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Key Points:

- Large-scale circulation types (CTs) can be used as precursors of local extreme precipitation events over Scandinavia
- The intensity of extreme precipitation events over Scandinavia increases with the warming strength in the future climate
- The relationship between extreme precipitation and CTs remains unchanged over Scandinavia in the future climate

Supporting Information:

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

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Relationship Between Circulation Types and Extreme Precipitation Over Scandinavia Is Stable Under Climate Change

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Abstract The atmospheric large-scale environment determines the occurrence of local extreme precipitation, and it is unclear how climate change affects this relationship. Here we investigate the present-day relationship between large-scale circulation types (CTs) and daily precipitation extremes over Scandinavia and its future change. A 50-member EC-Earth3 large ensemble is used to assess future changes against internal variability. We show that CTs are related to extreme precipitation over the entire domain. The intensity of extreme daily precipitation increases in all seasons in the future climate, generally following the strength of warming in the six different future scenarios considered. However, no significant future change is found in the relationship between extreme precipitation and the CTs in any season or scenario. The results have important implications for applications that rely on the stability of this relationship, such as statistical and event-based dynamical downscaling of future weather and climate predictions and long-term climate projections.

Plain Language Summary The occurrence of local devastating extreme precipitation events is influenced by the large-scale flow of the atmosphere, that is, high- or low-pressure systems and winds from different directions. Understanding this connection helps us to predict precipitation extremes using more readily available information about the large-scale flow. However, it is not known if the relationship that we observe in the present climate will hold under future climate conditions. Here we study the present-day relationship between the large-scale flow and local precipitation events over Scandinavia and analyze how it will change toward the end of the 21st century. We find that extreme precipitation events become more intense over entire Scandinavia in the future climate, but their connection to the large-scale environment remains unchanged.

1. Introduction

Extreme precipitation events have a considerable impact on various aspects of society, environment and economy as they can lead to severe flooding, landslides and other natural disasters. Over Scandinavia, mean precipitation is projected to increase and extreme precipitation events are projected to become more frequent and more intense in a future warmer climate (e.g., IPCC, 2012; Jacob et al., 2014; Rajczak & Schär, 2017). Generally, the increase in extreme precipitation has been linked to rising temperatures through the Clausius-Clapeyron equation, which relates the future warmer atmosphere to an increased capacity to hold moisture, even though the mechanisms of the increase are more complex in reality (e.g., Muller & Takayabu, 2020; Neelin et al., 2022; Pall et al., 2007; Trenberth et al., 2003).

Although these general changes of extreme precipitation under future climate change are understood, it is challenging to provide reliable information for extreme precipitation changes at a local scale. However, this information is required for impact and risk assessment, and ultimately for decision-makers to develop effective regional and local adaptation and mitigation strategies. Current global and regional climate models are too coarse to resolve local precipitation features and all the factors that influence them, particularly for convective storms, while the models that do resolve the small-scale processes—convection-permitting climate models (CPMs)—are often too computationally expensive to run to the extent of the global and regional models (e.g., Prein et al., 2015) even though recent developments are promising in terms of more affordable decadal simulations over larger domains (Lucas-Picher et al., 2021).



One approach to assess local extreme precipitation changes is to select episodes that are worth the time and cost of high-resolution model runs, that is, event-based downscaling (e.g., Cholette et al., 2015). In event-based downscaling, global climate model (GCM) simulations are scanned for large-scale situations that are associated with extreme weather events. These large-scale fields are then used as boundary conditions to drive the high-resolution models to obtain more accurate representations of the extreme events (e.g., Beaulant et al., 2011). Another approach could rely on statistical methods, including machine learning, to directly relate local extremes to large-scale conditions (e.g., Chan et al., 2018; Gomez-Navarro et al., 2019).

These approaches could become compromised if the connection between the large-scale conditions and the local extremes is not stable but changes, for example, with a general change in climate. This study investigates the present-climate relationship between the large-scale atmospheric circulation and local precipitation extremes, and whether this relationship is maintained in different scenarios of future climate development during the 21st century.

To assess the large-scale circulation, this study applies a circulation type classification (CTC) method to sea level pressure (SLP) fields from GCM simulations performed with EC-Earth3 as part of the SMHI Large Ensemble (SMHI-LENS; see Wyser et al., 2021). In general, CTC can be used to compress information from individual complex large-scale atmospheric circulation fields into a reasonably small set of representative patterns. In the context of extreme precipitation events, CTC can be used to identify those large-scale atmospheric patterns that are most associated with regional extremes (e.g., Fernandez-Montes et al., 2012, 2014; Iannucci et al., 2021; Ramos et al., 2014). Herrera-Lormendez et al. (2023) analyze the future changes in summer precipitation over Europe, with a focus on dry days, and decompose the part of the change signal that is due to changes in the dominant circulation types (CTs) obtained through a CTC. Our study also investigates the relationship between CTs and precipitation (wet extremes in all seasons), but instead of explaining the change in the intensity of the precipitation events, it examines whether the relationship between CTs and extremes is stable under climate change.

Assessing the future-climate relationship between the large-scale atmospheric circulation and local precipitation extremes is subject to the general uncertainties of future projections (see Knutti & Sedlacek, 2013). In this paper, we take into account two of the most important sources of uncertainty by using the single-model large ensemble of future climate projections from SMHI-LENS. Uncertainties due to external forcings, such as emissions of climate-relevant greenhouse gases and other socio-economic developments, are accounted for by different scenario simulations forced with different Shared Socioeconomic Pathways (SSPs) for the 21st century. Uncertainties related to internal variability are addressed by providing 50 realizations for each of the scenarios starting from slightly different initial conditions (e.g., Deser et al., 2012). The comprehensive data set provided by SMHI-LENS makes it an ideal testbed to study the ranges of variability spun by the scenarios and different realizations of each of them and allows us to compare them with other variabilities such as the annual cycle.

A third major source of uncertainties in future climate projections stems from model errors. These uncertainties are most pronounced around the middle of the 21st century and are often accounted for by applying the same methodology to more than one climate model or analyzing multi-model ensembles such as those provided in the Coupled Model Intercomparison Project framework (e.g., Donat et al., 2023). These uncertainties are not incorporated in this study.

2. Data and Methods

2.1. Input Data: SMHI Large Ensemble and Reanalysis Data

A detailed description of the SMHI Large Ensemble can be found in Wyser et al. (2021). To create SMHI-LENS, the coupled GCM EC-Earth3 (Döscher et al., 2022) was used, comprising IFS cy36r4 run at T255 spectral truncation with a linearly reduced Gaussian grid of N128 as the atmospheric component (i.e., 0.75° horizontal resolution) and NEMO3.6 on a 1° horizontal grid with refinement around the equator for the ocean. EC-Earth3 was used to perform a historical experiment covering the recent past from 1970 to 2014 and eight future scenario simulations extending to the end of the 21st century. Each of the simulations was run as an ensemble of 50 members, starting from different initial conditions in 1970, and seamlessly continuing the historical ensemble members after 2015. For this study we make use of daily mean sea level pressure (MSLP) fields and daily total precipitation from the SMHI-LENS historical simulation and six future experiments: the SSP1-1.9 (hereafter

SSP119), SSP2-4.5, SSP3-7.0, SSP4-3.4 (SSP434), SSP5-3.4-OS, and the SSP5-8.5 (SSP585) scenarios. We analyze the last 20 years of the historical simulation (1995–2014), as well as two future 20-year periods (2041–2060 and 2081–2100, representing the middle and the end of the 21st century, respectively). In the presentation of results below, we highlight the SSP119 and SSP585 simulations as these two scenario experiments represent the weakest (SSP119) and strongest (SSP585) global warming trends of all SMHI-LENS scenarios and thus span the range of potential climate evolutions. Results from the other scenarios are part of summarizing figures and conclusions.

The performance of the EC-Earth model family has been among the best compared to other climate models in terms of CTs (e.g., Brands, 2022; Brands et al., 2023). Hence, instead of comparing to other models which is beyond the scope of this article, we refer to those studies to provide some evidence for reliability of the results obtained with EC-Earth3.

To further evaluate the results obtained from EC-Earth3, we compare the SMHI-LENS historical simulation outcomes to those from ERA5 reanalysis data (Hersbach et al., 2020). As for the SMHI-LENS historical simulation, daily data for MSLP and total precipitation between 1995 and 2014 are used.

2.2. Circulation Type Classification

From the wide range of existing CTC methods, we use the Simulated Annealing and Diversified Randomization (SANDRA; Philipp et al., 2010) method in this study. SANDRA is based on conventional k-means clustering but implements two additional concepts (see details in Philipp et al. (2010)), thereby overcoming many of the limitations of established CTC methods. As a result, SANDRA has been widely applied to SLP or geopotential height fields in various contexts of atmospheric circulation studies (e.g., Jacobeit et al., 2009; Kuettel et al., 2011; Murawski et al., 2016; Røste & Landgren, 2022), also in the context of studying extreme precipitation (e.g., Meredith et al., 2018).

We apply the SANDRA algorithm as implemented in the COST733 software package (see Philipp et al., 2010) to daily mean SLP fields over a pan-Scandinavian domain (0–30°E, 50–73°N) as described in Hansen et al. (2023). Data from the whole year has been used together. The spatial mean is removed from each field before the classification, following the reasoning and procedure in Hansen and Belušić (2021). To circumvent the computationally challenging task of clustering the whole SMHI-LENS, we first compute a reference set of 10 SLP CTs from a combined 120-year data set over the same domain covering the historical and future periods. As described in Hansen et al. (2023), this combined data set is taken from regional climate model simulations and covers similar temporal and ensemble variability. Afterward, each daily SMHI-LENS SLP field from the historical as well as from the two future periods is assigned to the representative CTs based on the smallest Euclidean distance. All 50 ensemble members are assigned in this way from the historical period and the six future scenarios described above.

As described in Hansen et al. (2023), the CTs computed from year-round data capture the inter-seasonal variability of the circulation. Some CTs, namely CTs 1–4, occur mainly in the summer half year, while others such as CTs 7 and 10 can be considered as winter clusters.

Objective measures such as the Explained Variance or the Silhouette Index provide no clear indication for an ideal number of CTs (not shown). Therefore, the choice for 10 CTs was mainly based on visual inspection of the CTs, finding a good balance between low variability between fields assigned to the same CT and large differences between the CTs themselves.

2.3. Extreme Precipitation

2.3.1. Definition of Extremes

In this study, we use a common approach for defining extreme events that is based on percentiles of daily precipitation amounts (e.g., Lind et al., 2023; Pichelli et al., 2021). For each grid point in our pan-Scandinavian domain, each scenario, each ensemble member, each 20-year period and each season, we calculate the 99th percentile of daily total precipitation of all days, including dry days (e.g., Schär et al., 2016). Extremes are defined as exceedances of this threshold. This definition results in the same number of extreme events for all ensemble members, periods and seasons. This means that we do not draw any conclusions about the future changes in the

number of precipitation extremes. Instead, we analyze the change in the percentile threshold with future climate change, and more importantly we make a consistent association between extremes and CTs in historical and future periods based on the same number of events.

2.3.2. Definition of Significance

The significance of any signal S is assessed by comparing it to the model internal variability in the present climate, which is estimated from the model ensemble spread as one ensemble standard deviation N , that is, the standard deviation across the ensemble members. Even the future change signals are compared to the present-day ensemble spread to indicate whether the future climate forced response is larger than the expected perturbations resulting from the internal climate variability. Following Hansen et al. (2023) (and equivalent to, e.g., Chapman and Walsh, 2007; Christensen et al., 2007), a signal is considered significant if $S/N > 1$.

Three variables are tested here for significance: the future change in the extreme precipitation threshold value, the relationship between the CTC and extreme precipitation in the present climate, and the future change in this relationship. The latter two are described below, while for the threshold change, the signal S is the relative ensemble mean change of the precipitation 99th percentile (future 20-year period relative to the historical 20-year period), and the spread N is the ensemble standard deviation of the precipitation 99th percentile in the historical period relative to the ensemble mean.

2.3.3. Probabilities in CTs and Their Changes

For each of the 10 SLP CTs over the pan-Scandinavian domain, we compute at each grid point the probability of an extreme precipitation event to occur. This is done separately for each ensemble member, each 20-year period, and each season. If the extreme precipitation events were equally likely in all CTs, that is, if the CTC had no relationship to precipitation extremes, their probability of occurrence in each CT at each grid point would simply be 1%, since they are defined as the 99th percentiles. Therefore, the significant relationship between CTC and precipitation events is determined in each grid point as a significant difference to the no-relationship 1% chance. The significance is determined as above, by $S/N > 1$, where $S = \text{abs}(p - p_0)$, with p indicating the ensemble mean extreme precipitation probabilities in a CT and $p_0 = 0.01$ is the no-relationship 1% probability of extreme precipitation occurring in a CT. N is one standard deviation of extreme precipitation probabilities in a CT across the ensemble.

If there are significant differences from 1% in a particular CT, we can say that this CT is related to extreme precipitation. This can be helpful when a CT time series, for example, from a GCM simulation, is searched for potentially interesting situations worthy of dynamical downscaling with higher resolution models as outlined in the introduction.

Along with the present-climate probabilities of extreme precipitation events in each CT, we also analyze their future changes. The significance of the future changes is defined as above using $S/N > 1$, where S is the ensemble mean change of the extreme event probabilities (future 20-year period minus historical 20-year period) and N is, as above, one standard deviation of the probabilities across the 50 ensemble members in the historical period.

3. Results

3.1. Extreme Precipitation Threshold in Present and Future Climate

This is the first study addressing precipitation extremes over the pan-Scandinavian domain from SMHI-LENS. Therefore, before analyzing the relationship between the precipitation extremes and CTs, the characteristics of the precipitation extremes and their future change in SMHI-LENS, together with the ability of SMHI-LENS to reproduce precipitation extremes in the present climate, need to be examined.

Precipitation patterns in general and also their extremes can be influenced by different factors. In our pan-Scandinavian domain of interest, it is first of all the topography of the region that influences the intensity of precipitation extremes, as can be seen from Figure 1. The 99th percentile of daily precipitation totals, which we use to define extreme events, is highest over the Scandes mountain chain, where moist air masses from the North Atlantic are lifted by the prevailing westerly winds. It reaches its maximum in autumn and winter due to the stronger winds and increased frequency of passing low-pressure systems during these seasons. During autumn

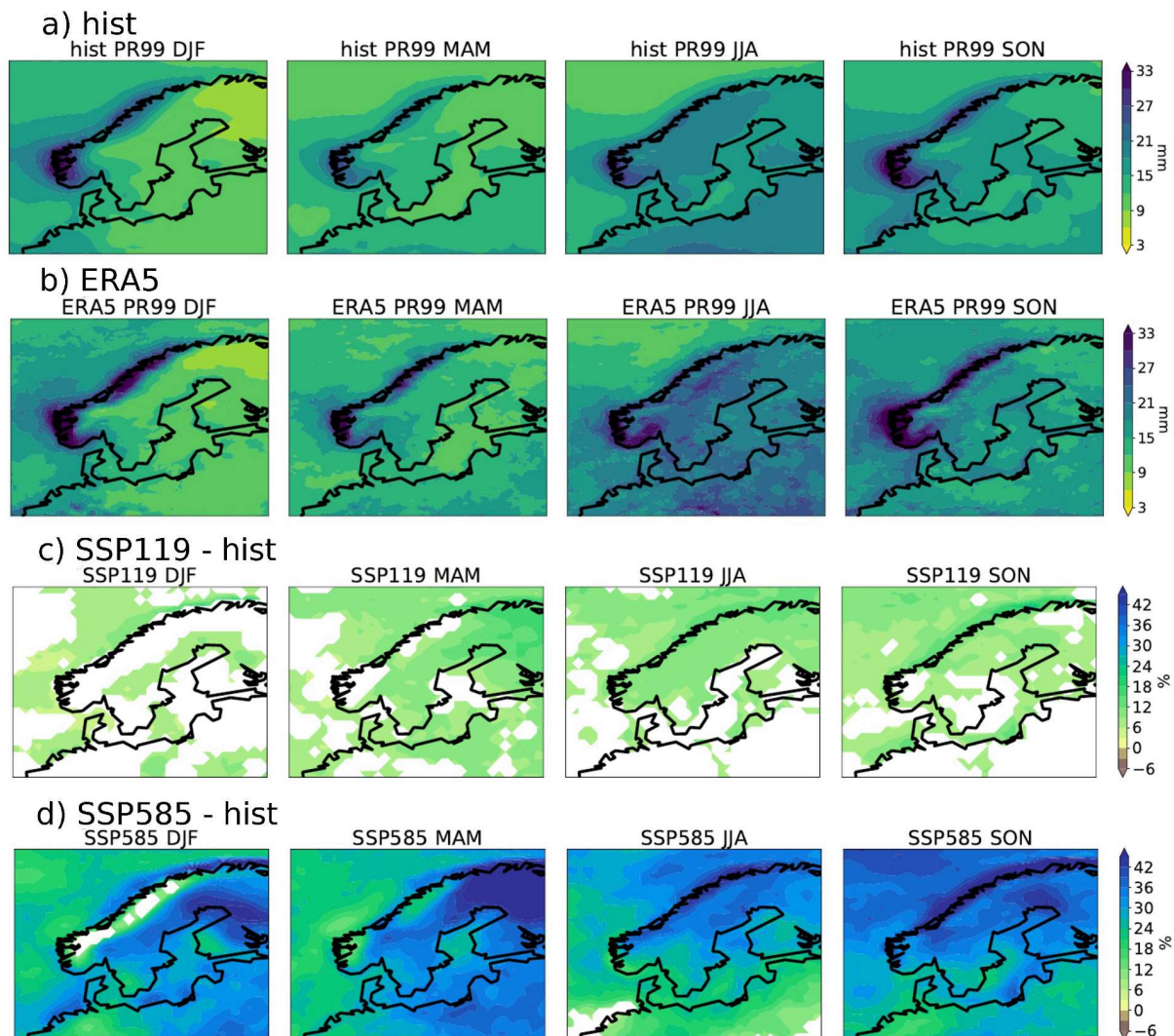


Figure 1. 99th percentile of daily precipitation in the four seasons DJF, MAM, JJA, and SON from left to right. (a and b): SMHI-LENS and ERA5, present climate, in mm. For SMHI-LENS, the ensemble average computed from 50 ensemble members in the historical simulation is shown. (c and d): Relative future changes (in %) in SSP119 and SSP585, respectively. Shown are the ensemble mean changes toward the end of the 21st century in the scenarios compared to the historical simulation; only significant changes are colored.

and winter, days with approximately more than 30 mm of precipitation are counted as extreme in the historical period according to the ensemble mean (Figure 1a).

The 99th percentile of daily precipitation from SMHI-LENS compares very well to ERA5 (Figure 1b). All three aspects of spatial pattern over the domain, maximum intensity as well as seasonal variations are captured well by the EC-Earth3 model.

Variability of the 99th percentile is expressed as the normalized ensemble spread, where the standard deviation computed across the 50 ensemble members is normalized by the local 99th percentile (see Figure 1a) to allow for a fair comparison between different grid points (e.g., Hohenegger et al., 2006). This normalized ensemble spread is highest over the Scandes in winter (Figure S1 in Supporting Information S1). In the other seasons, there is more variability in the extreme threshold also in other (flatter) parts of the domain, indicating the role of more local convective events and other processes (not shown).

The 99th precipitation percentile value generally increases throughout the domain in all four seasons and all six future scenarios toward the middle and the end of the 21st century, as shown exemplarily by the relative

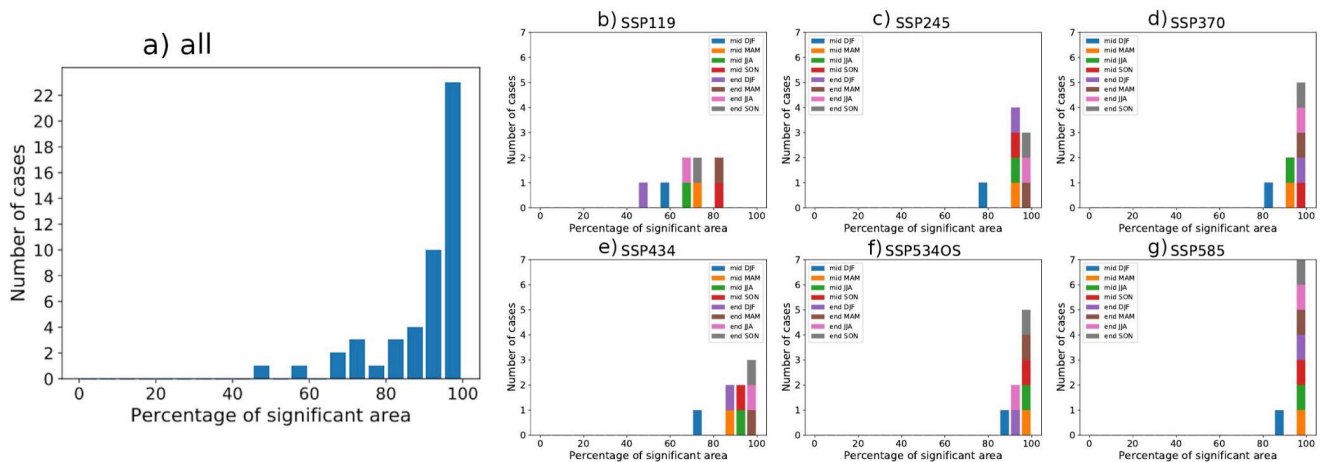


Figure 2. Spatial extent of significant future changes in the 99th percentile of daily precipitation between the mid- and end century climates in the six scenarios and the historical simulation. The spatial extent is given as the percentage of area of the whole domain. (a) Summary for all the scenarios, seasons and change periods (2 periods $\times$ 6 scenarios $\times$ 4 seasons = 48 cases); (b–g) Individual scenarios (2 periods $\times$ 4 seasons = 8 cases per panel).

end-century ensemble mean changes of the weak SSP119 and the strong SSP585 scenarios in Figures 1c and 1d respectively. The increase in extreme precipitation over the domain is consistent with the increase in mean precipitation: the stronger the change in mean precipitation, the stronger the change in the 99th percentile (not shown). This is the case for all scenarios and all seasons. Further, the changes in both the mean and the extreme precipitation scale with the strength of the warming in the scenarios. The ensemble mean scaling rates in the different seasons are around 2%–4% change in mean precipitation per degree warming and 3%–5% change in extreme precipitation per degree warming. The scaling rates do not systematically depend on the period (mid- or end of century) nor on the SSP. These values are consistent with the reported scaling rates for GCMs in the extratropics (e.g., O’Gorman, 2015) and Scandinavia (Lind et al., 2023).

The relative ensemble mean changes of the 99th percentile are strongest over the Scandes and over northern Sweden and Finland, reaching an increase of about 15% in the weak SSP119 scenario and up to 45% in the strong SSP585 scenario, both in spring (Figures 1c and 1d).

The sporadically occurring decreasing values are not significant. On the other hand, the increasing values are significant at most grid points. Figure 2a summarizes the spatial extent (percentage of domain) of significantly changing (i.e., increasing) values toward the middle and the end of the 21st century in all six scenarios and all four seasons. Of these 48 spatial fields, about half show significant changes over more than 95% of the domain. On average, 90% of the domain area changes significantly. Smallest-scale changes are seen in the SSP119 scenario toward the end of the 21st century during winter (48% of the domain; Figure 2b), and for mid-century winter changes in all other scenarios (Figures 2b–2g). The strongest scenario (SSP585; Figure 2g) shows significant changes over more than 95% of the domain toward the mid and end century periods in all seasons except for winter and summer in the mid century.

3.2. Extreme Precipitation in CTs in the Present and Future Climate

Figure 3 shows that the extreme precipitation events are not equally likely to occur in all 10 SLP CTs in present-day climate. The 10 CTs, which are exemplarily shown for spring in Figure 3a (equivalent plots for the other seasons can be found in Figure S2 in Supporting Information S1), are sorted by their frequency of occurrence, with CT1 occurring most frequently in the 20-year historical simulation considering all seasons together, and CT10 occurring least frequently. To summarize the information, for the other three seasons the CTs that predominantly affect extreme precipitation in each grid point are shown (Figures 3c–3e).

The probabilities shown together with the CTs’ SLP patterns in Figure 3a indicate significant deviations from the climatological 1% probability for the extremes due to the specific CT. In particular, when a large-scale circulation pattern can be assigned to CT10, the probability of extreme precipitation events over the Scandes mountain chain increases significantly. CT10 shows a mostly westerly flow with a strong SLP gradient indicating strong winds

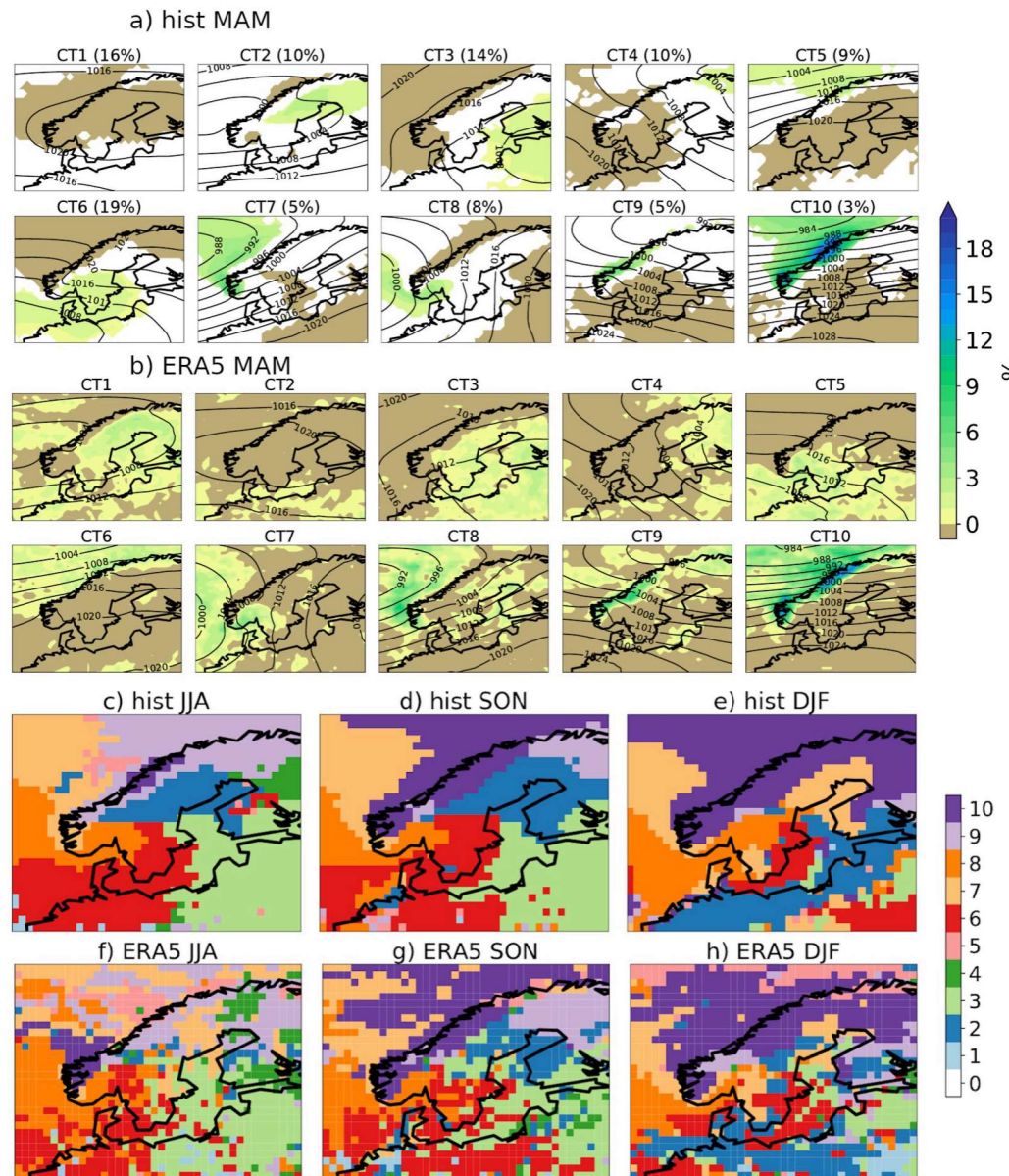


Figure 3. (a and b): 10 CTs with their present-climate sea level pressure spatial patterns (contours; in hPa) and probability of extreme precipitation occurrence (colors; in %) in spring (MAM). (a) SMHI-LENS; shown is the ensemble average over all 50 members in the historical simulation. The numbers in brackets indicate the relative frequencies of occurrence of the CTs. The probability is expressed as the significant deviation from the 1% climatological probability (see text). (b) ERA5; the probability is expressed as the deviation from the 1% climatological probability. Note that significance cannot be assessed for ERA5 with the chosen method. (c–h): Spatial distribution of CTs with highest probability for extreme precipitation in summer (JJA), autumn (SON) and winter (DJF); from SMHI-LENS (c–e) and ERA5 (f–h). Note that for ERA5, the CT numbers refer to the corresponding CTs in SMHI-LENS (see text for details). White colors mean that no CT has significant probability for extreme precipitation at that grid point.

impinging on the Scandes. The resulting uplift of moist air from the North Atlantic induces not only wetter-than-normal conditions upstream and drier-than-normal conditions downstream of the mountains in general (Hansen et al., 2023), but also precipitation extremes over the mountains as can be seen from Figure 3a. The probability of extreme precipitation in CT10 is particularly high over the Scandes in spring (20%), but also in autumn and winter (Figures 3d and 3e). CT10 occurs only very rarely in summer (not shown; see Hansen et al. (2023)) and therefore

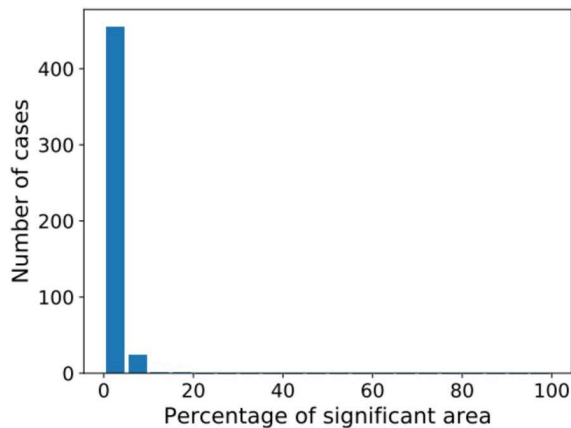


Figure 4. Same as Figure 2a, but for significant changes in the probability of extreme precipitation occurrence in a circulation type (CT), for all 10 CTs (2 periods $\times$ 6 scenarios $\times$ 4 seasons $\times$ 10 CTs = 480 cases).

does not play a significant role for extreme precipitation in this season. Over the Scandes, it is the occurrence of CT9 situations in summer that significantly increases the probability of extreme precipitation events (Figure 3c).

In other parts of the domain, the probability of extreme precipitation is less systematically affected by the occurrence of specific CTs, but some CTs still show significantly increased probabilities and thus can be used as predictors for extreme precipitation predictions. The probability of extreme precipitation events over southern Norway is particularly increased in all seasons in CT8 where a flow from the south toward the southern end of the Scandes leads to a similar effect as described above for CT10. The probability of precipitation extremes in this region reaches its maximum in summer with values up to 10% (Figure S2 in Supporting Information S1). CT6, with its (south-)easterly flow toward southern Norway, also shows increased extreme precipitation probabilities of up to 7% in summer (somewhat lower, but still significant in spring and autumn) in this region. This CT6 is also beneficial for the detection of extreme precipitation in southern Sweden between spring and autumn, with probabilities reaching a maximum of about 5% there in summer. For central and northern Sweden, CT2, with its anticyclone centered in the western part of the domain, increases the probabilities of extreme precipitation mainly in spring and autumn (3%), and somewhat less in summer. When combined together, the CTs are related to extreme precipitation events over practically the entire domain (Figures 3c–3e).

In ERA5, the frequency of occurrence of the individual CTs is slightly different from those in SMHI-LENS (Figure 3b). This leads to a slightly different order of CTs, such as CTs 1 and 2, 5 and 6, as well as 7 and 8, being swapped. However, the relationship between the CTs and extreme precipitation is again very similar in its main characteristics that are described above (Figures 3b and 3f–3h), which confirms the good performance of the EC-Earth model with respect to circulation as documented in for example, Brands (2022).

As the final step, we analyze the changes in the relationship between CTs and extreme precipitation events. Figures S3 and S4 in Supporting Information S1 show that the general seasonal patterns of dominant CTs over the domain (Figures 3c–3e) are basically unchanged toward the middle and the end of the 21st century in all six SSP scenarios, and that there are no systematic (e.g., due to scenario strength) differences between the six scenarios.

Regarding the probabilities for extreme precipitation events (Figures 3a and 3b), we find that only very small parts of the domain show a significant future change and summarize the results for all CTs, both periods, all four seasons and all scenarios in Figure 4. The majority of these spatial fields have significant changes in less than 5% of the domain, with the overall average change in 1.3% of the domain. In summary we see that the internal climate variability in the SMHI-LENS historical simulation exceeds the ensemble mean future changes in all scenarios. This means that the relationship between CTs and extreme precipitation is stable under climate change in the EC-Earth3 model, and that the probability of finding an extreme precipitation event at a given location in a specific CT does not change toward the end of the 21st century. This in turn may justify the use of CTs as predictors of extreme precipitation even in the future climate, for example, in the context of event-based downscaling studies.

4. Summary and Conclusions

This study focuses on a particular aspect of extreme precipitation events in the future climate: their relationship to large-scale CTs. If the present-day relationship between CTs and extreme precipitation events is sustained even under future climate change, CT projections from relatively coarse global model simulations can be employed even for local scales, for example, for heavy precipitation impact and risk assessment. Extreme daily precipitation events are defined in this study as exceedances of the 99th percentile threshold. The response of extremes to the forcing of different emission scenarios is distinguished from the internal climate variability using the SMHI large ensemble with 50 members per scenario for six different SSP scenarios. Hence, the significant future change is defined as the difference between the future and present characteristics of extremes (or their relationship to CTs) that is greater than the standard deviation of the present-climate ensemble.

The analysis shows the following:

1. Over Scandinavia, the present-climate 99th percentile reaches its maximum over the Scandes mountain chain in autumn and winter. It increases for all scenarios in all seasons in the future climate throughout the domain. The strength of the increase roughly follows the strength of the warming in the scenarios, that is, the largest percentile changes are seen in the warmest SSP585 scenario. The ensemble mean scaling rates are around 3%–5% extreme precipitation change per degree warming.
2. CTs are related to extreme precipitation over practically the entire domain. Generally, the strongest significant relationship is seen in spring and summer, and over the Scandes mountain chain.
3. In the future climate, there is no significant change in the CTs' relationship with extreme precipitation events. Instead, the future changes in the relationship between CTs and extremes fall within the present-climate internal variability. This result does not depend on the strength of the scenario, the season and the period considered in the 21st century.

The main implication of these results is that despite the significant intensification of extreme precipitation in the future climate, the present-day relationships between the large-scale circulation patterns and local extremes hold in the future climate too. Different methodologies that depend on this relationship—for example, detection of large-scale conditions as precursors for extremes, or downscaling machine learning algorithms trained on present-day data—can therefore be used with a similar setup for the future climate.

However, three caveats should be noted. First, only one model large ensemble was analyzed in this study, since a comparison with other climate models or multi-model ensembles was beyond the scope of this paper. However, Brands (2022) showed that the EC-Earth3 model family performs among the best CMIP5 and CMIP6 models with respect to CTs in the Northern hemisphere, and our comparison with ERA5 shows considerable similarity.

Second, these results are valid only for the Scandinavian domain and cannot be extended to other regions without further testing.

Third, the conclusions drawn about the relationship between the CTs and extremes in a GCM are not necessarily valid for the real-world extremes (e.g., Herrera-Lormendez et al., 2023), even though our analysis shows that the SMHI large ensemble compares well with ERA5 in the present climate. Namely, even reanalyses like ERA5, or coarse gridded observations, are limited in representing realistic local precipitation extremes (e.g., Lin et al., 2020; Médus et al., 2022). The next step in approaching reality would be to test similar relationships within a CPM (e.g., Lundquist et al., 2019), or between a parent GCM and the CPM used for downscaling, and particularly for sub-daily precipitation extremes.

Conflict of Interest

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

Data Availability Statement

The SMHI-LENS data on which this article is based are available in EC-Earth Consortium (2019a, 2019b, 2019c, 2019d, 2019e, 2020a, 2020b). All results can be accessed from any ESGF data node as part of CMIP6; search for EC-Earth3 and <variant_label> in the range r10i1p1f1 and r150i1p1f1.

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