figure 6~~Figure 5~~i). The values below the threshold of ~~10~~ 6.2 m s^{-1} appear to become higher in the western part of the study area and lower within the eastern part. These trends are however insignificant over the entire study area (Figure 6~~Figure 5~~j, l) and $WS_{10m\text{-}500hPa}$ ~~DLS~~ is considered to remain largely unchanged.

The complete set of analysed atmospheric parameters is shown in Appendix A.

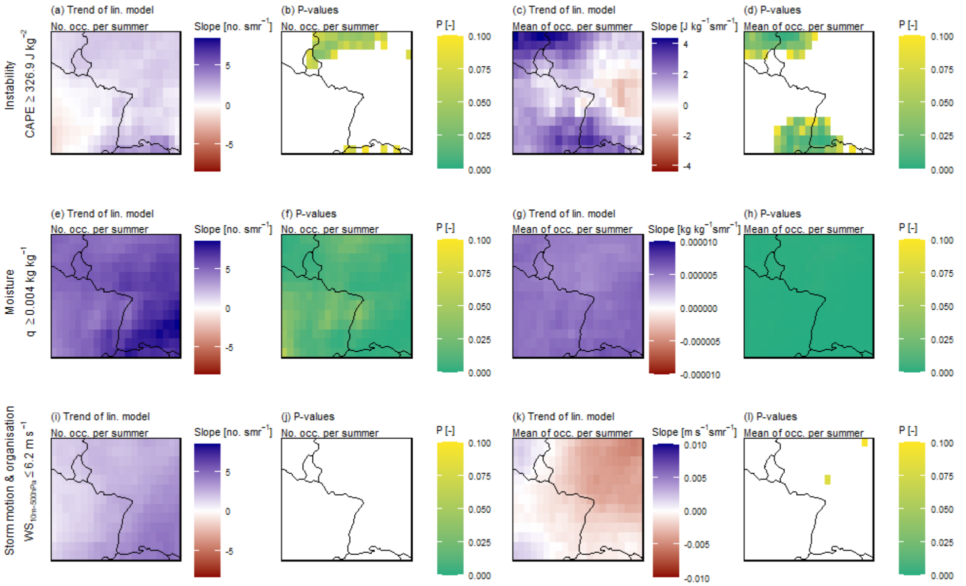

Figure 6~~5~~: Trend analysis of the most suitable variables for instability (CAPE), moisture (specific humidity q), and storm motion and organisation (~~DLS~~wind speed, $WS_{10m\text{–}500hPa}$). The first column (a, e, i) shows the trends of the numbers of hourly occurrences of values above or below their respective threshold, including their significance-levels ~~p~~ in the second column (b, f, j). The third column (c, g, k) shows the trends of the mean values of all hourly occurrences above or below the threshold and the last column (d, h, l) their respective significance-levels ~~p~~. White areas mark insignificance.

3.5 Spatial distribution of atmospheric conditions favouring extreme precipitation and flash flood events

The simultaneous occurrence of the three most characteristic identified atmospheric parameters from each component (CAPE, q, $WS_{10m\text{–}500hPa}$~~DLS~~) within extreme event favouring parameter ranges is correlated with topography (Figure 1c). Favourable atmospheric conditions occur most frequently over the Vosges Mountains in France and in south-western Germany, compared to the rest of the study area. Over eastern Belgium, favourable atmospheric conditions have occurred less than half as often between 1981 and 2020 (Figure 7~~Figure 6~~a). Within this period, the occurrence of favourable atmospheric conditions changed very little. Over south-western Germany, the simultaneous occurrence of these three parameters occurred only 1-2 h per ~~year~~ summer more often, while over north-eastern France these conditions occur slightly less often (Figure 7~~Figure 6~~b). There is, however, no significance of trends regarding these combinations~~ is however low.~~ (Figure 7~~Figure 6~~c). Splitting the 40-year period in two, 1981-2000 (Figure 7 d-f) and 2001-2020 (Figure 7 g-i), shows a decreasing trend within the first 20 years and a positive trend within the last 20 years. As these seem to be clear tendencies, they more or less level out over the entire time period. In line with the large variation of the number of occurrences of favourable atmospheric conditions per summer, none of the calculated trends are significant (Figure 7 f, i).

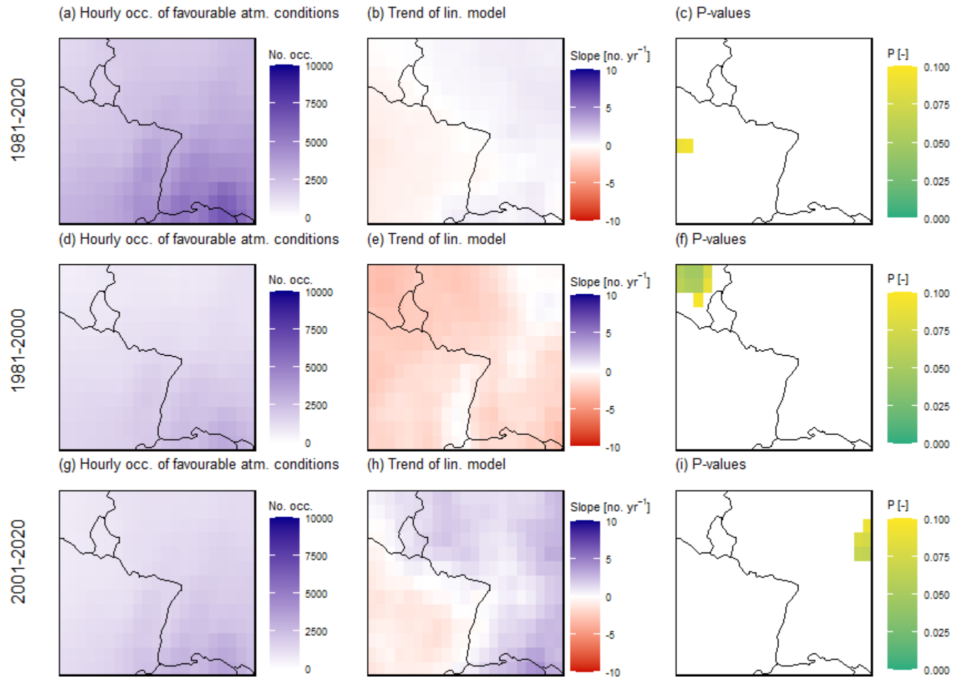

Figure 7~~6~~: Panel (a) shows the overall number of hourly occurrences of atmospheric conditions favouring extreme precipitation and flash flood events during the summer months between 1981 and 2020. Panel (b) illustrates the positive trends of atmospheric conditions favouring extreme precipitation and flash flood events per year, and panel (c) the significance of the linear model. White areas mark insignificance. The panels (d)-(f) show the same for the time period of 1981-2000, and (g)-(i) for 2001-2020.

4 Discussion

~~Furthermore, this increase is in line with similar observations in the~~In the Mediterranean area (Llasat et al., 2016) and lowland catchments of Alpine regions increases in flash floods have been observed (Sikorska-Senoner and Seibert, 2020). In central western Europe, there is moreover an increase in the number of reports and scientific publications on ~~the topic~~flash floods (e.g. Bronstert et al., 2018; Van Campenhout et al., 2015; Marchi et al., 2010; Ruiz-Villanueva et al., 2012). ~~The compiled database shows an increase in flash floods occurrences in temperate central western Europe between 1981 and 2020. Barely any events were found in the two first decades. This increase is further supported by the recently increasing number of reports and~~

~~scientific publications on the topic (e.g. Bronstert et al., 2018; Van Campenhout et al., 2015; Marchi et al., 2010; Ruiz-Villanueva et al., 2012). In a wider context, these flash floods might even be seen as an extension of the continental “flash flood belt” ranging from the Black Sea via Slovakia, Slovenia, northern Italy, and Austria, to south-western Germany and now potentially extending into Luxembourg (Marchi et al., 2010; Ruiz-Villanueva et al., 2012). Furthermore, this increase is in line with similar observations in the Mediterranean area (Llasat et al., 2016) and lowland catchments of Alpine regions (Sikorska-Senoner and Seibert, 2020).~~ However, as per their nature, flash floods are rare phenomena. Therefore, we are not able to proof any trends based on the data we have collected.~~categorized a wide range of floods triggered by thunderstorms as flash floods. Yet, uncertainties about their precise spatial and temporal distribution remain. Beyond that, t~~ The method of data collection is influenced by the progress of digitalisation which might make recent years appear more often in search engines. Additionally, we browsed through historical archives but did not find further entries. ~~Note, that the~~Any identified trend ~~we identified is~~would moreover be strongly influenced by two years in which especially many events occurred: 2016 and 2018 (and possibly the July 2021 floods, that were not considered in this manuscript but may further strengthen the increasing trend). During these event series, atmospheric conditions were characterised by exceptionally long-lasting weather patterns associated with very moist and unstable air masses. These conditions led to the extraordinarily high number and severity of thunderstorms with substantial flooding in central western Europe (Mohr et al., 2020; Piper et al., 2016).

Based on the DWD’s RADOLAN dataset we were not able to detect any linear trends in the number of precipitation events per year, their maximum hourly ~~sums or their maximum~~and 5-minute intensit~~y~~ies between 2002-2020. These findings are in line with similar analyses done by the DWD and GDV (2019). As the detection of extreme precipitation events remained challenging due to their localised occurrence, large-scale data were only available through the deployment of a dense radar station network as of 2002. Note that this observation period remains rather short and does not allow to infer solid conclusions on potential trends. Also, while weather radars provide precipitation data of high spatial resolution, various sources of uncertainty may prevail – related to precipitation type and intensity, topography, distance to the radar source, etc. (Meischner, 2014; Strangeways, 2007; Winterrath et al., 2017). We accounted for some of these potential effects (e.g., rain gauge adjustments, detection, and correction of possible anomalous propagation echoes). Perhaps, trends in extreme precipitation events could be detected when considering preceding decades as well. Müller and Pfister (2011) analysed longer time series starting in 1980 and indeed found an increase in intense rainstorms during summer months in western Germany (Emscher-Lippe catchment). However, precipitation generally varies considerably on an interannual basis and makes trend analyses challenging. In previous work (Meyer et al., 2020), we analysed 98 daily precipitation station data in the Moselle catchment over a 65-year period and could not find trends in the daily precipitation maxima as well as the number of days with precipitation amounts above 50 mm d^{-1}. While the daily precipitation sum should be a reliable indicator for extreme precipitation amounts, the coarse station network probably missed high rainfall amounts that fell in between stations. As both~~,~~ the~~is~~ long-term coarsely resolved dataset and the highly resolved short-term dataset did not show clear ~~signs of~~ trends, we could not confirm the hypothesis of an increase in extreme precipitation events within the study area.

Commented [JM26]: RC 2: I am concerned whether that is a long enough record to make climate-related conclusions? Especially the radar dataset, which only covers 20 years, seems too short to make climate trend-related conclusions. I do see the advantage of the high space-time resolution of radar for such an analysis, and it makes me happy to see it used, but the database length seems not sufficient yet. Although I find it hard to say what the minimum number of years should be in the dataset, I think the work needs at least a more extensive written support for the use of the dataset and the uncertainty that gives in the results.

We found that atmospheric conditions favouring extreme precipitation and subsequent flash flood events became slightly more frequent and intensities of relevant atmospheric parameters increased. The most significant increases were found for the moisture parameters which are in line with the assumption of the Clausius-Clapeyron relationships (Lenderink and Van Meijgaard, 2008; Martinkova and Kysely, 2020; Mishra et al., 2012). Both, TCWV and q, increased significantly over central western Europe indicating potentially higher precipitation amounts. Yet, rising air temperatures inhibit an increase in higher RH (Rädler et al., 2018). The increase of q also influences instability parameters, such as CAPE and the K-Index, to increase at a significant level in some areas. This matches well with the findings by Taszarek et al. (2021b) who documented an increase of CAPE over central Europe. Trends of CIN are however ambiguous within the same period. While in some areas favouring conditions do occur more often, there are indications that CIN increases as well. This increase in CIN might offset some of the instability increases through CAPE (Taszarek et al., 2021a). In this study, we did not analyse the simultaneous occurrences of CAPE and CIN in detail, but Chen et al. (2020) found highly complex interactions, suggesting that future moist convection and rainstorms may become less frequent but more intense. Regarding low wind speeds and weak ~~bulk shear~~DLS, we found slightly increasing but barely significant trends. Increasing trends in low LLS are partly significant. ~~Therefore~~Overall, the organisation and motion of storm systems stayed largely unchanged with tendencies favouring the occurrence of extreme precipitation. Studies looking at substantial DLS for other convective hazards such as hail or tornadoes did not identify significant trends either (Púčik et al., 2017; Rädler et al., 2018). Wind speed and shear are not directly relevant for triggering precipitation but slightly increasing the duration of an event, they are potentially contributing to the development of flash floods. The coarse resolution of the ERA5 atmospheric data might miss smaller-scale wind features related to orography. Even though extreme precipitation and flash floods tend to occur locally, they happen during meso- to large-scale favouring conditions, which should be well captured by the reanalysis data.

The values of the considered atmospheric parameters cover the expected ranges of occurrence. However, to include 75 % of all precipitation and flash flood events, we had to include an even wider parameter range. This holds especially true for the lower and respectively upper thresholds of CAPE and CIN, that appear low and respectively high compared to common values present during thunderstorms (Púčik et al., 2015; Taszarek et al., 2017). In the ERA5 data, both parameters showed an extremely high variability in space and time. ~~As for our identified events we found that CAPE, as well as CIN, were often higher and respectively lower in a neighbouring grid cell or time step, compared to the grid cell and time step in which we identified most rain.~~ This variability of CAPE also leads to a relatively low number of hours with all parameters within their ranges, as shown in Sect. 3.5 (Figure 7~~Figure 6~~). What is striking, however, are the consistently low values of DLS. While we stated in the beginning, that DLS can be either low or high, this does not seem the case in this region. Extreme rainfall and flash flood events seem to be consistently caused by slow-moving single-cell thunderstorms. In the US, in contrast, many flood-producing storms are larger and more organized mesoscale convective systems (Ashley and Ashley, 2008; Schumacher and Johnson, 2006). The floods considered in US American studies are however relating to rather large and deadly flash floods, while in central Europe flash floods generally do not reach comparable dimensions.

Commented [JM27]: RC1: By examining the trend in individual component of the comprehensive conditions as the authors did here offer limited insights into the real changes in flood potential

Commented [JM28]: RC2: Lines 266 – 267 “Moisture conditions during extreme precipitation and flash flood events were found to be mostly within the upper percentiles of the overall simulated values.”: That is also what you expect seeing the Clausius-Clapeyron (CC) relation and in fact even the 2CC relation for extreme precipitation. It probably deserves mentioning that, including some references (e.g. Lenderink & Van Meijgaard, 2008; Mishra et al., 2012; Manola et al., 2018; Wasko et al., 2018; Dahm et al., 2019).

Commented [JM29]: RC1: Increases in moisture content are kind of expected according to the Clausius-Clapeyron relationships,

Commented [JM30]: RC2: Lines 361 – 362 “Regarding low wind speeds and weak bulk shear, we found slightly increasing but barely significant trends.”: But you did find a significant trend for LLS, right?

The focus of our work was the attempt to link atmospheric conditions, extreme precipitation and flash floods: The observed increase in flash floods is a consequence of more intense or more often occurring precipitation events, that are initiated by thunderstorm favouring atmospheric conditions. However, reality seems a lot more complex. While atmospheric conditions tend to become more unstable, and overall warmer air masses potentially possess a higher amount of water vapour, the expected increase in (convective) precipitation events were not obvious from the 20 years of analysed data~~. Thus, the increase in flash flood occurrences cannot be explained by the sole increase in precipitation intensity or occurrence frequency~~.

Other factors than those that we have considered in this study may influence the development of flash floods. One could be the duration of favouring atmospheric conditions. Both remarkable flash flood series from 2016 and 2018 occurred during atmospheric blocking situations (Mohr et al., 2020; Piper et al., 2016) that stymied the movement of the atmosphere, ultimately causing weather constellations to last longer and thus creating extreme situations. In recent years they have been increasingly observed, especially in summer (Detring et al., 2021; Lupo, 2020). This could hint to a change in the intra-annual distribution of precipitation, while the number of precipitation events, their maximum 5-minute~~ intensity, ~~and ~~their ~~hourly ~~sum ~~intensity stayed – apart from their large intra-annual variations – at a similar level between 2001 and 2020. Sequences with abundant rainfall may eventually rise a catchment's soil moisture and accelerate the development of a flood event. While the low top-level soil moisture before the precipitation events might show the typical pattern of central Europe, where thunderstorms mostly occur after a few warm and dry days, this does not seem to not be the case, when flash flooding is caused. The soil moisture is then already elevated at the top layers of the soil to the 'average' level by previous rainfall and causes a faster runoff response. Flash floods in continental regions mostly occur when soil moisture is high at the onset of an event (Marchi et al., 2010; Pfister et al., 2020). Moreover, catchment-specific parameters such as topography, land use, soil properties, geology or other factors may equally impact the development of flash floods (Marchi et al., 2010).

Commented [JM31]: RC2: Lines 420 – 422 "In addition to the hypothesis, we found mostly higher upper (0-7 cm) and lower (28-100 cm) layer soil moisture during flash flood events compared to general extreme precipitation events.": This did not seem that significant in the results.

5 Conclusion

The goal of ~~this ~~our study was to ~~investigate~~identify and analyse the atmospheric conditions ~~the causes for a more frequently observed~~prevailing during extreme precipitation and flash flood events in temperate regions of central western Europe. For this purpose, we compiled a flash flood database based on scientific literature, water agency data and the information of local consultants and analysed it using linear regression models. For the identification of extreme precipitation events potentially triggering flash floods, we relied on a 5-minute radar dataset (RADOLAN, DWD) and analysed all precipitation events exceeding the threshold of 40 mm h^{-1} statistically considering maximum hourly and 5-minute precipitation intensities ~~precipitation sums ~~as well as the temporal and spatial coverage of events~~5-minute maxima~~. The identified flash flood and precipitation events were then connected to convection relevant atmospheric parameters of the ERA5 reanalysis dataset representing instability, moisture content and system motion and organisation. We leveraged these data for testing our hypothesis that a change in atmospheric conditions led to more frequent extreme precipitation events that subsequently ~~led to~~

~~more~~triggered flash flood events in central western Europe~~.~~. Note, that the conjectured increase in the occurrence of flash floods could not be tested due to inconsistencies in the data base. We tested our hypothesis in t~~hree~~wo steps:

~~I) The hypothesised increase in the occurrence of flash floods was confirmed, despite possible minor biases in the database.~~

~~II)~~I) An increase in the frequency and intensity of extreme precipitation events could not be ~~confirmed~~ supported with the available database and analysis due to a large interannual variation in events and a relatively short period of 20 years. Future analyses could incorporate the intra-annual temporal distribution of extreme precipitation events. Perhaps, formerly evenly distributed rainfall events tend to occur more condensed within a few days.

~~III)~~II) Via proxy parameters we did find changes in the occurrence of atmospheric conditions favouring extreme precipitation and flash flood events. High absolute moisture content (q, TCWV) has increased significantly between 1981 and 2020, while RH decreased slightly. Proxy parameters representing sufficient instability (CAPE, K-Index) increased as well and so did CIN, which might oppose some of the instability gains of CAPE (Taszarek et al., 2021a). Parameters determining weak storm motion and organisation (WS$_{10m-500hPa}$, DLS) did not show significant changes, but the occurrence of weak LLS increased slightly. Overall, the most important components favouring flash flood relevant atmospheric conditions, abundant moisture and sufficient latent instability, have become more frequent and higher values indicate possibly more severe events.

Consequently, only the sub-hypothes~~i~~e~~s~~ ~~I and III~~II is ~~are confirmed~~supported, while ~~the second~~ sub-hypothesis I was rejected. Hence, the simple causal chain between the atmospheric conditions, extreme precipitation and flash floods assumed in the overarching hypothesis does not do justice to the entire complexity of problems. Interconnections seem far more complex than hypothesised. In addition to the hypothesis, we found mostly higher upper (0-7 cm) and lower (28-100 cm) layer soil moisture during flash flood events compared to general extreme precipitation events. These results might point us in other directions, possibly to changes in intra-annual temporal patterns of rainfall and consequently different pre-event soil moisture conditions. Another explanation might be non-atmospheric, catchment-specific parameters, that were not considered in this study.

To the best of our knowledge, this work is none the less among the first ones focussing on the convective hazard of extreme precipitation that was often neglected, giving priority to hail or tornadoes. As extreme precipitation is extremely variable in space and time and can derive from many different weather constellations, it remains a challenge to pinpoint atmospheric conditions that trigger them. This makes possible assumptions about the future extremely challenging.

Appendix A : Spatial trends of atmospheric parameters within central western Europe

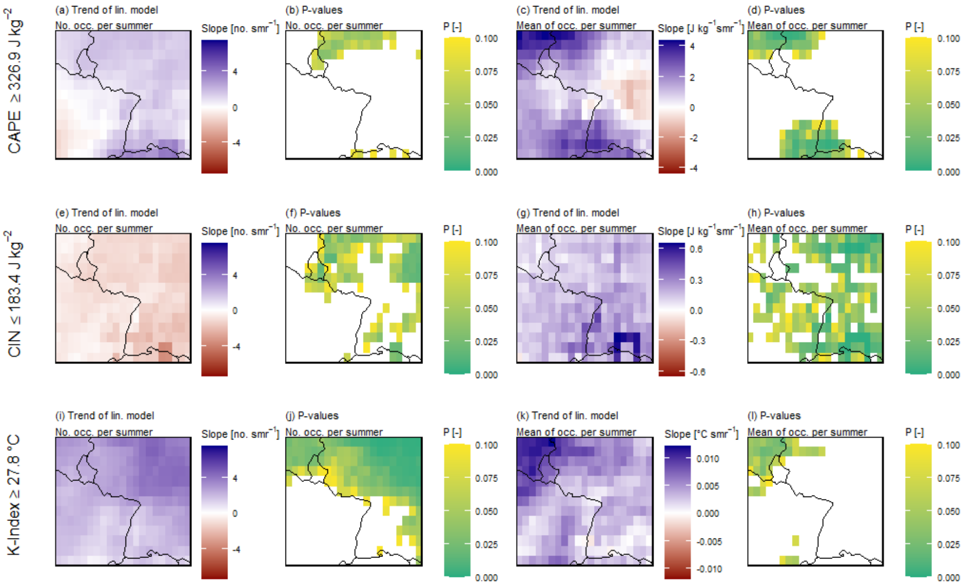

Figure A1: Trend analysis of the three variables for instability (CAPE, CIN, K-Index) per summer (smr). The first column (a, e, i) shows the trends of the numbers of hourly occurrences of values above their respective threshold, including their significance-levels ~~p~~ in the second column (b, f, j). The third column (c, g, k) shows the trends of the mean values of all hourly occurrences above the threshold and the last column (d, h, l) their respective significance-levels ~~p~~. White areas mark insignificance.

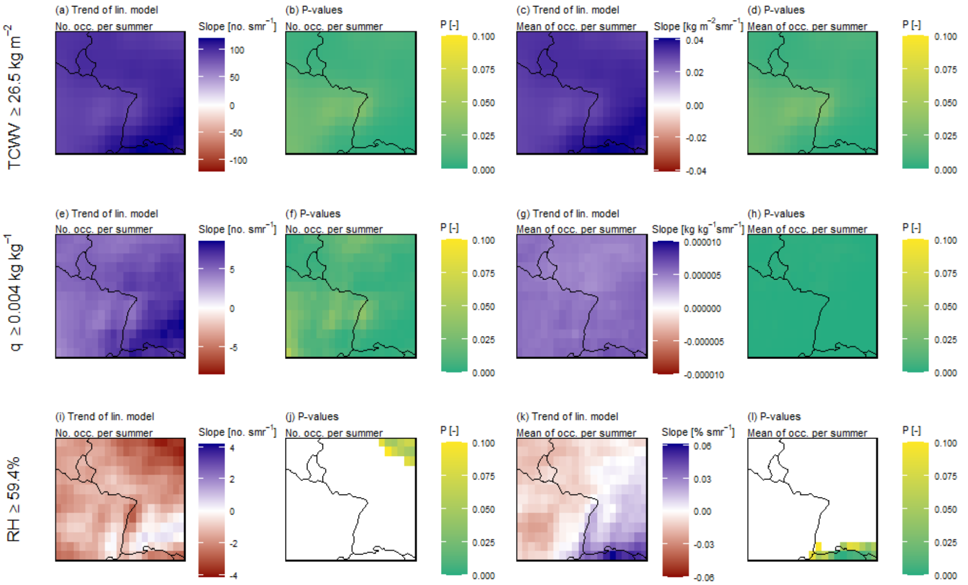

Figure A2: Trend analysis of the three variables for moisture (TCWV, q, RH) per summer (smr). The first column (a, e, i) shows the trends of the numbers of hourly occurrences of values above their respective threshold, including their significance-levels ~~p~~ in the second column (b, f, j). The third column (c, g, k) shows the trends of the mean values of all hourly occurrences above the threshold and the last column (d, h, l) their respective significance-levels ~~p~~. White areas mark insignificance.

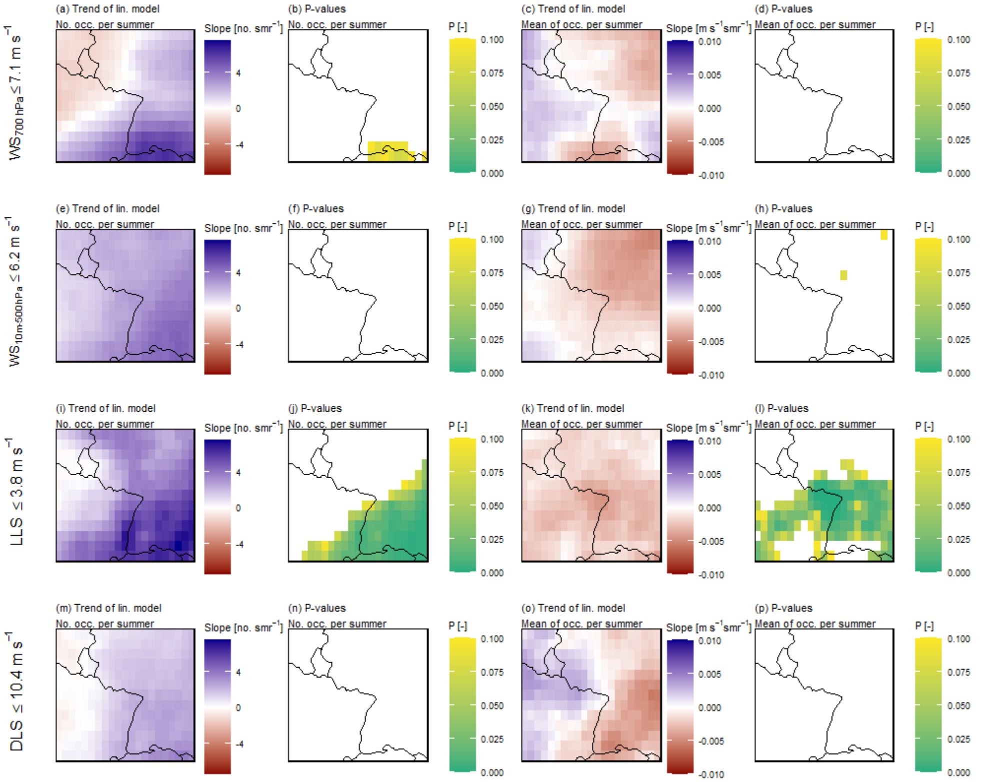

Figure A3: Trend analysis of the three variables for storm motion and organisation ($WS_{700\,hPa}$, $WS_{10m\text{–}500hPa}$, LLS, DLS) per summer (smr). The first column (a, e, i, m) shows the trends of the numbers of hourly occurrences of values above their respective threshold, including their significance-levels ~~p~~ in the second column (b, f, j, n). The third column (c, g, k, o) shows the trends of the mean values of all hourly occurrences above the threshold and the last column (d, h, l, p) their respective significance-levels ~~p~~. White areas mark insignificance.

Data availability

The flash flood database used in this manuscript is added to the supplements. The RADOLAN radar dataset by the German Weather Service (DWD) is free for download from their open data server [https://opendata.dwd.de/climate_environment/CDC/grids_germany/5_minutes/radolan/reproc/2017_002/, last accessed June

2021]. The ERA5 atmospheric parameters are also free for download from the Climate Data Store (CDS) of the Copernicus Climate Change Service (C3S) [https://cds.climate.copernicus.eu, last accessed November 2021].

Author contributions

JM, MN, LP, and LM conceptualized the study. JM collected the flash flood and ERA5 data, carried out the analysis and wrote the first draft of the manuscript. MN provided the processed precipitation radar data. All co-authors (JM, MN, LP, LM, EZ) contributed to and edited the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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