AGU ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2020GL092361

Key Points:

- Following an ingredients-based method, future changes in intense rainstorms in Europe are studied using convection-permitting simulations
- Environments favoring high rainfall rates are projected to be 7× more frequent by 2100, while the figure for quasi-stationary ones is 11×
- Reduction in storm speeds due to weaker jets, possibly via Arctic Amplification, can enhance accumulations further increasing flood risk

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:
Kahraman, A., Kendon, E. J., Chan, S. C., & Fowler, H. J. (2021). Quasi-stationary intense rainstorms spread across Europe under climate change. *Geophysical Research Letters*, *48*, e2020GL092361. https://doi.org/10.1029/2020GL092361

Received 19 JAN 2021
Accepted 16 JUN 2021

Quasi-Stationary Intense Rainstorms Spread Across Europe Under Climate Change

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Abstract Under climate change, increases in precipitation extremes are expected due to higher atmospheric moisture. However, the total precipitation in an event also depends on the condensation rate, precipitation efficiency, and duration. Here, a new approach following an "ingredients-based methodology" from severe weather forecasting identifies important aspects of the heavy precipitation response to climate change, relevant from an impacts perspective and hitherto largely neglected. Using 2.2 km climate simulations, we show that a future increase in precipitation extremes across Europe occurs, not only because of higher moisture and updraft velocities, but also due to slower storm movement, increasing local duration. Environments with extreme precipitation potential are 7× more frequent than today by 2100, while the figure for quasi-stationary ones is 11× (14× for land). We find that a future reduction in storm speeds, possibly through Arctic Amplification, could enhance event accumulations and flood risk beyond expectations from studies focusing on precipitation rates.

Plain Language Summary Intense rainstorms are expected to be more frequent due to global warming, because warmer air can hold more moisture. Here, using very detailed climate simulations (with a 2.2 km grid), we show that the storms producing intense rain across Europe might move slower with climate change, increasing the duration of local exposure to these extremes. Our results suggest such slow-moving storms may be 14× more frequent across land by the end of the century. Currently, almost-stationary intense rainstorms are uncommon in Europe and happen rarely over parts of the Mediterranean Sea, but in future are expected to occur across the continent, including in the north. The main reason seems to be a reduced temperature difference between the poles and tropics, which weakens upper-level winds in the autumn, when these short-duration rainfall extremes most occur. This slower storm movement acts to increase rainfall amounts accumulated locally, enhancing the risk of flash floods across Europe beyond what was previously expected.

1. Introduction

Local precipitation extremes on sub-daily time scales are known to be increasing due to anthropogenic climate change (Fischer & Knutti, 2016; Fowler et al., 2021; Kendon et al., 2014; Lehmann et al., 2015; Westra et al., 2014). Higher moisture availability in the atmosphere with warming has been extensively studied and partially explains the observed and simulated rise in short-duration precipitation extremes, with stronger updrafts also potentially contributing (Giorgi et al., 2016; Held & Soden, 2006; O'Gorman & Schneider, 2009). Many studies have reported increases in precipitation extremes with temperature following the Clausius-Clapeyron (CC) rate of 7% per K (Ali et al., 2021; Visser et al., 2020). However, higher scaling rates (so called 'super-CC scaling') have been found for hourly precipitation extremes (Ban et al., 2015; Berg et al., 2013; Drobinski et al., 2018; Hodnebrog et al., 2019; Lenderink & van Meijgaard, 2008; van de Vyver et al., 2019). Processes proposed to explain super-CC scaling include localized dynamics and convective organization (Chan et al., 2016; Feng et al., 2016; Lochbihler et al., 2019; Moseley et al., 2016; O'Gorman, 2015; Pfahl et al., 2017; Prein et al., 2017).

Here, for the first time, we use an "ingredients-based" approach to understand future changes in extreme precipitation over Europe from 2.2 km UK Met Office pan-European simulations. This includes consideration of the movement speed of intense thunderstorm systems; largely disregarded to date despite its obvious importance (except Prein et al., 2017, which finds regionally varying speeds of mesoscale convective systems [MCSs] around North America). To mention other tangential works, Dougherty and Rasmussen (2020) examined the duration factor for the US, Mahoney et al. (2013) studied Colorado Front Range storms with instability, moisture, and lift as ingredients (for thunderstorms), and Gutmann et al. (2018) focused on the speed factor for hurricanes (with larger spatial and time scales). Overall, the physical basis for future changes in European extreme precipitation-producing storms is studied for the first time, using two simple but effective metrics.

2. Data and Methods

Convective storms produce most short-duration (1–3 h) heavy precipitation events (Chappell, 1986); with MCSs predominating in the mid-latitudes (Jiang et al., 2006; Morel & Senesi, 2002; Schumacher & Rasmussen, 2020). The "ingredients-based approach" used by contemporary meteorologists for forecasting convective storms provides a physical basis for factors required for an event, for example, moisture, instability, and lift for thunderstorms. Heavy precipitation is one of the few meteorological phenomena for which the ingredients are known (Doswell et al., 1996):

$$P = \dot{\mathrm{R}}\, D \tag{1}$$

where P is amount of precipitation, $\dot{\mathrm{R}}$ is average precipitation rate, and D is duration (Doswell et al., 1996). From a Lagrangian perspective, the average rainfall rate for a storm system depends on available moisture and condensation rate (via upward motion), as well as the extent to which condensate reaches the ground as precipitation (the precipitation "efficiency"), formulated as:

$$\dot{\mathrm{R}} = E\, w\, q \tag{2}$$

where E is precipitation efficiency, w is vertical velocity, and q is specific humidity (Doswell et al., 1996).

Precipitation efficiency depends on many factors (Held & Soden, 2006), and is hard to analyze. Higher efficiency results from environments with higher relative humidity (due to reduced evaporation within dry air entrainment, Cotton & Anthes, 1989), greater depth of convective cloud below the freezing level (enabling a longer collision-coalescence process) and weak vertical wind shear (producing weaker entrainment and evaporation, Davis, 2001). Microphysical cloud properties (e.g., droplet size distribution) are also crucial factors.

Here we use pan-European climate simulations (RCP8.5) with 2.2 km grid spacing from the UK Met Office Unified Model (v10.1) that successfully simulate hourly precipitation (Berthou et al., 2020; Chan et al., 2020). At this high-resolution, the model is termed "convection-permitting" as convection can be represented explicitly on the model grid without the need for convection parameterization (Kendon et al., 2012). Convection-permitting models (CPMs) are routinely used for operational forecasting, and can forecast localized extreme events not captured by coarser resolution models (Clark et al., 2016; Lean et al., 2008). Improved representation of hourly precipitation characteristics by CPMs include the diurnal cycle, the spatial structure of precipitation, the intensity distribution and hourly extremes (Ban et al., 2014; Chan et al., 2014; Kendon et al., 2012; Prein et al., 2015). Overall, CPMs provide credible projections of future changes in short-duration precipitation extremes (Kendon et al., 2017). Model configuration details can be found in Supplementary Text S1 (Boutle, Abel, et al., 2014; Boutle, Eyre, & Lock, 2014; Mizielinski et al., 2014; Roberts & Lean., 2008; Wood et al., 2014).

At 2.2 km grid spacing, a typical low-level specific humidity value for forecasting severe convection is $q \geq 10$ g kg^{-1} at 850 hPa (Craven et al., 2002; George, 1960; Miller, 1972; Púčik et al., 2017; Showalter, 1947; Thompson et al., 2003); $w \geq 2$ m s^{-1} ascent at 700 hPa (Jeevanjee, 2017; Groenemeijer & van Delden, 2007; Kahraman et al., 2017; Melling & List, 1980; Morrison, 2017) is considered the threshold for a storm with sufficient condensation rate (Supplementary Text S2 and Figures S1, S2). We define "Extreme Precipitation Potential" (EPP) as cases when both thresholds are exceeded for 3-hourly instantaneous data, corresponding to environments with the potential for extreme precipitation rates. We count the number of EPP cases at each 2.2 km grid point in the domain (excluding 100 grid cells from each boundary, to remove any boundary artifacts) for current (1998–2007) and future (~2100 under RCP8.5) European climate. Land/sea analysis was done separately. EPP does not include precipitation efficiency, due to uncertainty in the complex factors involved, and thus disregards the wide range of environmental factors which control how much condensate actually reaches the ground. EPP therefore measures the "potential" for high precipitation rates, without providing one-to-one correspondence with actual precipitation. The model simulates >10 mm hourly precipitation for 78% of the EPPs, and >50 mm hourly precipitation for 45% of EPP cases (Figure S1). Examining the EPP proxy rather than actual high precipitation rates provides a physical basis for heavy precipitation changes (helps to discriminate controlling factors), which has wider applicability beyond those for a single (e.g., hourly) accumulation period.

Using the widely recognised Corfidi Vector technique for describing the motion of MCSs (Corfidi, 2003; Corfidi et al., 1996), we then define quasi-stationary storm systems as having Corfidi Vector ≤3 m s^{-1} (Supplementary Text S3). This very low threshold in terms of storm motion ensures that heavy precipitation is almost stationary, even for a single convective storm cell (with spatial scale typically comparable to the distance a slow-moving storm moves in its lifetime). Quasi-stationary storms with high levels of atmospheric moisture and strong vertical updrafts have the greatest potential for heavy precipitation accumulations. Hence, we define the co-occurrence of high moisture, high vertical velocity, and slow movement as "Slow-moving Extreme Precipitation Potential" (SEPP); a small subset of EPP cases, as most storm systems move faster. Other factors affecting rainfall duration not addressed here include storm size and orientation structure with respect to the propagation vector.

3. Results

Our results reveal that all of Europe is prone to intense rainstorms as measured by EPP, but the central Mediterranean experiences the highest frequency of cases, both currently and in the future (Figures 1a and 1b). In contrast, SEPPs are relatively rare in the current climate but become widespread across the continent by 2100 (Figures 1d and 1e). Significant warming under RCP8.5 produces a strong increase in EPPs (Figure 1c) but a more pronounced increase in SEPPs (Figures 1c and 1f). Across Europe as a whole, we find that EPP (SEPP) environments are 7.4 (10.6)× more frequent than today, by the end of century. Although SEPPs constitute only ~3–4% of all EPPs, they are important because of their potential for high precipitation accumulations and hence flooding.

In concert with these increases, the number of events with precipitation ≥100 mm h^{-1} (about 20% of EPPs in the current climate) increases threefold, while ≥150 mm h^{-1} is experienced 4× more frequently, and 200 mm h^{-1} 5.2× more frequently by 2100 (Figure 2). Frequency increases in 3-hourly extreme precipitation are similar (Figure S10). Smaller increases to the frequency of extreme hourly precipitation when compared to EPPs is likely due to lack of consideration of precipitation efficiency. However, the distribution of extreme hourly precipitation rates by month shows a similar pattern to EPPs, apart from lower frequencies during summer (Figure 2) when the environmental relative humidity—a key factor controlling precipitation efficiency—is reduced (detailed in Supplementary Text S6). This is consistent with earlier studies showing precipitation efficiency reductions in summer (e.g., Ye et al., 2014); although future changes are highly uncertain (Held & Soden, 2006). Despite this, frequency increases for autumn are significant for both EPP and SEPP (and associated extreme precipitation) cases. Indeed, with drier future summers, hourly precipitation extremes in Europe shift towards autumn with warming (Chan et al., 2020).

3.1. Precipitation-Tracking Analysis

To further assess the role of our proxies in explaining future increases in extreme precipitation events, we ran a precipitation-tracking algorithm (Crook et al., 2019; Stein et al., 2014) on re-gridded hourly model output (aggregated to 12 km horizontal grid intervals, which the code is optimized for; more details in Supplementary Text S5). We identified precipitation areas with at least one 12 km grid point with ≥20 mmh^{-1}, and calculated the movement speed distribution of such storms. The frequency of such storms robustly increases in the future (Figure S7). Similar to SEPPs, slow-moving storm systems (≤3 ms^{-1}) analyzed with this approach are most frequent in autumn in the current climate, but become much more frequent, with a frequency increase higher than that of faster-moving systems, in the future (Figure S7). Furthermore, storm

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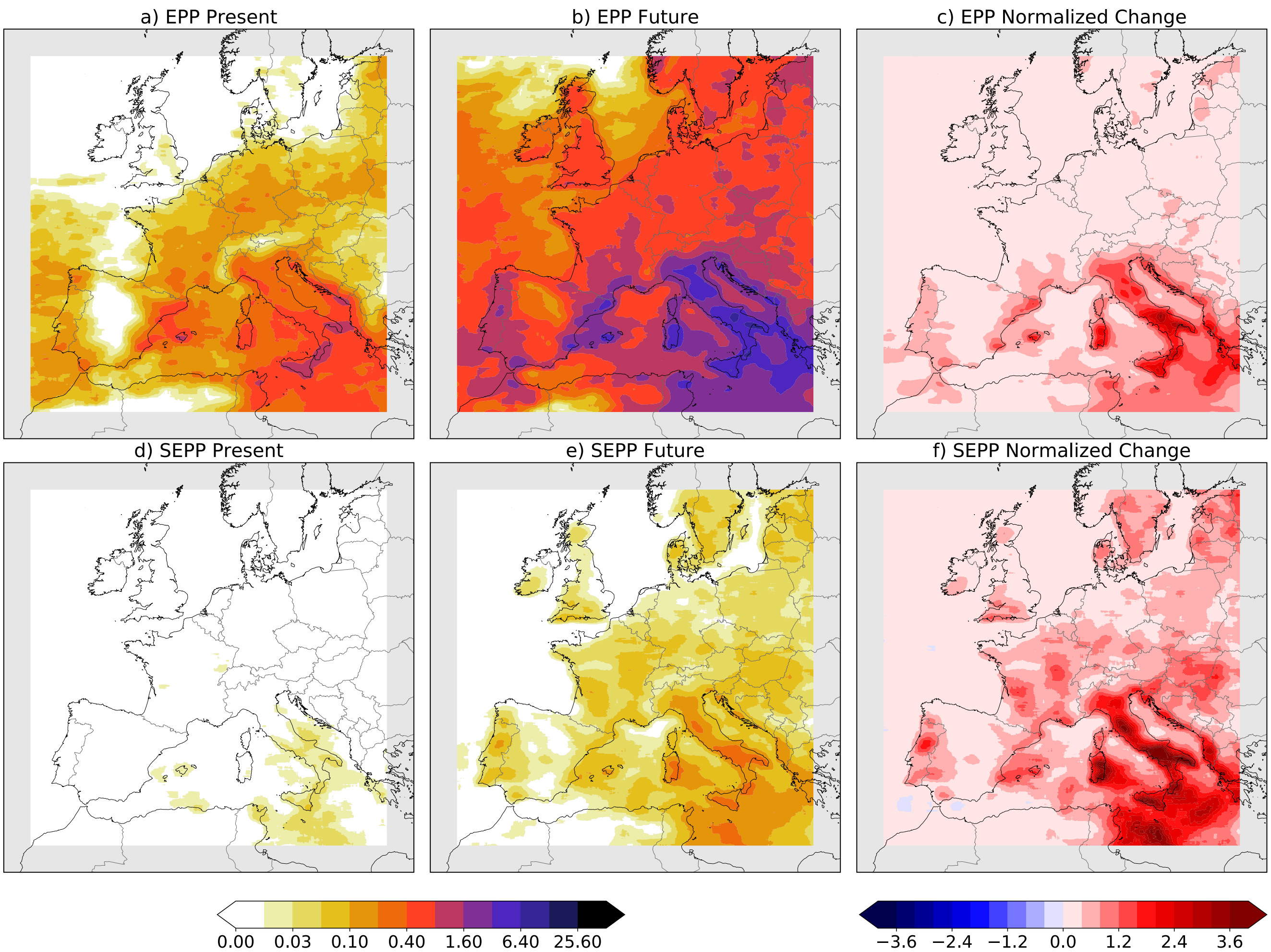

Figure 1. Number of (a) Extreme Precipitation Potential (EPP) cases in current climate (1998–2007), (b) EPP cases in future climate (10 years representing ~2100 under RCP8.5), (c) normalized change in EPP, (d) Slow-moving Extreme Precipitation Potential (SEPP) cases in current climate, (e) SEPP cases in future climate, (f) normalized change in SEPP, in 10-years of simulated output with 3-hourly intervals. Annual average EPP cases in current climate conditions for the whole domain is 20848.4 (corresponding to ~24 per 100 × 100 km area), and 153809.9 in the future (~175 per 100 × 100 km area). Annual average SEPP cases increase from 595.4 (~0.7 per 100 × 100 km) to 6335.3 (~7.2 per 100 × 100 km). The normalized change is calculated by dividing the future minus current value by the annual average number of current cases over 10,000 (0.05954 and 2.08484 for SEPP and EPP, respectively), in order to visually compare the EPP versus SEPP change. A smoothing to 113 km resolution has been applied by averaging the neighboring ±25 grid points. Note that the color scale of (a), (b), (d), and (e) is logarithmic.

speed distributions in all seasons become skewed to the left; and are thus slower on average year-round (Figure S7).

3.2. Seasonal and Regional Changes

EPPs and SEPPs (Figure 2) are mainly warm-to early cold-season phenomena. The geographical distribution of EPPs in the warm season corresponds with the distribution of MCSs around the Mediterranean in the current climate (Kolios & Feidas, 2010). However, it is notable that future EPPs are widespread across Europe (Figure 3), with almost the entire continent experiencing a similar or larger frequency of EPPs in summer as Southern Italy does from August to October currently. EPPs increase in all months, especially during an extended warm season, but with notable local decreases, that is, almost no future EPPs over the Adriatic Sea in August (Figure 3), or over parts of the Mediterranean Sea in September, likely due to changes in lift. This may be because of expected changes to large-scale dynamics, for example, a significant decrease in summertime Mediterranean precipitation with drying due to increasing anticyclonic circulations (Gior-

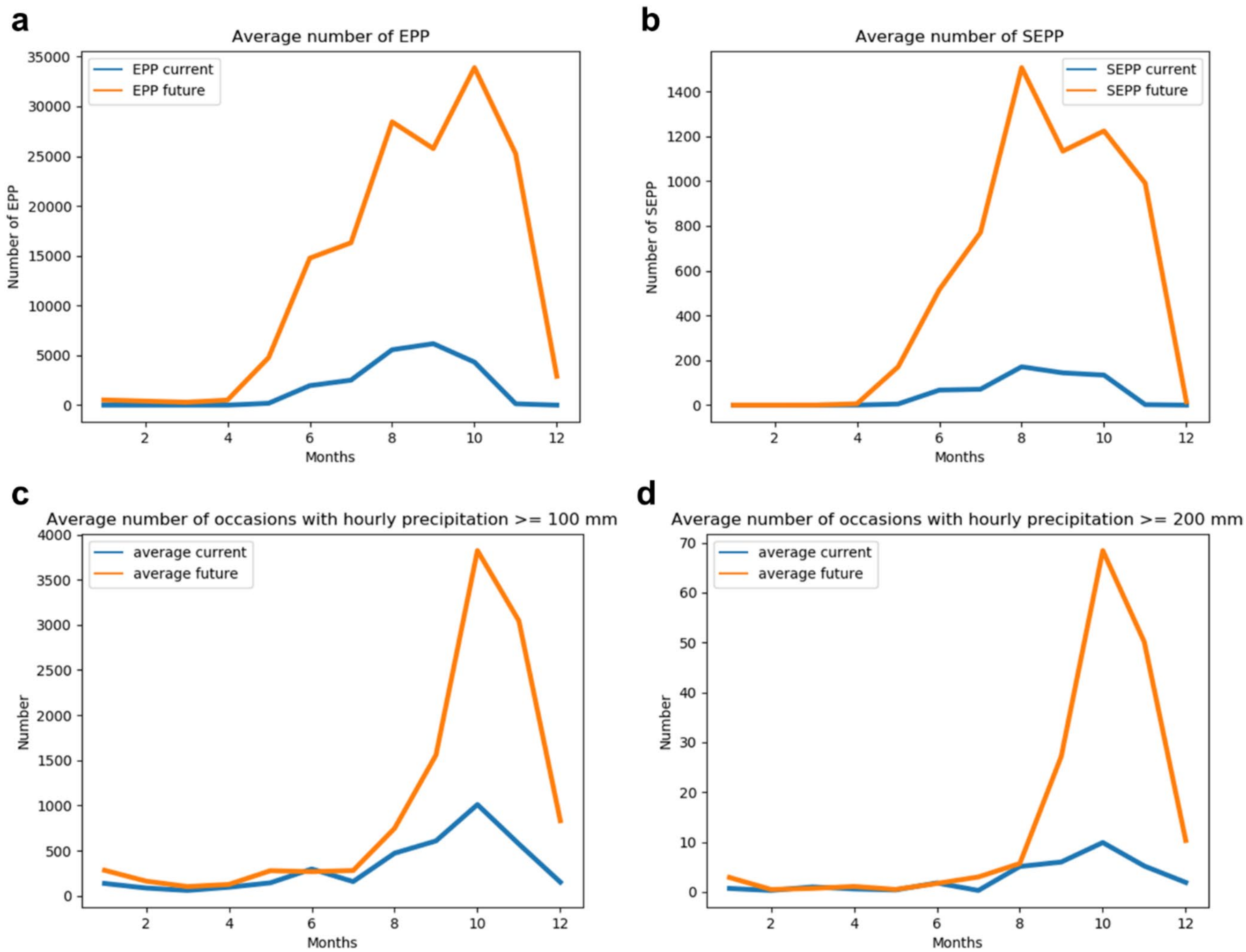

Figure 2. Average number of (a) Extreme Precipitation Potential cases, (b) Slow-moving Extreme Precipitation Potential cases, (c) hourly precipitation ≥100 mm, (d) hourly precipitation ≥200 mm, per month in current and future climates for whole domain (including land and sea).

gi & Lionello, 2008), or significant weakening of the summer circulation with Arctic Amplification (AA) (Coumou et al., 2015).

By 2100, in summer (especially August), SEPPs cover the entire continent, despite being very rare in today's climate in any month (Figure 3); with likely serious consequences for future flood risk. SEPP frequency by 2100 is comparable to current EPP frequency for many regions, putting the significant increase in these currently "unusual" slow-moving intense storms into context. Notably, the Mediterranean Sea is projected to experience more frequent SEPPs from October to November (Figure 3), extending the peak storm-season to later in the year.

The seasonality of EPPs and SEPPs over land and sea differ (Supplementary Text S7, Figure S11). Land EPPs and SEPPs peak in August, while sea EPPs and SEPPs do not peak until October. Currently, 52% of EPP cases occur over land; by 2100 this jumps to 61%, with increases in land (sea) EPP frequencies of 8.6× (6×) respectively. SEPPs occur relatively equally over land (48%) and sea (52%) in the current climate but an enormous increase in land SEPPs (14.3×), with a smaller, but still significant, increase in sea SEPPs (7.3×) increases the land fraction to 65% by 2100. This suggests that a larger fraction of change to our extreme precipitation proxies affect land, rather than sea. We speculate that this might result from the higher change to moisture availability and instability over land in a warming climate, and the northward extension of the subtropical belt leading to a decrease in vertical velocity threshold exceedance over the Mediterranean Sea.

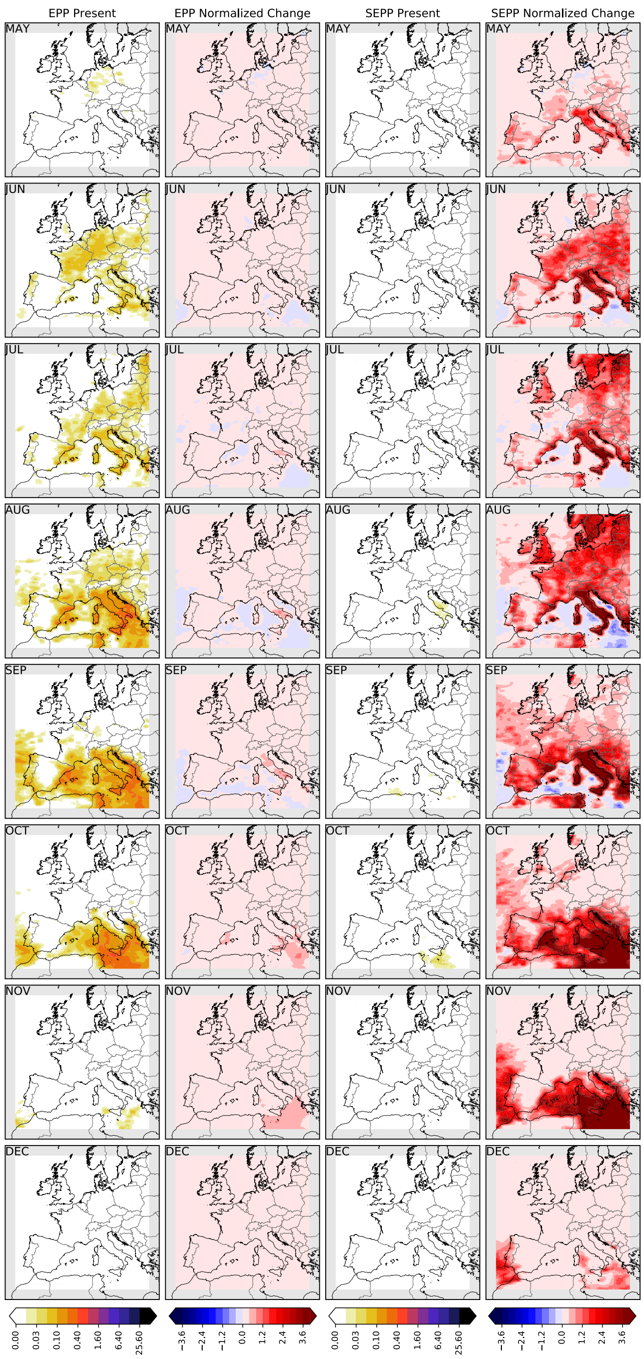

Figure 3. Same as Figure 1, but for number of Extreme Precipitation Potential and Slow-moving Extreme Precipitation Potential per month from May to December, and only for the present climate and future normalized changes.

3.3. Contributions From Ingredients

To disentangle drivers of the increase in the highest hourly precipitation rates we now analyze the "ingredients" separately. The large increase in EPPs stems mainly from the moisture ingredient, with a dramatic increase of cases with $q \geq 10$ gkg^{-1} in all months, while projected $w \geq 2$ ms^{-1} cases are higher only from June to September (Figures 4a and 4c). By 2100, the CPM projects 29× more cases with very moist environments (exceeding the q threshold) than for the current climate. This is consistent with large increases in average q of ∼35%. The moistest environment is found in August (5.42 g kg^{-1} for current climate, increasing to 7.26 g kg^{-1} by 2100), but change in q peaks in November with a 51% increase (Figure 4b). Given this substantial change, one might expect a dramatic increase in updraft strength, since it depends on convective available potential energy (CAPE), and CAPE is a function of low-level moisture and lapse rate through the atmosphere. However, we find an interesting seasonal pattern in the vertical velocity threshold exceedance (Figure 4c), with an annual decrease in the number of cases with $w \geq 2$ ms^{-1}, but summer-time increases in EPPs with $w \geq 2$ ms^{-1} (Figure 4c) mainly over the continent. A decrease of EPPs over the Mediterranean is consistent with the "stabilization of the troposphere" (Kröner et al., 2017) and fewer cyclone tracks (Pinto et al., 2007) in the future climate.

Our results show large projected increases in the frequency of extreme hourly precipitation rates in unstable environments (Supplementary Text S4 and Figure S6); this is consistent with recent studies showing relatively greater increases in daily extremes with increasing rarity (Hodnebrog et al., 2019; Myhre et al., 2019). Although September is generally the peak month for hourly precipitation extremes across Europe in the current climate, this shifts later to October by 2100 (Chan et al., 2020). Overall, our results suggest that future increases in EPP are caused by very large increases in atmospheric water vapor. This thermodynamic effect is enhanced by slight increases in cases of high vertical velocity in the warm-season from June to September and compensates for the small decrease in other months. Our findings confirm the primary importance of thermodynamic contributions to future increases in short-duration precipitation extremes, together with the assumed decrease in precipitation efficiency.

3.4. Changes in Slow-Moving Storms

We now move on to examine the changing role of storm movement for precipitation extremes. As noted, the annual distribution of SEPP is skewed towards summer, when compared to EPP (Figures 2a and 2b), related to generally weaker winds in summer. We find that by 2100, there is higher frequency of slow-storm environments, except during February–April (Figure 4d), with the annual number of slow-moving storms projected to increase by 20%. We find the largest increases in August–November, ranging from 31% to 65%, and peaking in September. Since this coincides with the peak exceedance months of thermodynamic thresholds, the kinematic environment of these high accumulation storms also contributes to, and enhances, the extreme precipitation rate for a given locality, resulting in an almost 11-fold increase in SEPPs compared to a 7.4-fold increase in EPPs by 2100.

Changes to the annual distribution of average Corfidi Vector magnitude (Figure 4e) demonstrate an analogous pattern to changes to the threshold-based graph described above (compare Figures 4d and 4e). We find

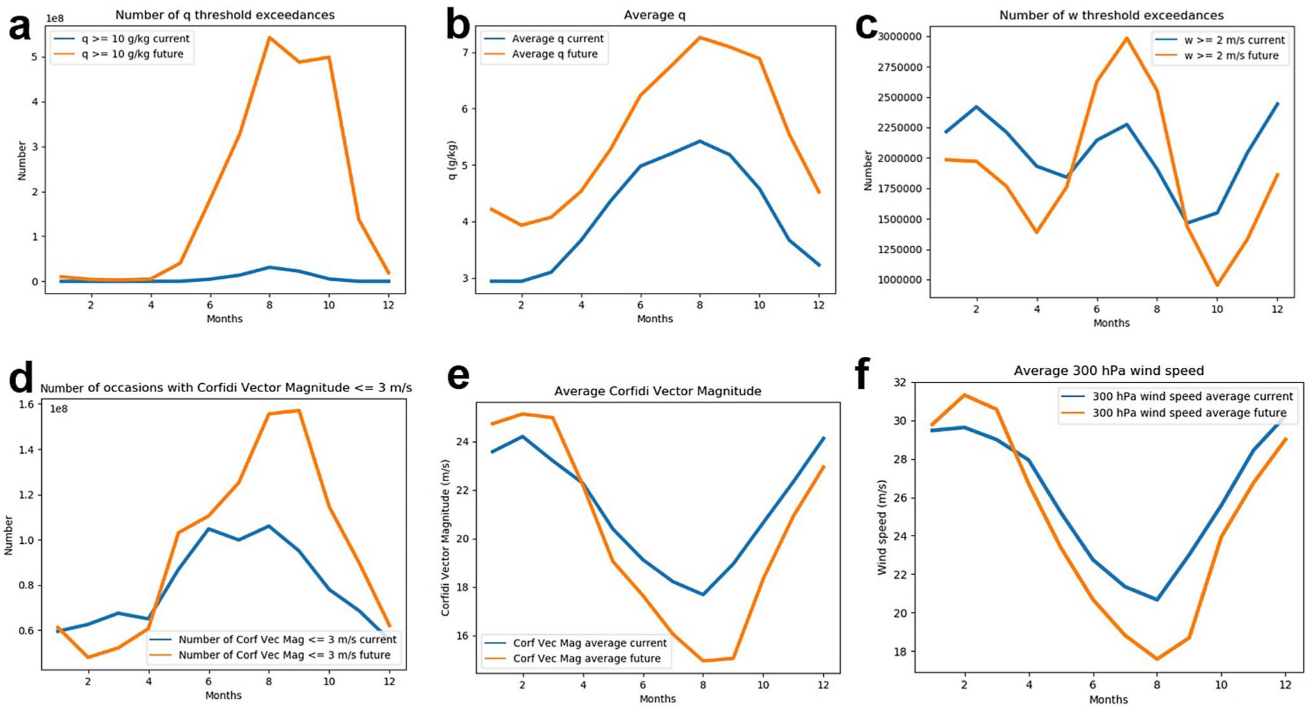

Figure 4. Distribution of Extreme Precipitation Potential and Slow-moving Extreme Precipitation Potential components and relevant variables by month for whole domain: (a) Total number of occasions with specific humidity threshold (10 g/kg) exceedance, (b) Average specific humidity, (c) Total number of occasions with vertical velocity threshold (2 m/s) exceedance, (d) Total number of occasions with Corfidi Vector magnitude ≤3 m/s, (e) Average Corfidi Vector magnitude, (f) Average 300 hPa wind speed.

a decrease in average Corfidi Vector magnitude in all months, except for January–March (Figure 4e), with the most dramatic decrease in September (−21%). This indicates not only an increased frequency of "stagnant" MCSs, but also a general future decrease in the speed of all MCSs. As the Corfidi Vector is based on upper-level wind environments, and tropospheric wind generally increases with height, it is most sensitive to high-level winds. Accordingly, the average Corfidi Vector magnitude and 300 hPa wind velocity follow each other throughout the year (Figures 4e and 4f). This suggests that the effect of climate change on the strength of the jet stream in Europe is positive in winter, while negative in other seasons. This finding has complicated implications for the debate of AA versus midlatitude extreme weather, which spans considerable uncertainty (Cohen et al., 2020): In general, stronger jets around a convective storm environment result in more shear, hence increasing the likelihood of storm organization. On the other hand, they make storms move faster, which shortens the local duration. This is in agreement with projections of stronger winter storms, with the seasonal cycle of storm-track intensity increasing in amplitude (O'Gorman, 2010), and with summer AA effects in Europe, that is, overall weakening circulation (Coumou et al., 2015; Francis & Vavrus, 2012; Overland et al., 2015).

4. Discussion and Conclusion

Our study is based on metrics stemming from the severe weather forecasting approach—an "ingredients-based methodology." This approach provides a holistic view of heavy precipitation changes, which helps explain the underlying processes, important for assessing the reliability of the projections. It also highlights the importance of considering event accumulations rather than precipitation rates. Our results from CPM projections suggest substantial future increases in hourly precipitation extremes across Europe. We find that by 2100, climate change will significantly increase the number of storm systems with high moisture and higher vertical velocity; the main drivers of high precipitation rates. Importantly for flood impacts, we find a considerable increase in the number of slow-moving storms, leading to high hourly and

3-hourly precipitation accumulations. Furthermore, these systems increase more sharply over land, compared to over sea.

The increased frequency of SEPP cases appears related to the seasonal weakening of the jet stream due to AA, which overlaps with the timing of frequent high precipitation-rate storm systems (i.e., high EPP) in Europe. It is known that synoptic-scale meandering patterns associated with AA result in more persistent weather systems in the midlatitudes, including Europe, especially in the autumn (Francis & Vavrus, 2015). Our findings suggest that there will be similar effects of AA on mesoscale systems with shorter time-scales, such as convective storms.

Changes to the duration of heavy precipitation events, with the slower movement of MCSs, partly demonstrate why CC scaling (~7% per °C increase in extreme precipitation) might not be universally valid for diagnosing future short-duration precipitation extremes (Lenderink & van Meijgaard, 2008) due to possible additional contributions from non-thermodynamic factors, as also shown (Pfahl et al., 2017) for daily accumulations. We speculate that there will be a decrease in precipitation efficiency in the future, due to lower EPP and SEPP correlations with high hourly precipitation rates, particularly in the European summer. This finding is in agreement with expectations of a shift of the subtropical belt towards the north, further drying the Mediterranean region in the warm season (Kröner et al., 2017).

We expect added value from CPMs for many of the metrics used in this study. The vertical velocity component is much more realistic, as convection is explicitly represented in CPMs (Prein et al., 2015, 2021). The distribution of low-level moisture is also better represented in CPMs, which is crucial especially over areas with complex topographical features resulting in locally modified winds, affecting moisture advection (e.g., Demirtaş, 2016; Tan et al., 2020). The storm motion vector can also be better captured with improved wind fields, at least in the lower troposphere (e.g., Kann et al., 2015).

In summary, our study uses a novel method to examine changes to the ingredients of heavy precipitation. Our results suggest that storms will have higher peak intensity, longer duration and will be more frequent across the whole of Europe. Current storms already produce a large number of flash floods, with their potential impact depending on land use, terrain slope, drainage, and other factors. SEPP increases would significantly increase this flash flood potential, as an MCS would be more likely to "stagnate" on a locality, exposing it to extreme precipitation of longer duration. Additionally, storm system movement is associated with upper level winds and, hence, large-scale dynamics. This may increase fluvial flood risk through consecutive events in one favorable synoptic setting spanning days or more; blocking is also favored by large-scale meandering patterns associated with slower flows. Understanding the underlying ingredients for heavy precipitation change is crucial from an impacts perspective, helping to discriminate controlling factors, which have wider applicability beyond those for a single accumulation period, and to identify the reliability of projected changes. This suggests that future studies should focus on precipitation accumulations over space and time.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data sets for this research are available at DOI:10.5281/zenodo.4449697. Wider European 2.2 km data set can be used under license from the Met Office, but restrictions to the use apply, and must respect the work plans of EUCP partners and of CORDEX-FPS-Convection.

Acknowledgments
This work is supported by the FUTURE-STORMS project (NE/R01079X/1). EJK gratefully acknowledges funding from the EU under H2020 project European Climate Prediction System (EUCP; Grant agreement: 776613) and Joint UK BEIS/Defra MOHC Climate Programme (GA01101). HJF is funded by the European Research Council Grant, INTENSE (ERC-2013-CoG-617329), and the Wolfson Foundation and the Royal Society as a Royal Society Wolfson Research Merit Award holder (grant: WM140025).

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