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The Effect of 3°C Global Warming on Hail Over Europe

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Key Points:

- We investigate the effect of 3°C global warming on hail occurrence over Europe
- The number of intense and severe hail days will increase over northeastern and decrease over southwestern Europe in summer
- Changes in hail occurrence depend on low-level moisture content, convective available potential energy and convective inhibition

Supporting Information:

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

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Abstract Hail severely impacts humans, crops, and infrastructure. Quantifying future hail trends is extremely challenging due to the complex dynamic, thermodynamic, and microphysical processes behind severe convective storms. Here, we combine a km-scale convection-permitting regional climate model and an online hail diagnostic to quantitatively assess changes in hail frequency in Europe imposed by a 3°C global warming level. Results show increases in summer hail frequency in northeastern Europe and decreases to the southwest for intense and severe hail days, related to changes in low-tropospheric water vapor content, convective available potential energy and convective inhibition. Small hail days generally decline across continental Europe, due to increased melting of hailstones with higher melting level height. The physical-based simulation approach captures convection and hail processes consistently, providing a solid basis for assessing the socioeconomic implications of hail and its trends with global warming.

Plain Language Summary Hailstorms can lead to large damage to crops and infrastructure. Due to the small size of hailstorms, it is challenging to accurately simulate their occurrence in the present-day climate. Even more, it is not yet clear how hail frequencies in Europe will change due to global warming. We apply here a new method by simulating hail in a convection-permitting regional climate model with 2.2 km grid spacing in the present climate and in a globally 3°C warmer future climate. The simulations show an increase in summer hail frequency over northeastern Europe, and a decrease over southwestern Europe for hail sizes $d \geq 12.5$ mm. In autumn, hail occurrence increases over the Adriatic Sea and adjacent coastal areas. Days with small hail ($10 \text{ mm} \leq d < 12.5$ mm) are projected to decrease with a warmer climate. These projected changes of hail occurrence are important to estimate the expected impacts of hail in a warmer climate.

1. Introduction

Hail events, though rare, have a significant impact on infrastructure, agriculture, and ecosystems across Europe (Carver et al., 2017; Dessens, 1986; Nisi et al., 2016; Portmann et al., 2024; Púčik et al., 2019; Puskeiler et al., 2016; Schmid et al., 2024). A single hailstorm can cause economic losses exceeding 1 billion € (Banerjee et al., 2024; Kunz et al., 2018; Punge & Kunz, 2016). Due to their considerable damage potential, it is essential for policymakers and stakeholders from different industry sectors to understand the processes leading to hail events and to assess how their frequency and intensity may change in the future.

Assessing past hail trends from observations is difficult, as hail events exhibit tremendous spatial variations, and observational time series are comparatively short and often inhomogeneous (Punge & Kunz, 2016; Wilhelm et al., 2024). The detection of past trends is largely based upon the dynamic and thermodynamic factors that lead to severe convective storms (e.g., Mohr & Kunz, 2013; Púčik et al., 2015; Schemm et al., 2016), which are typically derived from reanalysis data. Such proxy fields for convection include convective available potential energy (CAPE), vertical wind shear, and melting level height (Mahoney et al., 2012; Prein & Heymsfield, 2020). Observed increases in CAPE in Central Europe suggest an increase in the frequency of thunderstorm-prone environments and (severe) hail events since the 1950s (Battaglioli et al., 2023; Mohr, Kunz, & Geyer, 2015; Taszarek, Allen, Brooks, et al., 2021; Wilhelm et al., 2024). Similar trends have also been detected in parts of North America (Brimelow et al., 2017; Tang et al., 2019).

Recent studies addressing future changes in thunderstorm and hail frequency used similar proxy-based methodologies. However, they relied on simulations conducted with global climate models (GCMs) (Chen et al., 2020) or regional climate models (Púčik et al., 2017; Rädler et al., 2019; Sanderson et al., 2015), with grid spacings between 200 and 12 km. Overall, while there is considerable uncertainty (Raupach et al., 2021), the studies suggested that much of continental Europe is likely to see more frequent thunderstorm-prone environments with

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climate change, increasing the overall risk of severe hazards, including hail and lightning. A future increase in hail occurrence can be counteracted by enhanced melting of hailstones due to a higher melting level as shown in a study over the US (Gensini et al., 2024). Similar processes are likely to affect hail over Europe in a warmer future climate (Raupach et al., 2021), warranting further investigation.

Explicitly simulating future changes in hail frequency is challenging, in particular because of the mismatch in scales between the horizontal dimension of hail events and the resolution of climate models. Hail occurs within severe convective systems with a horizontal updraft width of ∼1–5 km (Musil et al., 1991) and develops rapidly. In conventional global and regional climate simulations, these processes are represented through parameterizations. However, this approach introduces biases in the diurnal timing of convection (Brockhaus et al., 2008) and in the intensity of intense precipitation (Ban et al., 2014; Dirmeyer et al., 2012). In this study, we utilize a convection-permitting model (CPM) with a high computational resolution of 2.2 km. This yields a better representation of the spatial distribution, intensity, and diurnal cycle of mesoscale convective systems, heavy precipitation, clouds, snow, and local winds (Ban et al., 2021; Belušić et al., 2018; Chapman et al., 2023; Ding et al., 2023; Estermann et al., 2025; Gensini et al., 2023; Hentgen et al., 2019; Lüthi et al., 2019; Pichelli et al., 2021; Prein et al., 2017; Schumacher & Rasmussen, 2020). It also enables the use of the online hail diagnostic HAILCAST (Adams-Selin & Ziegler, 2016), which has demonstrated good performance in capturing both individual hail events (Adams-Selin et al., 2019; Cui et al., 2023; Malečić et al., 2023) and the climatological distribution of hail across Europe (Cui et al., 2025).

The main objective of this study is to estimate the impact of global warming on hail day frequencies across Europe, for different seasons and hail diameter thresholds, using CPM simulations with a pseudo-global-warming approach (PGW). The second goal is then to relate the simulated changes in hail to those in environmental variables, such as CAPE, humidity, and melting level height.

2. Data and Methods

2.1. COSMO Climate Simulations

This study presents projected changes in hail occurrence due to climate change at a 3°C global warming level, using two CPM simulations over Europe with the climate version v6 of the non-hydrostatic COSMO model (see online at http://www.cosmo-model.org/, Baldauf et al., 2011). Both simulations use the same model setup, employing a nesting approach with a horizontal grid spacing of 12 km in the outer domain and 2.2 km in the inner domain (Figure S1 in Supporting Information S1). The domains encompass $361 \times 361 \times 60$ and $1542 \times 1542 \times 60$ grid points, respectively, with the inner domain simulation including online hail and lightning diagnostics. For hail, we use the one-dimensional hail growth model HAILCAST (Adams-Selin & Ziegler, 2016), which simulates the maximum hail diameter at the ground. HAILCAST estimates the growth of hail embryos based on the vertical profiles of temperature, humidity, and wind speed from the COSMO simulation. The maximum simulated hail diameter is output every 5 min.

For the control simulation (hereafter referred to as CTRL), the 12 km simulation is driven by 3-hourly ERA5 reanalyses (Hersbach et al., 2020) for the period 2011–2021. A detailed validation of the CTRL simulation against observations is provided in Cui et al. (2025), showing overall good agreement in spatial patterns, seasonal and diurnal cycles of hail occurrences between the simulation and observations. The main limitation of the simulated hail is an underestimation of very large hail. Nevertheless, the simulation captured seasonal cycles in hail size distributions and represented well frequencies of hail sizes up to 50 mm. Further details on the model configuration and output can be found in Cui et al. (2025).

2.1.1. Pseudo Global Warming Approach

For the future simulation (hereafter referred to as PGW simulation), we apply a PGW approach following Brogli et al. (2023) with a global warming level of 3°C. The PGW approach consists of extracting the monthly mean climate change signal (referred to as climate Δ) from a single GCM or a GCM ensemble for sea-surface temperature, surface skin temperature, and the three-dimensional fields of temperature, horizontal winds, relative humidity, and geopotential height. This procedure includes a sophisticated reconstruction of the sea-surface temperatures, as the 12 km outer domain has a higher resolution than the ERA5 grid. The climate Δ is then added to the present-day lateral boundary conditions, specifically to the ERA5 reanalyses in this study. For more information on the PGW approach, see Brogli et al. (2023), and for the detailed PGW simulation setup, see Supporting Information S1. The advantage of applying the PGW approach is its reduced computational demand due to shorter integration times compared to traditional downscaling of climate change simulations. Previous studies have demonstrated that, when using the PGW approach, the simulated fields such as temperature, pressure, wind speed, and precipitation are comparable to those from full downscaling approaches (Brogli et al., 2023; Estermann et al., 2025; Hall et al., 2024).

We note that winter precipitation in our PGW simulation does not increase across most of Europe compared to CTRL (see Figure S2 in Supporting Information S1), in contrast to results from multi-model ensembles (Estermann et al., 2025; Rajczak & Schär, 2017; Rajczak et al., 2013). However, precipitation during the convective season is not affected by these deviating changes in winter precipitation (see Text S2 in Supporting Information S1).

2.2. Definition of Hail Days, Hail Size Categories, and Heavy Precipitation

A hail day at a model grid point is defined as the period from 06:00 to 06:00 UTC the following day, during which the maximum simulated hail lies within a specific size range. To compare hail size distributions between the CTRL and PGW simulations, we compare three hail size categories. "Small hail days" are defined as hail days with a diameter d between 10 and 12.5 mm. "Intense hail days" are defined for diameters between 12.5 and 20 mm. The threshold of 12.5 mm is based on a comparison with radar-based hail occurrence over the Alpine region, which showed the best agreement between the mean number of hail days in the CTRL simulation and radar observations (Cui et al., 2025). In addition, a distinctly different behavior of hail in a warmer climate for sizes below and above 12.5 mm has been identified as further discussed in Section 3. The upper bound of 20 mm represents the threshold for large hail over Europe (Dotzek et al., 2009), above which infrastructure damage is expected (Hohl et al., 2002; Stucki & Egli, 2007). The third category for hail sizes above 20 mm, is referred to as "severe hail days." We do not refer to this category as "large hail" to not confuse this category with the large hail category above 1 in, which is generally used in the US (see e.g., Cecil & Blankenship, 2012).

Heavy precipitation refers to the hourly precipitation amount exceeding the 99.9th all-hour percentile (p99.9H) following Schär et al. (2016).

3. Changes in Hail Day Frequency Over Europe

The hail climatology based on the CTRL simulation shows regional variability across Europe. Prominent local hail maxima include the Po Valley in northern Italy, the slopes of the Pyrenees in western Europe, and the Carpathian Mountains in eastern Europe (Figures 1a–1c). In addition, hail frequency is above average in regions such as the northern Pre-Alps, northeastern Europe, southern France, Italy, and the Mediterranean Sea. This spatial variability is accompanied by a pronounced seasonal cycle, characterized by the maximum hail day frequency in summer over the continent and in autumn over the Mediterranean Sea (see also Figures S3 and S4 in Supporting Information S1, and Cui et al., 2025). This modeled climatology is consistent with observations of hail (Nisi et al., 2018; Punge et al., 2017) and thunderstorms (Feldmann et al., 2023; Fischer et al., 2024).

To assess the impact of 3°C global warming on hail day frequency, we compare the relative changes in hail days between the CTRL and PGW simulations (Figures 1d–1f). For intense ($12.5 \leq d < 20$ mm) and severe ($d \leq 20$ mm) hail days, large positive changes in hail days occur over the Alps, central to eastern Europe and the Mediterranean Sea, while decreases prevail over southwestern Europe. For example, over Poland, intense and severe hail days increase by about +30%. While for Spain, there is an overall decrease in intense and severe hail days by −29% and −34%, respectively. The sign of these changes is consistent for all hail sizes above 12.5 mm, also for very large hail above 30 mm (not shown). For small hail days, there is an overall decrease over continental Europe (e.g., −23% for Poland, −44% for Spain) and neutral changes or a small increase over most of the Mediterranean Sea and in the Alpine region (e.g., −1% for the Adriatic Sea and +7% for Austria). Seasonal details on changes in the intense hail day frequency are shown in the bottom panels of Figure 1. The increase in intense hail days over the Alps and central to eastern Europe peaks in summer, while increases over the Mediterranean Sea predominantly occur during autumn. Southwestern Europe experiences a decrease in hail days in all three seasons.

The seasonal and diurnal cycles of intense hail occurrence have been analyzed separately in 26 European countries, as shown in Figures S4–S8 in Supporting Information S1. The amplitude of the seasonal cycle increases

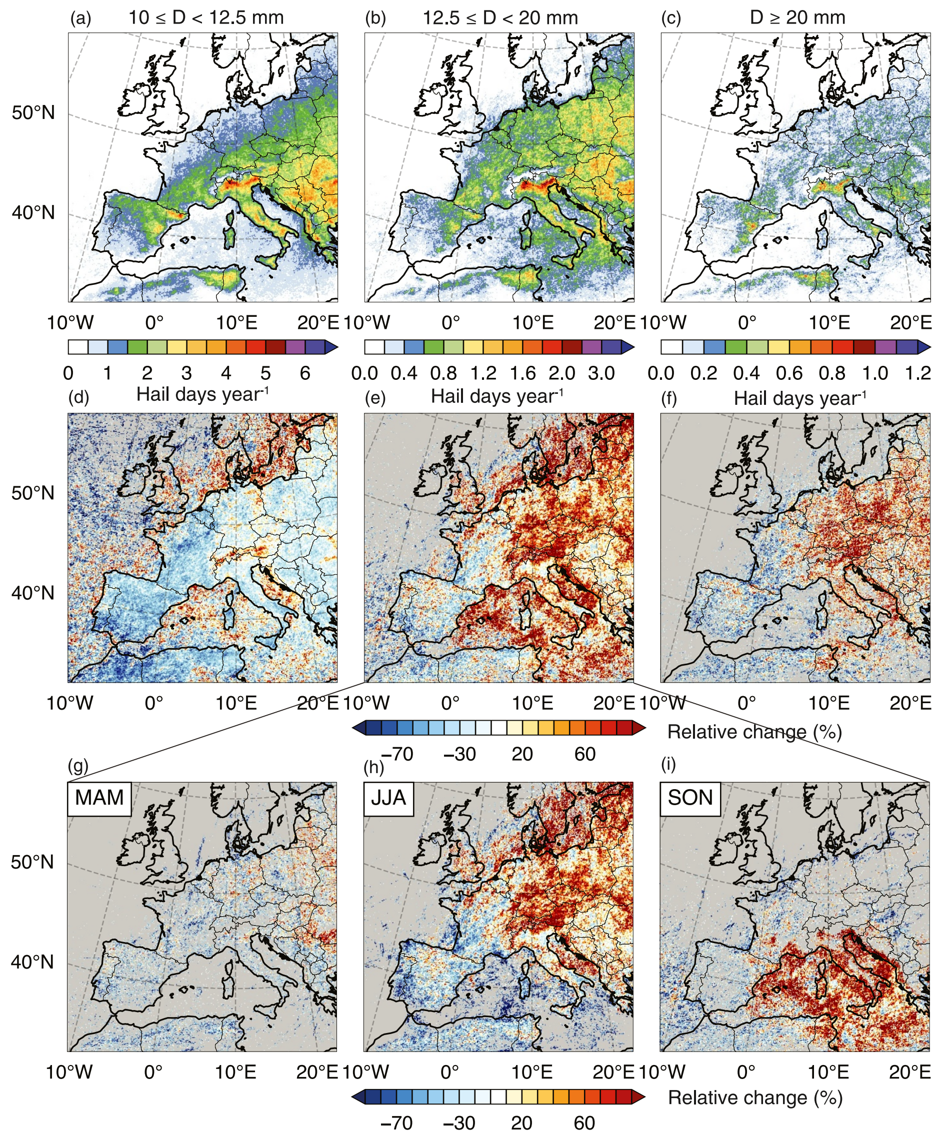

Figure 1. Mean annual climatology (CTRL, top row) and relative changes of hail days (PGW-CTRL, middle row) for hail with a diameter of 10–12.5 mm (small hail, left panels), 12.5–20 mm (intense hail, middle panels), and >20 mm (severe hail, right panels). The bottom row shows relative changes in intense hail days, from left to right for spring (MAM), summer (JJA), and autumn (SON). No results are shown for winter due to low hail frequencies (see Figure S3 in Supporting Information S1).

in northeastern and decreases in southwestern Europe, accompanied by a weak shift in the peak month to later in the season (Figure S9 in Supporting Information S1). The diurnal cycles are similar in the CTRL and PGW simulation, except for continental and northeastern Europe where a clear prolongation in the diurnal cycle and nearly a doubling of hail occurrences in the late evening and early morning occur (see e.g., Austria in Figure S5a in Supporting Information S1). The drivers of the partly contrasting climate change signals in hail occurrence across Europe are discussed in the next section.

4. Drivers of Hail Climate Change Signals

To better understand the changes in hail day frequencies between the CTRL and PGW simulations, we analyze mean seasonal changes in precipitation and selected key environmental variables that influence the occurrence of convection. We begin by comparing changes in hail day frequency with changes in precipitation characteristics. While mean precipitation and wet-hour frequencies decrease across much of Europe in summer (Figures 2a and 2b), heavy precipitation increases northeast of the Alps (Figure 2c). Notably, patterns of change over land in

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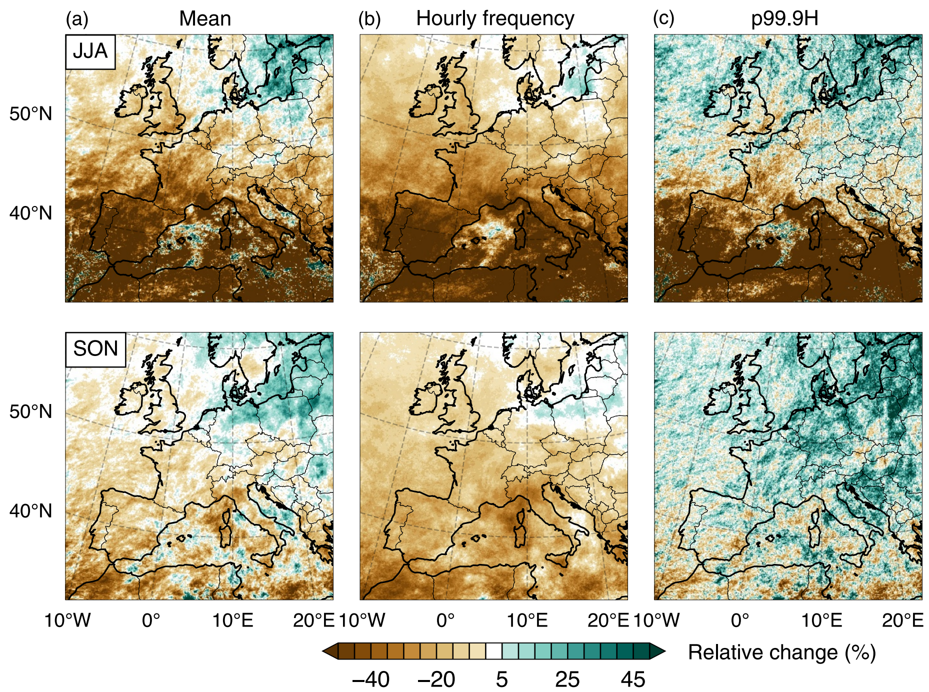

Figure 2. Relative changes in seasonal mean precipitation characteristics: (a) mean hourly precipitation, (b) wet hour frequency, and (c) heavy hourly precipitation (99.9th all-hour percentile) in summer (JJA, upper row) and autumn (SON, lower row).

intense and severe hail days closely match with heavy hourly precipitation in summer (Figures 1 and 2c). Areas with fewer hail days also see reduced heavy precipitation. For the Mediterranean, heavy precipitation decreases in summer and increases in autumn, when there is the strongest increase in intense and severe hail days. The relationship between changes in hourly heavy precipitation and hail days larger than 12.5 mm does not hold for continental regions in autumn. Convective systems over the land are too weak in autumn to produce hail and, thus, heavy precipitation and hail days are not related.

In summer, heavy precipitation and hail are associated with severe convection. Therefore, the similarity in changes between these two fields in the CTRL and PGW simulations is expected if these changes result from changes in environmental conditions. To explore this, we compare the changes in hail days with those in convection indicators, separately for summer and autumn. The changes in hail days over land closely mirror changes in daily maximum CAPE and in strong updraft velocities in summer (Figures 3a and 3c). Regions with a strong increase in hail days, such as the Alpine region and central to eastern Europe, also show an increase in CAPE and strong updraft velocity in the PGW simulation. In contrast, Spain sees fewer hail days and consistent decreases in CAPE and strong updraft velocity. Decreases in CAPE are related to reduced moisture availability in southern Europe. We see a pronounced decrease in relative humidity in regions of decreasing CAPE during summer (Figure 3d), co-occurring with only small increases in 2 m specific humidity (see Figure S10 in Supporting Information S1). The mid-tropospheric lapse rate, with mostly negative changes over Europe (see Figure S10 in Supporting Information S1), has a smaller influence on changes in CAPE than low-level humidity.

In contrast to Spain, where a decrease in hail days coincides with a decrease in CAPE, most of France does not show a decrease in CAPE even though the number of hail days decreases in most regions. This decrease in hail days might be related to an increase in convective inhibition (CIN) over southwestern Europe, including France (Figure 3b), indicating a suppression of convection initiation. Interestingly, vertical wind shear shows an increase over all of continental Europe during summer (Figure 3f) and cannot explain the contrasting SW-NE pattern for hail days. The comparison of changes in hail days simulated with HAILCAST versus convection and hail indicators such as CIN, CAPE and vertical wind shear shows the advantage of the former, which relies on convection initiation based on a fully three-dimensional simulation of trigger mechanisms.

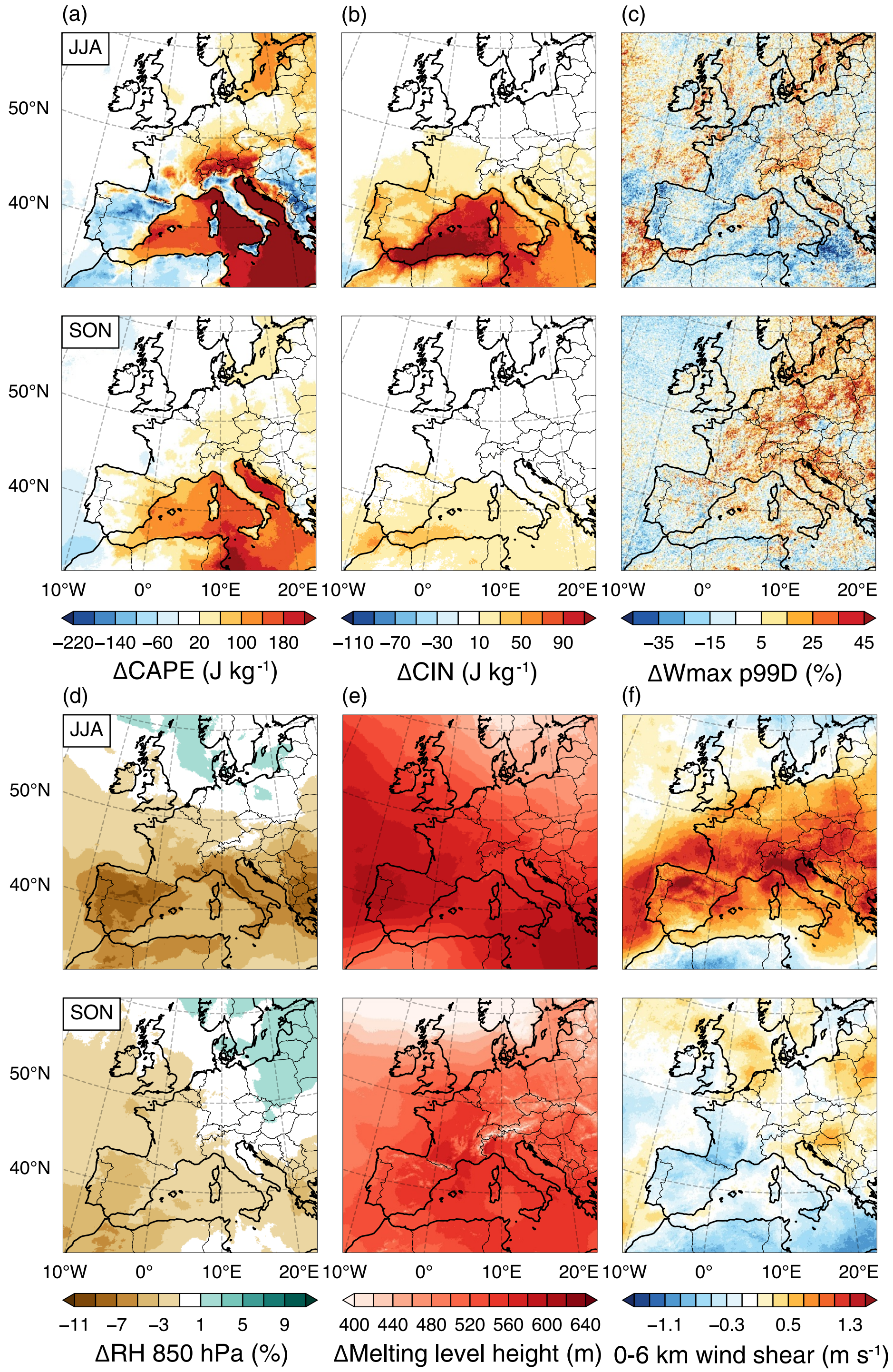

Figure 3. Mean seasonal changes in (a) daily maximum most-unstable convective available potential energy (CAPE), (b) most-unstable convective inhibition at the time of daily maximum most-unstable CAPE, (c) relative change in strong (99th percentile) hourly column maximum vertical velocity, (d) relative humidity at 850 hPa, (e) melting-level height, and (f) 0–6 km vertical wind shear between the CTRL and PGW simulations in summer (JJA, top row) and autumn (SON, bottom row).

An additional factor influencing hail occurrence at the surface is the melting of falling hailstones. The melting-level height increases by up to 600 m in the PGW simulation (Figure 3e), which enhances the melting of the falling hailstones, resulting in a more widespread decrease in small compared to intense and severe hail days (second row in Figure 1).

While changes in CAPE over land mostly align with changes in hail occurrence, the strong increase in CAPE over the Mediterranean Sea during summer does not lead to a corresponding increase in hail days. Despite the higher CAPE, comparatively low temperatures over the sea surface result in higher CIN, which is rarely overcome in summer due to a lack of synoptic disturbances to trigger convection. However, this situation changes in autumn, when an increased frequency of cyclones (Campins et al., 2011), cold fronts (Rüdisühli et al., 2020), and intense air-sea interaction events (Givon et al., 2021) over the northern Mediterranean Sea provides favorable triggers of convective storms. In autumn, the increase in low-level specific humidity over southern Europe in the PGW simulation is more pronounced than in summer, leading to a modest CAPE increase over land and more hail days along the Mediterranean coast and nearby sea.

5. Discussion

The findings of this study are consistent with previous projections of increased hail potential over northeastern Europe (Mohr, Kunz, & Keuler, 2015; Rädler et al., 2019). However, the decrease in hail occurrence over western and southern Europe identified in this study is in contrast to the results of Rädler et al. (2019), a study based on convective environmental proxies for hail, despite their model ensemble also indicating a decline in low-level relative humidity in southern Europe. Similarly, other studies on future changes in convective environments across Europe showed an increase in storm-relevant indices, such as CAPE and the lifting index (Chen et al., 2020; Púčik et al., 2017). Our findings highlight regional and seasonal variations in hail projections, especially in southern Europe. We regard the "explicit" simulation of convective storms, despite the limitations of km-scale models, coupled with an online hail diagnostic, as an important improvement over statistical analyses of hail-prone environmental conditions.

Historical changes in hail occurrence and convective environments are mostly consistent with our study, showing an increase over central and southern Europe (Battaglioli et al., 2023; Mohr & Kunz, 2013; Piani et al., 2005; Taszarek, Allen, Marchio, & Brooks, 2021; Wilhelm et al., 2024), although some hail pad observations in northern Italy showed a neutral or decreasing trend in hail occurrence in recent years (Manzato et al., 2022). Decreasing convection potential over southwestern Europe has been seen in CAPE, thunderstorm and lightning proxies and measurements (Augenstein et al., 2024; Battaglioli et al., 2023; Taszarek, Allen, Marchio, & Brooks, 2021), while hail proxies revealed an increase in hail occurrence in this region (Battaglioli et al., 2023). Due to the use of different time periods and reliance on hail proxy variables, the origin of the differences between the future projections analyzed in this study and historical trends is difficult to interpret.

We identified fewer days with hail sizes below 12.5 mm and more days with hail sizes above 12.5 mm in a future warmer climate. A similar pattern was identified by Gensini et al. (2024) over the US, but for a larger threshold of 40 mm. The melting level height increases by a similar magnitude of 500 m in both studies and cannot explain these differences. Possible reasons could be that the generally more severe convective systems in the US compared to Europe lead to different hailstorm growth dynamics or different hail representations in the two studies (explicit modeling vs. HAILCAST diagnostic). A study investigating changes in hail storms over the US using the PGW approach and an explicit simulation of hail, showed a general increase in convective parameters such as CIN and CAPE, together with larger hailstones in the cold season and a decrease in hail sizes in the warm season (Mallinson et al., 2024). This differing behavior of hailstones in cold and warm season storms was hypothesized to be related to microphysical processes. Despite many advances in simulating hail, uncertainties in model representation remain. Further studies are needed to compare projections of future hail trends based on different microphysical schemes, hail proxies and diagnostics in various climate simulations.

While our study applies a novel approach to assess the impact of climate change on hail formation, offering a more accurate and physically consistent analysis of hail occurrence compared to studies based on hail proxy calculations, we recognize that it cannot capture all aspects of future hail formation. The PGW approach used in this study cannot account for changes in dynamical forcings, such as potential frequency changes of extratropical cyclones entering the domain across the boundaries. Nevertheless, incoming cyclones adjust themselves to the imposed changes in the large-scale circulation and grow faster or slower than in the CTRL simulation (Brogli et al., 2023).

Additionally, the future hail trends presented here are based on a single climate simulation, an explicit simulation of convective clouds, and an online hail diagnostic. Our simulations cover an 11-year period, which is insufficient to assess return periods for hail events exceeding 10 years, potentially missing some of the most extreme hail events. Due to the high computational costs of convection-resolving climate simulations, running multi-year simulations with various models, climate scenarios, and hail parameterizations is beyond the scope of this project.

The HAILCAST hail diagnostic, which is a one-dimensional hail growth model, does not explicitly simulate the formation of hailstones. Nonetheless, it has been shown that HAILCAST adequately simulates the intensity of hail storms (i.e., maximum hail size) over the US and Europe (Adams-Selin et al., 2019; Brennan et al., 2025; Cui et al., 2023, 2025; Malečić et al., 2023). In COSMO simulations with HAILCAST, hail sizes are slightly smaller within larger hail swaths compared to simulations using the same setup in the Weather Research and Forecasting Model (Malečić et al., 2023), and hail sizes above 50 mm are generally underestimated (Cui et al., 2025). These differences were attributed to different updraft intensities and microphysical properties between the models (Malečić et al., 2023). In conclusion, the results of this study are representative for hail sizes between 10 and 50 mm.

6. Conclusions

This study employed a km-scale convection-resolving model with an online hail diagnostic to quantify the impact of climate change on hail occurrence covering large parts of Europe. The results reveal contrasting changes across the continent for hail sizes above 12.5 mm with an increase along the northern Alps and in parts of central and eastern Europe and a substantial decrease in hail day frequencies in southwestern Europe. Over land, changes are almost limited to summer, but over the Mediterranean Sea and in coastal areas, the largest (positive) changes are projected to occur in autumn. Comparison of hail day frequency changes with changes in environmental conditions in summer consistently revealed that reduced low-level relative humidity in southwestern Europe in the future goes along with a slight reduction in CAPE and an increase in CIN, eventually leading to a decrease in heavy hourly precipitation and the formation of hail. The increase in melting level height helps to explain why the frequency of small hail days decreases across continental Europe.

This first-of-its-kind simulation of continuous 11-year CPM simulations with an online hail parameterization for the current and future climate over Europe demonstrates the value of such an approach, offering more detailed insights into hail occurrence than coarser-resolution statistical models. The main value of these findings and the utilized CPM approach is threefold: (a) they provide physically consistent explanations for contrasting trends in hail frequency across Europe, (b) they leverage the benefits of the CPM approach in simulating a more realistic diurnal cycle and spatial distribution of convective storms (compared to coarser-scale simulations), and (c) the precipitation and hail fields with very high spatial (2.2 km) and temporal (5 min) resolution are most useful for the coupling with hail impact models and for country-specific analyses. The first two points are important for building trust in future trend estimates, while the third point is very important when pondering the socioeconomic implications of hail and its trends in the context of global warming. Given the spatially highly variable hail vulnerability, very high-resolution data is required for modeling future hail impact on infrastructure and agriculture. Moreover, such model chains also support policymakers and industry stakeholders in developing targeted protection strategies. Despite the limitations in the utilized modeling framework, our study pinpoints regions of increased future hail risk and provides the basis to develop urgently needed strategies for hail damage mitigation.

Data Availability Statement

The output fields (maximum hail diameter, CAPE, CIN, 0–6 km vertical wind shear, 700–500 hPa lapse rate, specific humidity at 2 m above sea level, relative humidity at 850 hPa, melting level height, precipitation, and column maximum vertical wind speed) from the COSMO simulations used in this study are publicly available in the ETH research collection (Thurnherr et al., 2025a, 2025b). Additional model output is available upon request from the authors.

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