
The Chaucer White Papers

Large Hail in Europe

A changing risk



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Introduction

Severe convective storms (SCS) and the weather hazards associated with them cause significant economic losses worldwide.¹

Although several weather hazards are associated with SCS such as tornadoes and heavy precipitation, the most damaging of these hazards is often hail, and yet it is one of the least understood.

Although there have been several studies on European hail in recent years, which we have reviewed to compile this white paper, complications with how data is collected and the variance of the topography within Europe makes determining future trends challenging.

Our review highlights that the science of large hail risk is relatively immature compared to other catastrophic natural perils, which the insurance industry is more accustomed to managing.

What is clear from current data, however, is that hail risk in Europe is changing and as an industry we need to better understand these shifts in order to prepare for the future.

In this paper we share the output of our research review and discuss implications for the insurance industry.

¹ Fan et al., 2022

The problem

Annually, large hail, defined as hail with a diameter of >2cm or more,² causes billions of dollars' worth of damage worldwide³ to property and crops, and even causes loss of life.

Although severe convective storms in Europe are often seen as less severe when compared to the United States, large hail is common across many parts of Europe and single severe storms can be just as damaging.³

In 2023, severe convective storms caused around \$12 billion of damage across Europe, with hailstorms in Italy that year causing \$3 billion of damage alone.⁴ In 2022, insured losses reached €4.8 billion from hailstorms in France, whilst a hailstorm in Catalonia killed one person⁵ and injured 67 others.

Despite this, research into severe convective storms in Europe lags that of the United States.⁶

The research

When comparing hail favouring conditions in Europe, studies have shown that conditions favouring large hail ($\geq 2\text{cm}$) and very large hail ($> 5\text{ cm}$) have become 100% to 200% more frequent in the decade 2010-2019, when compared to 1950-1959.⁷

Given the threat hail poses to Europe and the lag in research there is a considerable need to better understand the peril, highlighted by the fact the environments in which hailstones form are changing due to anthropogenic climate change.⁸

² Hulton and Schultz., 2024

³ Púčik et al., 2019 and Gensini, 2021

⁴ Púčik, 2024

⁵ Púčik, 2023

⁶ Pacey et al., 2021

⁷ Ghasemifard et al., 2024

⁸ Raupach et al., 2021

As we explore within this paper, these changes particularly impact human experience and (re)insurance exposure due to the population shift towards urban areas as discussed in Section 3. Further research is needed into where impacts are most keenly felt, but could be evidenced by, for example, increase in solar panel usage, property renovations and the development of cars, which are more vulnerable to hail damage.

To assess and understand hail risk in Europe and how it is altering with climate change, three key areas have been examined:

- Historical trends and projections
- Physical science
- Human Behaviour

Key Physical Drivers of Large Hail Risk in Europe and how they impact the peril

Drivers of Hail Risk	Frequency	Intensity (Quantity)	Severity (Size)
Convective Available Potential Energy	x	x	x
Topography	x		
Sea Surface Temps	x	x	x
Melting Level Height		x	x
Wind Shear	x	x	x

“Understanding perils, their drivers and how they may change is key to managing exposures. This research therefore helps to shape our view of a risk which is becoming more and more material. Models are of course an important part of this view, but supplementing them with deeper insight can only be beneficial to the underwriting process.”

– Werner Joubert, Chief Risk Officer

This paper will:

— Section 1: Historical Trends and Future Projections

Provide an overview of the historical trends, observational data and reanalysis studies which measure hail risk currently, and projections for the century ahead

— Section 2: Physical Science

Summarise the physical science of changing hail risk in macro and micro trends

— Section 3: Human Behaviour

Discuss how human behaviours may impact hail risk

— Section 4: What does this mean for (re)insurers?

Outline the takeaways for the (re)insurance industry



Section 1: Historical Trends and Future Projections

There are several branches in historical data analysis:

- observations in the form of reports from the public and hail pad data
- reanalysis studies, which blends meteorological observations with forecasting models to demonstrate where hail has historically occurred
- spatial factors

Projections are used to give an indication of what is most likely to happen given certain warming and emissions trends. They are derived from climate model ensembles which themselves are compiled by academics and institutions worldwide.

Together, these indicate a changing picture of hail conditions in Europe, which we have examined below.

1 Observations

Recent research into European hail notes that there are currently no consistent, comprehensive estimates for hail days or hail frequency based on direct observations in Europe,⁹ largely due to the lack of a standardized and widespread hail observing system, and the availability of data varying greatly from country to country.¹⁰

Despite these challenges, work has been done to try and examine historical trends using observational data in the European Severe Weather Database (ESWD), which provides the only Europe-wide observational dataset for severe convective storms.¹¹

Hail reports

As shown in Figure 1, the ESWD suggests that between 1900 and 2020, the annual number of large hail reports was low for most of the twentieth century, with peaks during the 1930s and 1940s-50s caused by a sudden increased scientific interest in the peril within Poland.

This study of the ESWD demonstrates an upwards trend in the number of large hail days from the 2000s onwards.

The annual number of large-hail days was derived from the annual number of large-hail reports and removing duplicate dates.

Research using observational data on hail severity across the whole of Europe for the period 2000-2020 indicated no detectable change in severity in the ESWD dataset.¹¹

Given the difficulty of measuring hail severity however, the data is limited. For example, hail is often under-reported, as the largest hailstone in any given event may not be found, or it may melt before being found, meaning the largest recorded diameter¹² can be inaccurate. Due to these limitations the study notes that hail size could be changing, but the dataset is unable to detect it.

Although there are limitations with this data, including reporting bias which naturally favours areas of denser population, the ESWD reliably represents aspects of European large hail climatology and appears to show trends of an increase in the frequency of large hail across Europe from the 2000's onwards.

⁹ Raupach et al., 2021

¹⁰ Punge and Kunz., 2016

¹¹ Hulton and Schultz., 2024

¹² Pilorz and Lupikasza 2020 and Hulton and Schultz, 2024

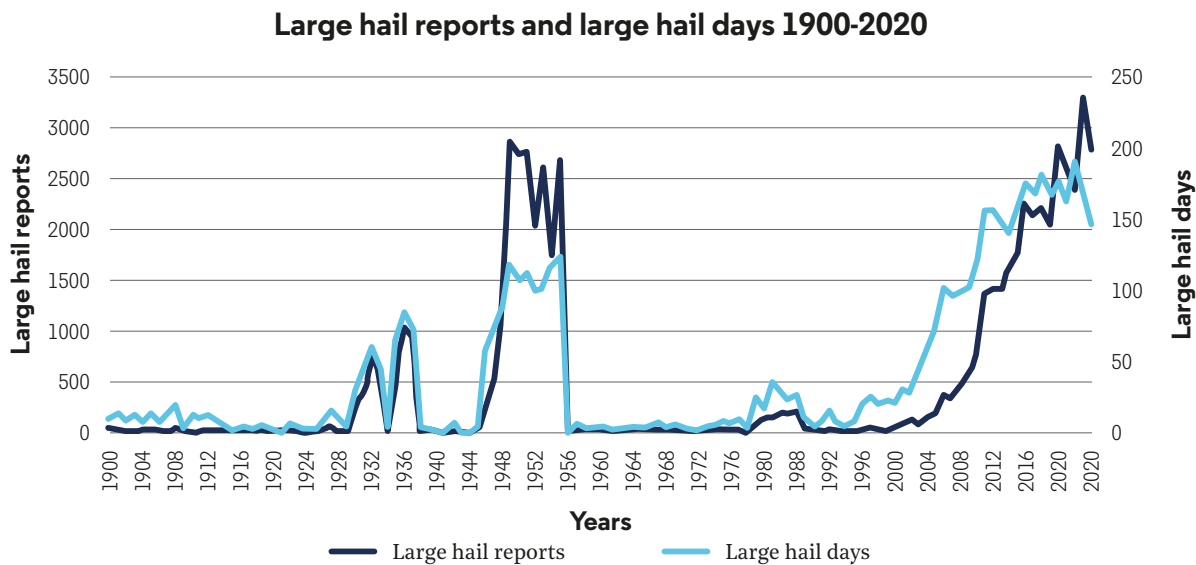


Figure 1: Time series of annual numbers of large-hail reports (dark blue line) and large-hail days (light blue line) across Europe for 1900–2020 (Hulton and Schultz., 2024).

Hail pads

Hail pads are flat pads made of material sensitive to the impact of hailstones such as Styrofoam. When hail occurs, they collect dents, these dents can then be used to measure the diameter of the stones. This means when examining trends in severity, hail pad data can be extremely useful.¹³

One study which examined hail pad data in Northeastern Italy found that between 1975 and 2009 there had been an increase in the severity of hail.¹⁴ Similarly, another study that examined hail pad data in France from 1989–2009 showed an increase in the size of hail.¹⁵

Like the observational data, hail pads do have limitations, however they are one of the most valuable datasets for trend analysis.¹⁶ Therefore, we can have more confidence in the increasing severity trends we are seeing.

¹³ Dieling, Smith and Beruvides (2021)

¹⁴ Eccel et al., 2012

¹⁵ Berthet, Dessens and Sanchez, 2011

¹⁶ Raupach et al., 2021

2

Reanalysis Studies

Increase in occurrence

Due to reliability concerns with observational data, studies on long-term hail trends have traditionally focussed on large scale variables as drivers of hail. Reanalysis studies integrate historic weather data from a variety of sources to accurately simulate past states of the atmosphere.

Research trained on hail reports, lightning observations and atmospheric reanalysis data has suggested that between 1950 and 2021 the occurrence of large hail ≥ 2 cm and very large hail ≥ 5 cm had increased across most of Europe, with some regions such as Northern Italy seeing more significant trends¹⁷ (Figure 2).

Furthermore, this study showed that in Northern Italy hail >5 cm in diameter is now three times more likely than it was in the 1950s. This finding supports the increasing severity trends seen from the hail pad data.¹⁸

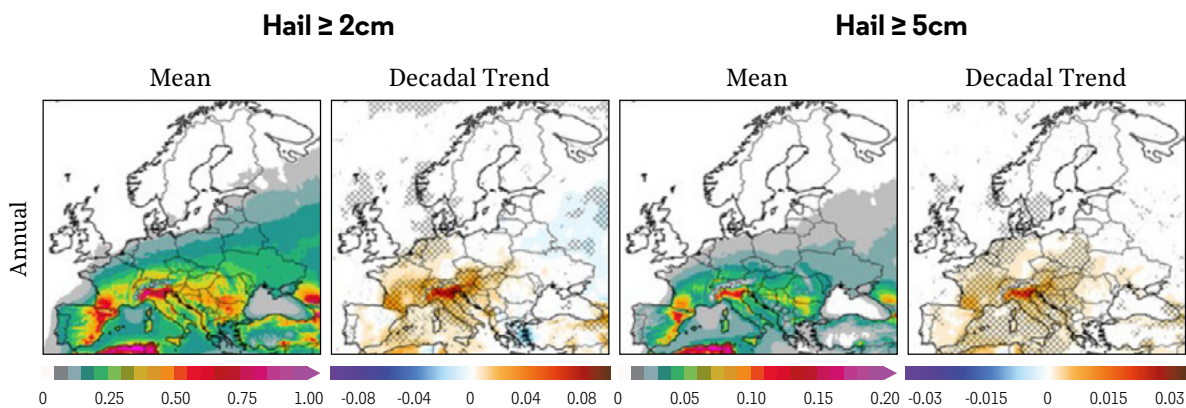


Figure 2: Mean modelled annual and seasonal number of hail hours between 1950 and 2021 across Europe, for large hail ≥ 2 cm and very large hail ≥ 5 cm. Annual and seasonal trends are also shown and are expressed as the change in the number of hail hours per decade. Trends significant at a 95th percentile level are cross hatched (Battaglioli et al., 2023).

¹⁷ Battaglioli et al, 2023, building on work by Tazsarek et el. 2021 used an additive logistic model to examine the evolution of hail in Europe. Based off this data, the model assigns hourly probabilities to locations and times on a $0.25^\circ \times 0.25^\circ \times 1$ -hourly grid.

¹⁸ Battaglioli et al. 2023

Increase in convective available potential energy (CAPE)

CAPE is the amount of fuel available for a thunderstorm to develop, with higher CAPE meaning the atmosphere is more unstable and therefore more likely to develop a thunderstorm.¹⁹

Between 1960-2023 there was a significant increase in convective available potential energy (CAPE) across Europe, with overall hail risk rising faster than the USA, at about 1% per year compared to 0.7%.²⁰

This research also suggests an increase in the potential for large hail in Europe.²¹ For example, reanalysis data for the past 30-60 years shows hail-favouring environments have become 10-30% more likely over large parts of southern and central Europe, including southern France, Italy, northern Switzerland, Germany and the Iberian Peninsula.²²

Despite certain limitations with the data, such as reliability being greatest in areas of flat topography compared to mountainous areas, there is still a consensus that CAPE and the frequency of large hail in Europe has increased.

¹⁹ National Weather Service (2024)

²⁰ National Weather Service (2024)

²¹ Mohr and Kunz, 2013

²² Mohr and Kunz, 2013: Study is supported by Sanchez et al. 2017 which found an increase in hail favouring environments and thermal instability in these regions.

3

Spatial factors

Topography

Whilst there are fluctuating factors for hail risk such as observed changes, there are also factors which remain unchanged, such as topography.

Although large hail can occur in any part of Europe, there are hotspots, and topography plays a key role in the location of these areas.²³

There are three key ingredients needed in the low-level atmosphere to form severe convective storms:

- **lift**
- **moisture**
- **instability**²⁴

Hail is produced when tiny specks of debris are lifted high into deep convective storms where they collect water and then freeze.

For storm-generating lift to occur, air must be forced to ascend, which can be triggered or enhanced by sloped terrain.²⁴ As seen in Figure 3, the majority of the large hail hotspots in Europe are located downstream below mountain ranges.

²³ Punge and Kunz 2016

²⁴ Schumacher and Rasmussen, 2020

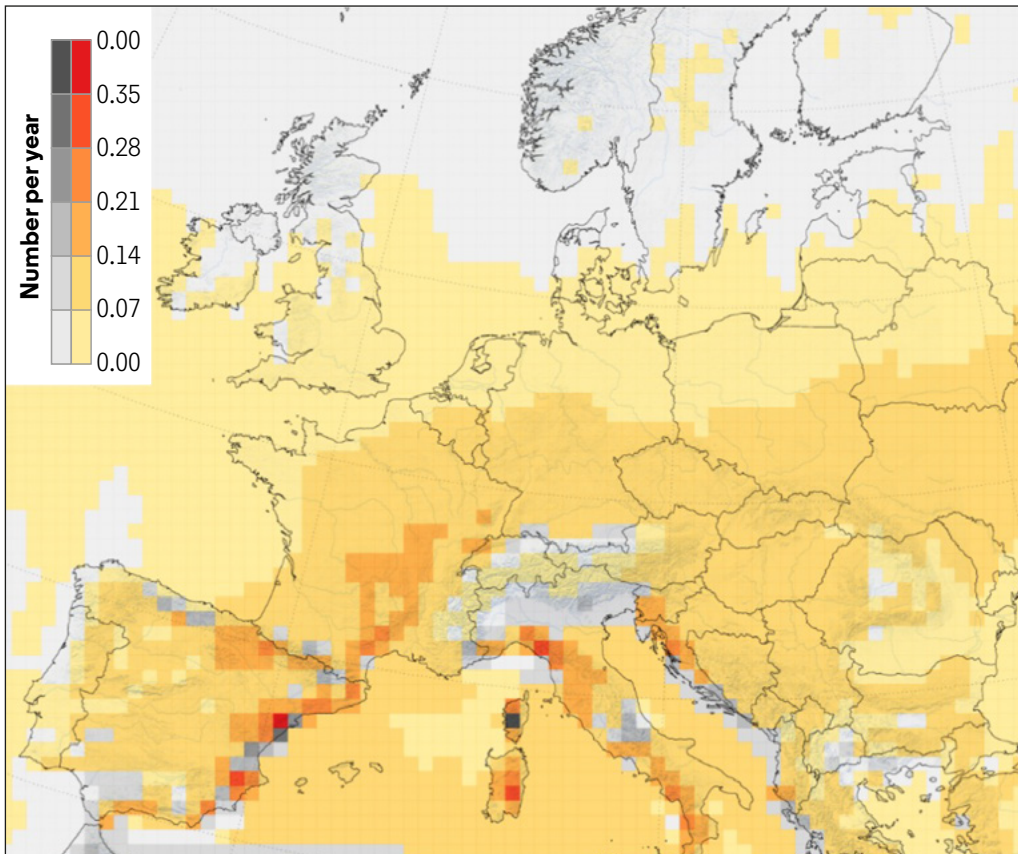


Figure 3: Number of hailfalls with hailstones >5cm, average 1971–2000 (Rädler and Faust, 2020).

Recent studies have noted that in the USA there has been a geographical shift in where severe convective storms occur, mainly due to climate change, which has shifted the area known as “tornado alley” eastward.²⁵ This shift has been enabled by the flat topography of tornado alley in North America. There has been no spatial shift detected in Europe where SCS and large hail occur²⁶ to date, likely due to this lack of topographical interruption.

²⁵ Cao, Cai and Zhang 2021, Krainz et al., 2022, Li et al., 2023, have noted the shift in SCS due to climate change, enabled by the topography of central North American states in the area generally known as Tornado alley.

²⁶ Punge and Kunz., 2016

Large bodies of water

The Mediterranean Sea plays a key role in the spatial distribution of large hail in Europe,²⁷ touching many parts of the continent and providing much of the moisture needed to form severe convective storms. **This proximity to such a large volume of water partly explains why areas around the Mediterranean coast experience a higher frequency of SCS and large hail (Figure 3).**

This influence is further evidenced by the lower hail frequencies seen in parts of central Europe, where continentality is a governing factor for hail frequency, because there are lower moisture levels and thus less favourable hail environments.²⁷

Summary

Overall, research into historical data – observations and reanalysis – show that large hail in Europe is increasing in intensity, and the upward trend in frequency, severity and CAPE seen in Europe is consistent across many different analyses.²⁸

Spatially, there has been no shift in where hail occurs in Europe due to topographical constraints, but research suggests hail frequency and intensity has increased across all of Europe, with larger increases seen in some hotspot areas.

²⁷ Studies by Punge and Kunz 2016, supported by Cui et al. in 2023, note that the Mediterranean Sea influence the development of hail in Italy's Po Valley, and South eastern Europe respectively.

²⁸ Stormwise, 2024

4

Projections

It is difficult to predict the future effects of climate change on large hail with certainty, because there are many factors that influence hail formation. This complexity means only a few studies have assessed the impact of the trends noted above. All studies which assess the future projection of large hail in Europe under the influence of anthropogenic climate change have limitations.

In 2019, using hazard observations, reanalysis data and lightning detection data, Rädler et al indicated projections of a 30-80% increase in large hail >2cm across Europe.

The results also showed that by the end of the century, under the RCP 4.5 scenario (warming scenario of roughly 2.6 °C) the occurrence of very large hail (≥ 5 cm diameter) is projected to become 30-40% more likely across almost everywhere in Europe, as seen in Figure 4. The results show an even greater increase in southern France, parts of the Adriatic coast and parts of Italy.

As this study only examined hail trends for 2071-2100 it does not help to understand more near-term trends and projections, however the findings can still be used to build a picture of what the future risk of hail may be in Europe.²⁹

²⁹ Rädler et al., 2019

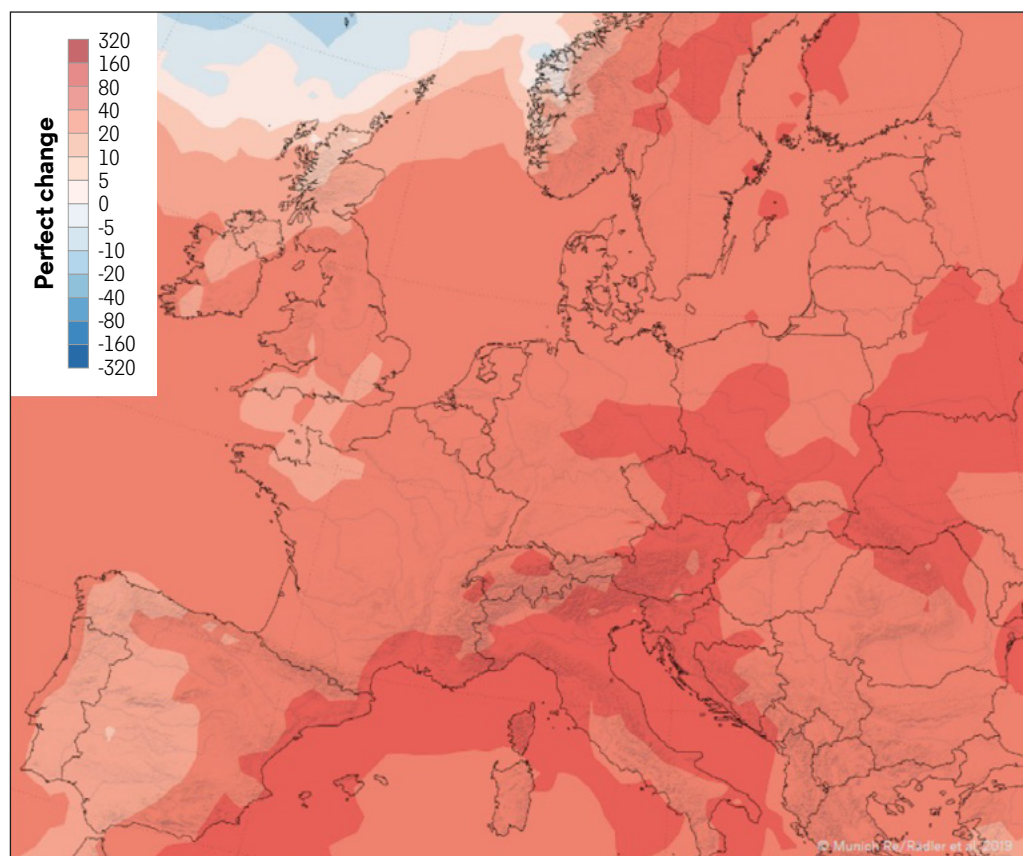


Figure 4: Anticipated change in hailfalls with hailstones >5cm in a moderate climate scenario, with a temperature increase of approx. 2.6°C, 2071–2100 (Rädler and Faust, 2020).

Other studies have examined climate projections for specific countries. For example, in Germany one study examined possible changes in hail potential in the future.³⁰ The finding of this study showed that for the near future there was an increase of 10–41% in hail likelihood in Germany. There are a handful of other country specific studies however the results from these studies are highly uncertain.³¹

³⁰ Mohr, Kunz and Keuler, 2015

³¹ Sanderson et al., 2015

“Future projections are uncertain, but show an increasing large hail risk, and the uncertainty is itself an increase in risk.”

– Alexandra McConkey, Exposure Analyst and Project Researcher

Summary

Despite the lack of studies assessing the future projection of hail in Europe, the majority of studies referenced show an increase in hail frequency and severity across Europe in the future.

Furthermore, given the increasing trends seen in the historical data, it could also be inferred that these trends will continue in the future. These projected increases can also be explained by physical science.



Section 2:

Physical Science

1 Macro trends

Changes in Sea Surface Temperature

Rising Sea Surface Temperatures (SST) in the Mediterranean are leading to increased low-level moisture, which is in turn causing an increase in CAPE.³²

This rise in SST is expected to result in more intense and frequent hail events in Europe. From 1982 to 2019 studies have shown that the SST in the Mediterranean have risen by 0.035°C per year.³³

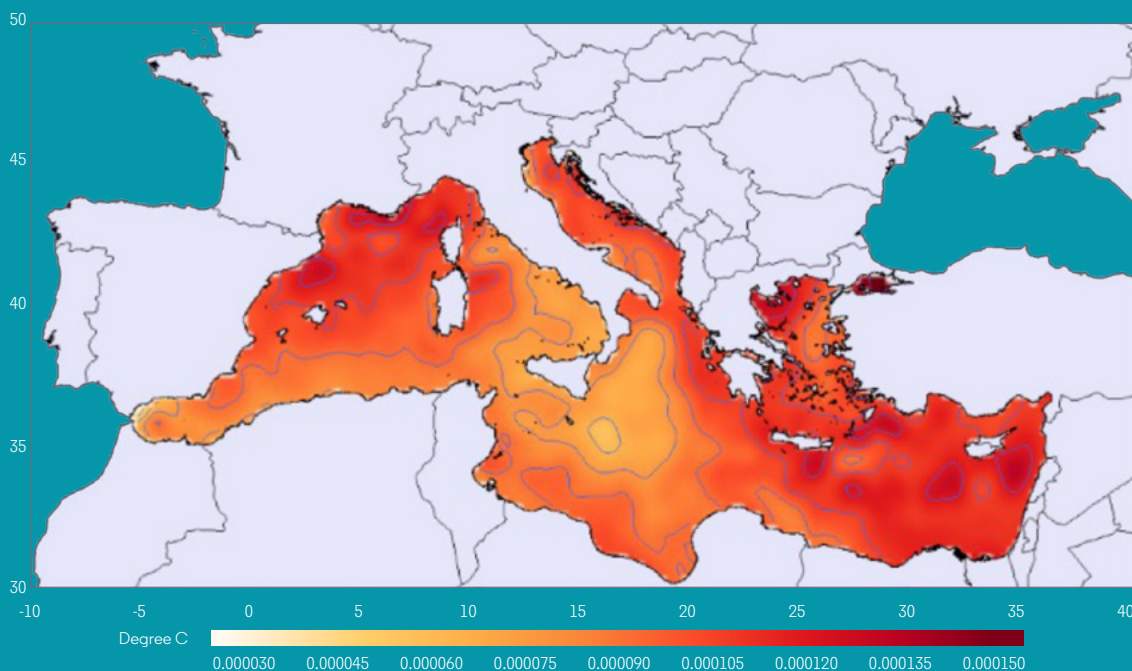


Figure 5: Daily warming trend in the Mediterranean basin from 1982 to 2019. Each contour denotes a change of $1.5 \times 10^{-5}^{\circ}\text{C/day}$.³⁴

Climate change is also driving a notable increase in the intensity (temperature), duration, and frequency of marine heat waves (MHW) in the Mediterranean region, which is further increasing low level moisture in Europe.³⁵

³² Martin et al., 2024

³³ Pastor, Valiente and Khodayar (2020)

³⁴ Pastor, Valiente and Khodayar (2020)

³⁵ Frölicher et al., 2018 and Martin et al., 2024

For example, in 2022, a six-week record-breaking heatwave in the western Mediterranean influenced hail size growth in a hailstorm event in Northeastern Spain, causing hailstones to reach a diameter of up to 12cm.³⁶

Overall, there is clear evidence that the rise in sea temperature caused by climate change is increasing convective instability (CAPE), which in turn is leading to more frequent and intense hail events in Europe.

Changes in Melting Level Height

As the troposphere warms due to anthropogenic climate change, the melting level height (MLH) is increasing, which affects the distribution of hailstones.³⁷

Higher melting level height leads to more supercooled liquid above this level, promoting the growth of larger, denser hailstones, while reducing the number of smaller stones reaching the surface due to enhanced melting.³⁸

This trend is expected across Europe, due to the changing MLH and increasingly unstable atmospheric conditions, especially in regions already experiencing large hail.³⁹

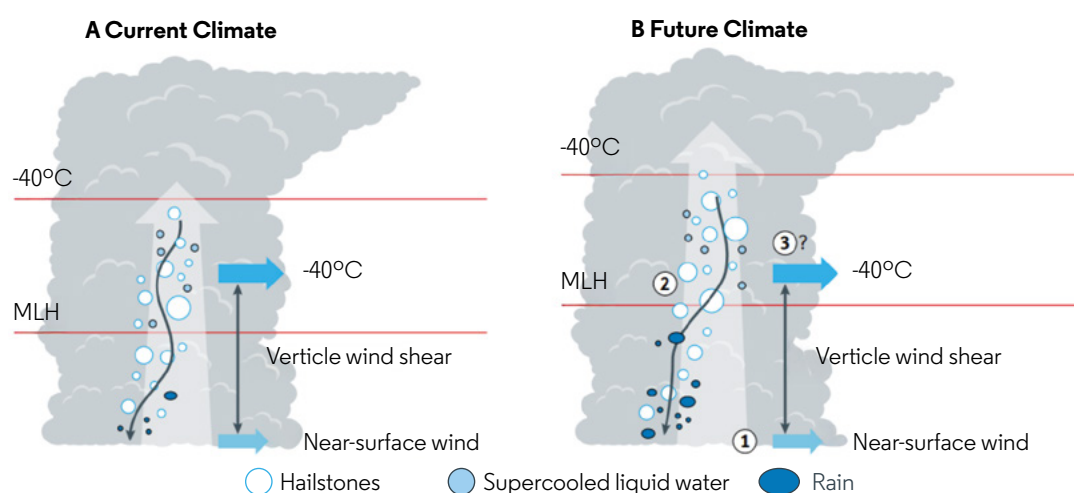


Figure 6: Hail-relevant atmospheric phenomena in current and future climates.

³⁶ Martin et al., 2024

³⁷ Raupach et al., 2021

³⁸ Prein and Heymsfield, 2020

³⁹ Raupach et al., 2021

Figure 6 demonstrates the expected changes in hail-relevant atmospheric phenomena between the current (panel a) and future (panel b) climates. The numbers in panel b correspond to the following changes:⁴⁰

- 1) increased low-level moisture leads to increased convective instability and updraught strength
- 2) an increase in the melting level height (MLH) leads to enhanced melting of hailstones and a shift in the distribution of hailstone sizes towards larger hailstones
- 3) changes in vertical wind shear may affect storm structure and hailstone trajectories but are generally overshadowed by instability changes.

Changes in Convective Available Potential Energy

Climate change has led to an increase in air temperature, which is expected to raise tropospheric water vapour by approximately 7% per °C of warming.⁴¹

As of 2024 the overall global surface air temperature has increased by around 1.5 °C since pre-industrial times (1850-1900) and Europe has warmed faster than any other continent.⁴² This rise in moisture and near-surface temperatures contributes to increased vertical thermodynamic instability, often measured as convective available potential energy (CAPE).⁴³

One of the ways in which CAPE plays a crucial role in large hail formation is by strengthening and lengthening updrafts, which allows hailstones to grow larger, as they can remain aloft for longer.⁴⁴

However, it should be noted that this increase in convective instability does not always lead to more intense and frequent hailstorms, as the effects of increasing convective instability can be offset by other hail relevant variables⁴⁵ such as storm structure and microphysical processes.⁴⁶ Despite this, CAPE remains one of the most influential factors in the formation of large hail in Europe.

⁴⁰ Raupach et al., 2021

⁴¹ Raupach et al., (2021), Held and Soden, (2006)

⁴² Copernicus, (2024)

⁴³ Allen, (2018)

⁴⁴ Lin and Kumjian, (2022)

⁴⁵ Raupach et al., (2021)

⁴⁶ Allen et al., (2019)

2

Microphysics

While the macro physical trends discussed can explain the potential impact of climate change on hail that has already formed, the ingredients required for hail formation must also be considered.

Firstly, a small particle (dust, salt, etc.) is required as that will be the nucleus that the hailstone grows around.

Secondly, 'an abundance of supercooled liquid water' is necessary for the hailstone to grow.

Thirdly, time is needed. The longer the hailstone spends in the convection surrounded by the super cooled water, the larger it becomes.

This seemingly simple process is actually quite complex and research on understanding the impact of climate change on the microphysics of hail is still emerging, and no consensus has yet been reached.⁴⁷ Further research into improving this understanding should greatly increase our ability to estimate future risk of hail and lead to improved modelling of the peril.

Summary

In Europe the changes seen to the frequency and severity of large hail are driven through an increase in CAPE caused by a rise in low level moisture and air temperatures. Changes to Melting Level height are causing a shift in the distribution of the size of hailstones that we are seeing. However, the process of hail formation is complex and research on understanding the impact of climate change on the microphysics of hail is still emerging.

⁴⁷ Allen et al., 2020

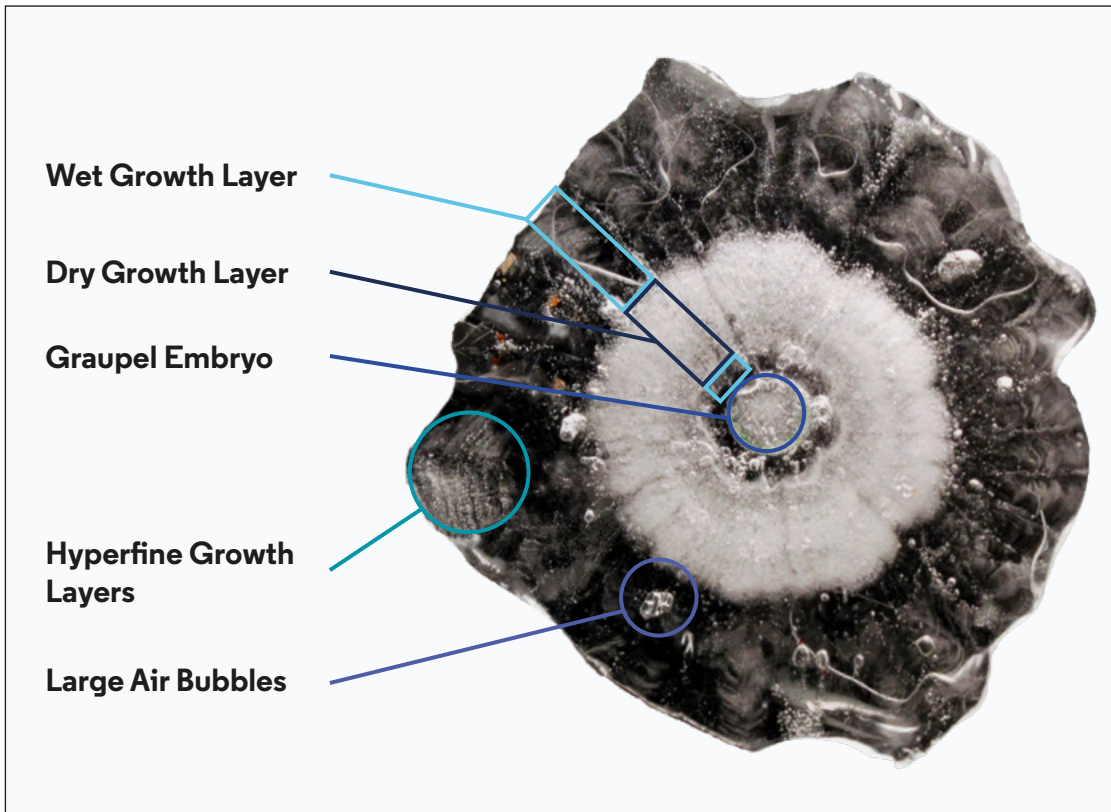


Figure 8 : Features observed within a hailstone cross section.⁴⁸

⁴⁸ Soderholm and Kumjian (2023)



Section 3:

Human Behaviour

Changes in exposure

Understanding hail risk requires consideration of how hail interacts with the built environment and whether this could create underlying trends in exposure:

- Hail falls in irregular swathes and the hail itself is irregular
- There are gaps within the hailstorm where there is no hail and parts where the hail stones are sparse
- Some storms have very dense clusters, which are of greatest concern

The irregularity of hail makes it hard to predict, but even harder to model because any model would have to estimate the impact of hail to buildings.

A single severe thunderstorm moving over a city, for example, might drop hail in areas with few buildings, such as parks or over bodies of water. Equally a storm may hit highly vulnerable areas such as outdoor parking lots, or a residential neighbourhood with solar panels on rooftops.

As a result of these factors, hail has a high miss factor, but also a high severity potential.

A global study on urbanisation changes found that, with regional variances, over the past forty years, overall, the share of the population of cities has increased from 37-48%, whilst it has dropped in towns and semi-dense areas

A 2022 study showed depopulation of Eastern Europe between 2000 and 2015, with corresponding growth in the West. Spain, Italy, and Sweden all had North-South disparities, whilst the internal regions of France, Germany, Croatia, and Portugal were all decreasing as people moved to more urban centres).⁴⁹

⁴⁹ Schiavina, M., Melchiorri, M., Corbane, C., Freire, S., and Batista e Silva, F. (2022). "Built-up areas are expanding faster than population growth: regional patterns and trajectories in Europe" OECD/European Commission (2020), "A new perspective on urbanisation", in Cities in the World: A New Perspective on Urbanisation, OECD Publishing, Paris. Schiavina et al (2022), OECD (2020)

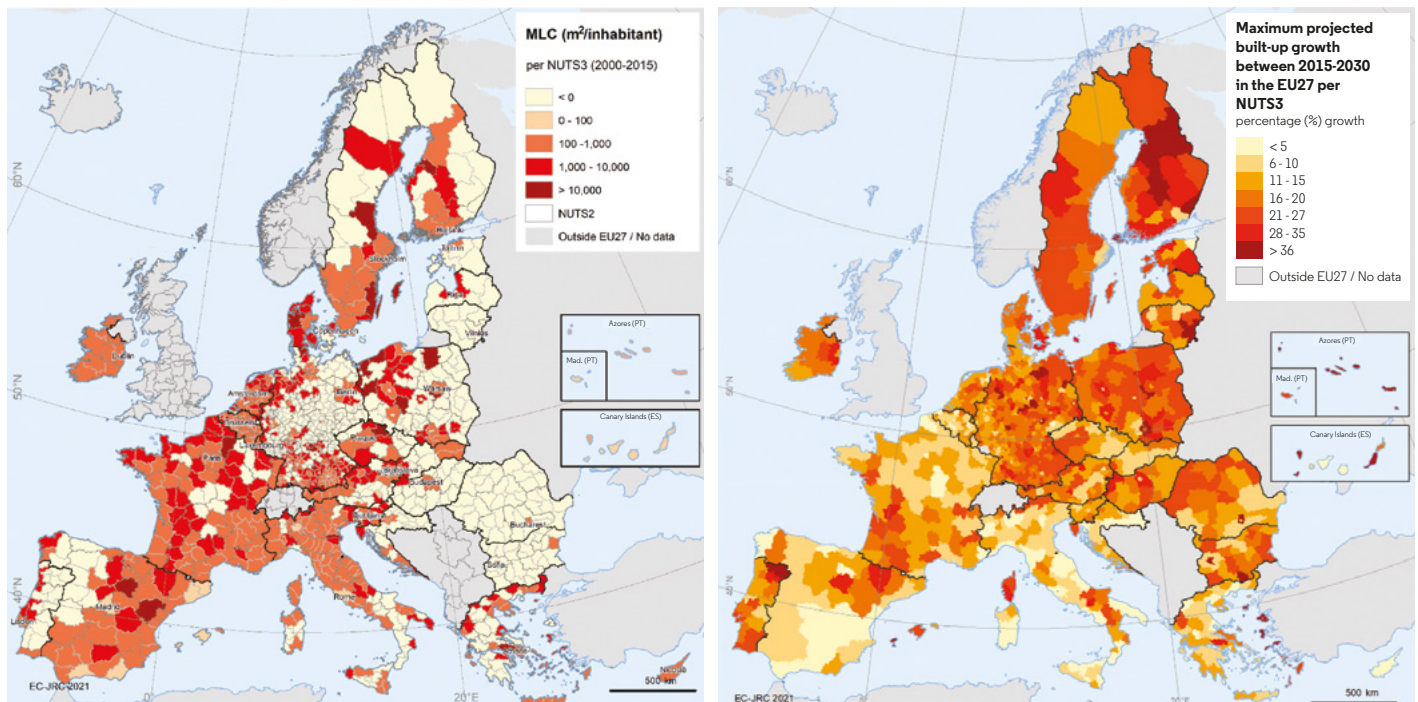


Figure 8: Increase in population from 2000 to 2015 (left) and maximum projected built-up growth between 2015 and 2030 (right). Contrasts the change which has happened v. what is projected for 2030. (Schiavina, M, et al 2022).

The same study showed that the population of urban areas was increasing at a rate of +7.4% over the period, against a Europe wide increase of +3.6%. In other words, in Europe, people are moving from the countryside into the cities, and cities are growing at a rate more than double that of the overall population.

This study also indicates that expansion of the built environment is occurring to accommodate the influx of people, rather than utilising existing buildings to house the growing population. In rural areas, building stock is not decreasing despite the decreasing population, and the growth of built-up land is increasing across all regions.

This effect of this trend is to concentrate exposure into fewer areas, likely resulting in urban centres having a higher proportion of the total exposed value of property in Europe, though rural risk still remains.

Given these anthropogenic trends, even if the hazard of hail was not changing, we should expect to see an increase in the frequency of hail losses in future years, as well as an increase in more severe events, due to the increased concentration of exposure in urban areas.





Section 4: What Does This Mean For (Re)Insurers?



Catastrophic hail loss probability increasing

Hail risk is a challenging peril to predict and model. As a result, there are a wide range of approaches for insurers when pricing and aggregating this risk across Europe.

The peril has a high ‘miss factor’, i.e. there are a lot of events which do not cause a loss compared to the number that do. Even within the area of a storm where hail falls there is variability in hail size, density, and speed.

This means historically we typically see a lot of smaller losses for hail in Europe. It is rare to get very large hail events aligning with high exposed areas to produce catastrophe events.

What we have shown in this paper is that both the likelihood of large hail events, and the number of highly exposed areas are increasing. This means the likelihood of the insurance industry experiencing catastrophic losses is going up.

However, it is not all going up. There is possibility that with an increase in Melting Level Height within the storms, as a result of global warming, that smaller hail stones will not make it to the ground. It is logical to suppose that this could mean a reduction in total hail frequency, yet the research suggests this is unlikely to impact hail of larger sizes.

The data shows that there is a greater concentration of people living in urban centres which is creating denser areas of peak exposure. Global warming is driving an increase in the probability of large hail across Europe, with particular increases noted around current hot spots in Southern Europe, as well as the Balkans.

We think this means that Europe is going to become increasingly exposed to catastrophic hail losses.

2

Catastrophe modelling limitations

When trying to understand this problem of increasing catastrophe risk, insurers should look towards catastrophe risk models to help. Since the late 1980s cat. models have proven themselves to be very good at estimating tail risk events – the losses which we know can occur but haven't yet happened. Such models will help resolve the increasing risk of large hail in Europe.

However, our review of the current research in Europe on large hail has highlighted a number of issues that will make it challenging to build a good catastrophe model:

Data gaps in observations and in reanalysis sets.

These gaps must be filled either with third party data, proxy data, simulated data or expert judgement. None of these can take the place of real data recording in Europe, but they will be necessary, and the method chosen to fill in the data gaps will greatly influence the outcome of the model.

Lack of research in this field

As established there has been less research into hail risk compared to other natural catastrophe perils insurers are used to dealing with, or even hail risk in the U.S. In particular, research into the micro-physics of large hail could greatly change our understanding of the risk.

Differences between data and scientific research across European countries

There are very few high-quality Europe-wide research projects, so again developers will be forced to leverage less reliable sources to build out Europe-wide catastrophe models for hail.

Even defining what Europe is for a catastrophe model is tricky with no two catastrophe model vendors including the same countries in their view of hail risk for Europe. These models then often have different countries in their model domain for flood and windstorm, despite them all being 'European' catastrophe models.

Cross country correlation of large hail remains a potential and ideally should be considered as part of a suite of atmospheric peril models for the region. Having a consistent domain will be important for quantifying this risk and being able to discuss it productively between insured, broker, and (re)insurer.

Despite these limitations, it is very important that these models continue to evolve and that investment in research and cat. model development grows. It must be said that some regions within Europe may develop faster than others due to differences in hazard and claims data, as well as differences in research. The problem of increasing risk is not going to go away, but with the right tools we may be able to understand it better.

3

Vulnerability shifts

Are Europe's buildings becoming more vulnerable to large hail?

This was a topic of study for this paper however, there was little data on the topic to be found.

There is extensive anecdotal evidence to suggest that there is change in vulnerability however, and it is having an impact on losses.

From government schemes promoting more solar panel installations on residential roofs, to more vehicles with glass tops and larger replacement costs, the risk to some assets seems to be increasing.

Our research has also yielded anecdotal evidence about certain exposures to hail risk which seem non-intuitive. For instance, reinforced glass for commercial greenhouses that is more resistant to hail damage are often not used because that specialised glass can reduce crop yields.

There are innovations in risk mitigation which should be encouraged. Hail nets for crop and car defence are not new but can greatly reduce losses if fitted correctly.

Catastrophe model vendors can accelerate the adoption of these by including debits and credits in the vulnerability component of models if appropriately backed up by data. This gives underwriters more information to continue to help set a fair price for the risk.

More data is needed, and a cross-class study backed by claims data would be an excellent resource to the industry to support our understanding of how specific areas of insurance will be affected by hail in the future.

4

Greater uncertainty due to climate change

The established understanding of hail and expectations about the kind of damage it can cause are often based on historical experiences.

We no longer live in a world of consistent climate, however. Atmospheric and oceanic temperatures are rising as a result of anthropogenic emissions of carbon dioxide and other greenhouse gases.⁵⁰

As a result, our past experience is increasingly less relevant in the current changing climate. Beyond the science of thunderstorms and hail there are interactions between the built environment and hail formation which we do not have data on. Dense urban areas can increase local temperatures, alter humidity levels, and perturb winds. These are just a few of many tertiary factors which science and engineering do not understand well enough. As a result, such uncertainty means we must inherently consider the risk of extremes, in this case catastrophic losses, of hail in Europe to have increased.

The research findings discussed in this paper are in addition to this baseline increase in the risk of uncertainty. Tracking new science and emerging understanding of this risk is a crucial part of the insurance industry staying resilient in the face of future catastrophes and avoiding unnecessary surprises.

The risk of catastrophic hail losses in Europe is rising due to more frequent severe events, growing exposure in urban areas, vulnerability changes, modelling challenges, and increasing uncertainty from climate change.

⁵⁰ IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115



Conclusion

Our view of the research taken in its entirety suggests an increased risk of large hail in Europe.

Large hail has historically occurred across the majority of Europe, but there do exist hotspots where hail is more frequent and severe. Furthermore, spatially, there has been no shift to-date in where large hail occurs, which can be explained by the complex topography of the region.

While the majority of the research on historical observations and reanalysis data show an increasing trend in the risk of large hail, future projections remain largely uncertain, due to the lack of studies and limitations in the data.

However, the few studies which have been done demonstrate that an increase in hail frequency and severity in Europe caused by climate change is likely, principally explained by increasing CAPE caused by rising low level moisture in Europe.

Furthermore, our examination of the physics of hail showed a number of driving factors which themselves are changing. In addition to increasing CAPE, sea temperatures in the Mediterranean Sea are making it more likely that severe thunderstorm systems are fuelled with warm, moist air. Both of these factors are likely drivers of increasing hail risk.

Conversely the change in hail melting level height within storms could be a driver that reduces hail frequency. As that level of melting moves up higher in a thunderstorm the hail falling down to the ground has further to fall through warmer air meaning we could see less small hail.

Taken together there should be an increase in frequency of very large hail, while seeing less overall hail of a smaller size.

Research on the micro level will be instrumental into a deeper understanding of this dynamic system and is another area of research that is sorely lacking. More studies are needed with real world data on hail development within the convection cycles of severe thunderstorms.

When considering changes to large hail in Europe, research has shown exposure and vulnerability must be taken into account,⁵¹ and a large driver for the increasing losses seen from hailstones is due in part to the expansion of the built environment.⁵² Although climate change is having an impact on large hail in Europe, these vulnerability and exposure factors are important to bear in mind when examining large hail trends in Europe.

Regardless of the causes, it is clear that the combination of any increase in likelihood of the most severe hail coupled with growing concentrations of exposure will require a review of the peril in the (re)insurance sector.

With the large threat that hail poses to Europe, the many uncertainties and lack of studies on how climate change will affect the peril, it is key that a better understanding is gained.

⁵¹ Raupach et al., 2021

⁵² Childs et al., 2020



References

- Allen, J.T., (2018).** Climate change and severe thunderstorms. In Oxford research encyclopedia of climate science.
- Bagagini, L., Ingrosso, R. and Miglietta, M.M., (2021).** Synoptic patterns and mesoscale precursors of Italian tornadoes. *Atmospheric Research*, 253, p.105503.
- Barras, H., Martius, O., Nisi, L., Schroeer, K., Hering, A. and Germann, U., (2021).** Multi-day hail clusters and isolated hail days in Switzerland–large-scale flow conditions and precursors. *Weather and climate dynamics*, 2(4), pp.1167-1185.
- Battaglioli, F., Groenemeijer, P., Púčik, T., Taszarek, M., Ulbrich, U. and Rust, H., (2023).** Modeled Multidecadal Trends of Lightning and (Very) Large Hail in Europe and North America (1950–2021). *Journal of Applied Meteorology and Climatology*, 62(11), pp.1627-1653.
- Beal, A., Hallak, R., Martins, L.D., Martins, J.A., Biz, G., Rudke, A.P. and Tarley, C.R., (2020).** Climatology of hail in the triple border Paraná, Santa Catarina (Brazil) and Argentina. *Atmospheric Research*, 234, p.104747.
- Brown, C.J., Schoeman, D.S., Sydeman, W.J., Brander, K., Buckley, L.B., Burrows, M., Duarte, C.M., Moore, P.J., Pandolfi, J.M., Poloczanska, E. and Venables, W., (2011).** Quantitative approaches in climate change ecology. *Global Change Biology*, 17(12), pp.3697-3713.
- Cao, Z., Cai, H. and Zhang, G.J., (2021).** Geographic shift and environment change of US tornado activities in a warming climate. *Atmosphere*, 12(5), p.567.
- Childs, S.J., Schumacher, R.S. and Strader, S.M., (2020).** Projecting end-of-century human exposure from tornadoes and severe hailstorms in eastern Colorado: Meteorological and population perspectives. *Weather, Climate, and Society*, 12(3), pp.575-595.
- Copernicus (2024)** C3S seasonal lookback: summer 2024 | Copernicus.eu. Available at: <https://climate.copernicus.eu/c3s-seasonal-lookback-summer-2024> (Accessed: 16 October 2024).
- Cui, R., Ban, N., Demory, M.E., Aellig, R., Fuhrer, O., Jucker, J., Lapillonne, X. and Schär, C., (2023).** Exploring hail and lightning diagnostics over the Alpine-Adriatic region in a km-scale climate model. *Weather and Climate Dynamics*, 4(4), pp.905-926.
- Da Silva, N.A. and Haerter, J.O., (2023).** The precipitation characteristics of mesoscale convective systems over Europe. *Journal of Geophysical Research: Atmospheres*, 128(23), p.e2023JD039045.
- Dessens, J., Berthet, C. and Sanchez, J.L., (2015).** Change in hailstone size distributions with an increase in the melting level height. *Atmospheric Research*, 158, pp.245-253.

- Diffenbaugh, N. S., Scherer, M. & Trapp, R. J. (2013)**, Robust increases in severe thunderstorm environments in response to greenhouse forcing. *Proc. Natl Acad. Sci. USA* 110, 16361–16366.
- Eccel, E., Cau, P., Riemann-Campe, K. and Biasioli, F., (2012)**. Quantitative hail monitoring in an alpine area: 35-year climatology and links with atmospheric variables. *International journal of climatology*, 32(4), pp.503–517.
- Fan, J., Zhang, Y., Wang, J., Jeong, J.H., Chen, X., Zhang, S., Lin, Y., Feng, Z. and Adams-Selin, R., (2022)**. Contrasting responses of hailstorms to anthropogenic climate change in different synoptic weather systems. *Earth's Future*, 10(8), p.e2022EF002768.
- Farnell, C., Rigo, T. and Heymsfield, A., (2022)**. Shape of hail and its thermodynamic characteristics related to records in Catalonia. *Atmospheric Research*, 271, p.106098.
- Feldmann, M., Rotunno, R., Germann, U. and Berne, A., (2024)**. Supercell Thunderstorms in Complex Topography—How Mountain Valleys with Lakes Can Increase Occurrence Frequency. *Monthly Weather Review*, 152(2), pp.471–489.
- Fluck, E., Kunz, M., Geissbuehler, P. and Ritz, S.P., (2021)**. Radar-based assessment of hail frequency in Europe. *Natural Hazards and Earth System Sciences*, 21(2), pp.683–701.
- Frölicher, T.L., Fischer, E.M. and Gruber, N., (2018)**. Marine heatwaves under global warming. *Nature*, 560(7718), pp.360–364.
- Gensini, V.V.A., (2021)**. Severe convective storms in a changing climate. In *Climate change and extreme events* (pp. 39–56). Elsevier.
- Ghasemifard, H., Groenemeijer, P., Battaglioli, F. and Púčik, T., (2024)**. Do changing circulation types raise the frequency of summertime thunderstorms and large hail in Europe? *Environmental Research: Climate*, 3(1), p.015008.
- Giordani, A., Kunz, M., Bedka, K.M., Punge, H.J., Paccagnella, T., Pavan, V., Cerenzia, I.M. and Di Sabatino, S., (2024)**. Characterizing hail-prone environments using convection-permitting reanalysis and overshooting top detections over south-central Europe. *Natural Hazards and Earth System Sciences*, 24(7), pp.2331–2357.
- Gualtieri, G., (2022)**. Analysing the uncertainties of reanalysis data used for wind resource assessment: A critical review. *Renewable and Sustainable Energy Reviews*, 167, p.112741.
- Hamouda, M.E., Pasquero, C. and Tziperman, E., (2021)**. Decoupling of the Arctic Oscillation and North Atlantic Oscillation in a warmer climate. *Nature Climate Change*, 11(2), pp.137–142.

- Held, I.M. and Soden, B.J., (2006).** Robust responses of the hydrological cycle to global warming. *Journal of climate*, 19(21), pp.5686-5699.
- Hermida, L., López, L., Merino, A., Berthet, C., García-Ortega, E., Sánchez, J.L. and Dessens, J., (2015).** Hailfall in southwest France: Relationship with precipitation, trends and wavelet analysis. *Atmospheric Research*, 156, pp.174-188.
- Hulton, F. and Schultz, D.M., (2024).** Climatology of large hail in Europe: characteristics of the European Severe Weather Database. *Natural Hazards and Earth System Sciences*, 24(4), pp.1079-1098.
- Hulton, F., (2023).** Hail Accumulation Layers in Europe (Master's thesis, The University of Manchester (United Kingdom)).
- Jelić, D., Telišman Prtenjak, M., Malečić, B., Belušić Vozila, A., Megyeri, O.A. and Renko, T., (2021).** A new approach for the analysis of deep convective events: Thunderstorm intensity index. *Atmosphere*, 12(7), p.908.
- Kahraman, A., Ural, D. and Öñol, B., (2020).** Future changes in Euro-Mediterranean daytime severe thunderstorm environments based on an RCP8.5 Med-CORDEX simulation. *Atmosphere*, 11(8), p.822.
- Kim, M.H., Lee, J. and Lee, S.J., (2023).** Hail: Mechanisms, Monitoring, Forecasting, Damages, Financial Compensation Systems, and Prevention. *Atmosphere*, 14(11), p.1642.
- Kopp, J., Manzato, A., Hering, A., Germann, U. and Martius, O., (2023).** How observations from automatic hail sensors in Switzerland shed light on local hailfall duration and compare with hailpads measurements. *Atmospheric Measurement Techniques Discussions*, 2023, pp.1-32.
- Krainz, T. and Hu, S., (2022).** Spatiotemporal shifts in tornadic activity of 1958–2017 in the Central United States. *Papers in Applied Geography*, 8(4), pp.468-482.
- Kunz, M., Wandel, J., Fluck, E., Baumstark, S., Mohr, S. and Schemm, S., (2020).** Ambient conditions prevailing during hail events in central Europe. *Natural Hazards and Earth System Sciences*, 20(6), pp.1867-1887.
- Li, F., Chavas, D., Medeiros, B., Reed, K. and Rasmussen, K., (2023).** Upstream surface roughness and terrain drive contrast in tornado potential between North and South America.
- Li, M., F. Zhang, Q. Zhang, J. Y. Harrington, and M. R. Kumjian (2017),** Nonlinear response of hail precipitation rate to environmental moisture content: A real case modeling study of an episodic midlatitude severe convective event, *J. Geophys. Res. Atmos.*, 122, 6729–6747, doi:10.1002/2016JD026373.

- Li, X., Zhang, Q., Zhou, L. and An, Y., (2020).** Chemical composition of a hailstone: evidence for tracking hailstone trajectory in deep convection. *Science Bulletin*, 65(16), pp.1337-1339.
- Lin, Y. and Kumjian, M.R., (2022).** Influences of CAPE on hail production in simulated supercell storms. *Journal of the Atmospheric Sciences*, 79(1), pp.179-204.
- Madonna, E., Ginsbourger, D. and Martius, O., (2018).** A Poisson regression approach to model monthly hail occurrence in Northern Switzerland using large-scale environmental variables. *Atmospheric research*, 203, pp.261-274.
- Manzato, A., Cicogna, A., Centore, M., Battistutta, P. and Trevisan, M., (2022).** Hailstone Characteristics in Northeast Italy from 29 Years of Hailpad Data. *Journal of Applied Meteorology and Climatology*, 61(11), pp.1779-1795.
- Martín, M.L., Calvo-Sancho, C., Taszarek, M., González-Alemán, J.J., Montoro-Mendoza, A., Díaz-Fernández, J., Bolgiani, P., Sastre, M. and Martín, Y., (2024).** Major role of marine heatwave and anthropogenic climate change on a Giant hail Event in Spain. *Geophysical Research Letters*, 51(6), p.e2023GL107632.
- Martius, O., Hering, A., Kunz, M., Manzato, A., Mohr, S., Nisi, L. and Trefalt, S., (2018).** Challenges and recent advances in hail research. *Bulletin of the American Meteorological Society*, 99(3), pp.ES51-ES54.
- Mir, M.A., Verma, P., Sharma, N.C., Sharma, N. and Sarma, U., (2024).** Apple (*Malus domestica* Borkh.) production and quality in response to anti-hail nets. *International journal of biometeorology*, 68(5), pp.927-938.
- Mohr, S. and Kunz, M., (2013).** Recent trends and variabilities of convective parameters relevant for hail events in Germany and Europe. *Atmospheric Research*, 123, pp.211-228.
- Mohr, S., Kunz, M. and Keuler, K., (2015).** Development and application of a logistic model to estimate the past and future hail potential in Germany. *Journal of Geophysical Research: Atmospheres*, 120(9), pp.3939-3956.
- Montopoli, M., Picciotti, E., Baldini, L., Di Fabio, S., Marzano, F.S. and Vulpiani, G., (2021).** Gazing inside a giant-hail-bearing Mediterranean supercell by dual-polarization Doppler weather radar. *Atmospheric Research*, 264, p.105852.
- Pacey, G.P., Schultz, D.M. and Garcia-Carreras, L., (2021).** Severe convective windstorms in Europe: Climatology, preconvective environments, and convective mode. *Weather and Forecasting*, 36(1), pp.237-252.
- Pastor, F., Valiente, J.A. and Khodayar, S., (2020).** A warming Mediterranean: 38 years of increasing sea surface temperature. *Remote sensing*, 12(17), p.2687.

- Pielke Jr, R. and Ritchie, J., (2021).** Distorting the view of our climate future: The misuse and abuse of climate pathways and scenarios. *Energy Research & Social Science*, 72, p.101890.
- Pilorz, W. and Łupikasza, E., (2020).** Radar reflectivity signatures and possible lead times of warnings for very large hail in Poland based on data from 2007-2015. *Environmental & Socio-economic Studies*, 8(3), pp.34-47.
- Piper, D. and Kunz, M., (2017).** Spatiotemporal variability of lightning activity in Europe and the relation to the North Atlantic Oscillation teleconnection pattern. *Natural Hazards and Earth System Sciences*, 17(8), pp.1319-1336.
- Piper, D.A., Kunz, M., Allen, J.T. and Mohr, S., (2019).** Investigation of the temporal variability of thunderstorms in central and western Europe and the relation to large scale flow and teleconnection patterns. *Quarterly Journal of the Royal Meteorological Society*, 145(725), pp.3644-3666.
- Prein, A.F. and Heymsfield, A.J., (2020).** Increased melting level height impacts surface precipitation phase and intensity. *Nature Climate Change*, 10(8), pp.771-776.
- Pucik, T. (2023).** Major hailstorms of 2022 | European Severe Storms Laboratory. [online] Essl.org. Available at: <https://www.essl.org/cms/major-hailstorms-of-2022/#:~:text=The%20year%202022%20was%20another> [Accessed 12 Aug. 2024].
- Púčik, T. (2024).** Hailstorms of 2023 | European Severe Storms Laboratory [online] Essl.org. Available at: <https://www.essl.org/cms/hailstorms-of-2023/#:~:text=24%20July%3A%20The%20true%20%E2%80%9Chail> [Accessed 12 Aug. 2024].
- Púčik, T., Castellano, C., Groenemeijer, P., Kühne, T., Rädler, A.T., Antonescu, B. and Faust, E., (2019).** Large hail incidence and its economic and societal impacts across Europe. *Monthly Weather Review*, 147(11), pp.3901-3916.
- Púčik, T., Groenemeijer, P., Rýva, D. and Kolář, M., (2015).** Proximity soundings of severe and nonsevere thunderstorms in central Europe. *Monthly Weather Review*, 143(12), pp.4805-4821.
- Punge, H.J. and Kunz, M., (2016).** Hail observations and hailstorm characteristics in Europe: A review. *Atmospheric Research*, 176, pp.159-184.
- Rädler, A. and Faust, E. (2020).** Climate change will result in more severe hailstorms in Europe: Munich re, Home. Available at: [https://www.munichre.com/en/insights/natural-disaster-and-climate-change/climate-change-and-severe-hailstorms-in-europe.html#:~:text=There%20will%20be%20a%20significant,Severe%20Storms%20Laboratory%20\(ESSL\).](https://www.munichre.com/en/insights/natural-disaster-and-climate-change/climate-change-and-severe-hailstorms-in-europe.html#:~:text=There%20will%20be%20a%20significant,Severe%20Storms%20Laboratory%20(ESSL).) (Accessed: 29 July 2024).

- Rädler, A.T., Groenemeijer, P., Faust, E. and Sausen, R., (2018).** Detecting severe weather trends using an additive regressive convective hazard model (AR-CHaMo). *Journal of Applied Meteorology and Climatology*, 57(3), pp.569-587.
- Rädler, A.T., Groenemeijer, P.H., Faust, E., Sausen, R. and Púčik, T., (2019).** Frequency of severe thunderstorms across Europe expected to increase in the 21st century due to rising instability. *npj Climate and Atmospheric Science*, 2(1), p.30.
- Raupach, T.H., Martius, O., Allen, J.T., Kunz, M., Lasher-Trapp, S., Mohr, S., Rasmussen, K.L., Trapp, R.J. and Zhang, Q., (2021).** The effects of climate change on hailstorms. *Nature reviews earth & environment*, 2(3), pp.213-226.
- Ricchi, A., Sangelantoni, L., Redaelli, G., Mazzarella, V., Montopoli, M., Miglietta, M.M., Tiesi, A., Mazzà, S., Rotunno, R. and Ferretti, R., (2023).** Impact of the SST and topography on the development of a large-hail storm event, on the Adriatic Sea. *Atmospheric Research*, 296, p.107078.
- Rigo, T. and Farnell, C., (2024).** A Comparison between Radar Variables and Hail Pads for a Twenty-Year Period. *Climate*, 12(10), p.158.
- Sanchez, J.L., Merino, A., Melcón, P., García-Ortega, E., Fernández-González, S., Berthet, C. and Dessens, J., (2017).** Are meteorological conditions favoring hail precipitation change in Southern Europe? Analysis of the period 1948–2015. *Atmospheric Research*, 198, pp.1-10.
- Sanderson, M.G., Hand, W.H., Groenemeijer, P., Boorman, P.M., Webb, J.D.C. and McColl, L.J., (2015).** Projected changes in hailstorms during the 21st century over the UK. *International Journal of Climatology*, 35(1).
- Schemm, S., Nisi, L., Martinov, A., Leuenberger, D. and Martius, O., (2016).** On the link between cold fronts and hail in Switzerland. *Atmospheric science letters*, 17(5), pp.315-325.
- Schumacher, R.S. and Rasmussen, K.L., (2020).** The formation, character and changing nature of mesoscale convective systems. *Nature Reviews Earth & Environment*, 1(6), pp.300-314.
- Soderholm, J.S. and Kumjian, M.R., (2023).** Automating the analysis of hailstone layers. *Atmospheric Measurement Techniques*, 16(3), pp.695-706.
- Stormwise (2024)** Climate change and hail. Available at: <https://stormwise.co.uk/climate-change-and-hail> (Accessed: 29 July 2024).
- Taszarek, M., Allen, J.T., Brooks, H.E., Pilguy, N. and Czernecki, B., (2021).** Differing trends in United States and European severe thunderstorm environments in a warming climate. *Bulletin of the American Meteorological society*, 102(2), pp.E296-E322.

Tippett, M.K., Allen, J.T., Gensini, V.A. and Brooks, H.E., (2015). Climate and hazardous convective weather. *Current Climate Change Reports*, 1, pp.60-73.

Torralba, V., Hénin, R., Cantelli, A., Scoccimarro, E., Materia, S., Manzato, A. and Gualdi, S., (2023). Modelling hail hazard over Italy with ERA5 large-scale variables. *Weather and Climate Extremes*, 39, p.100535.

Twardosz, R., Walanus, A. and Guzik, I., (2021). Warming in Europe: recent trends in annual and seasonal temperatures. *Pure and Applied Geophysics*, 178(10), pp.4021-4032.

United States Department of Agriculture (2017). Greece and Italy, Usda.gov. Available at: <https://ipad.fas.usda.gov/highlights/2017/08/greeceitaly/index.htm> (Accessed: 9 September 2024).

Appendix

List of Countries included in the WMO Region VI: Europe

Albania	Latvia
Andorra	Lebanon
Armenia	Lithuania
Austria	Luxembourg
Azerbaijan	Malta
Belarus	Monaco
Belgium	Montenegro
Bosnia and Herzegovina	Netherlands
Bulgaria	North Macedonia
Croatia	Norway
Cyprus	Poland
Czech Republic	Portugal
Denmark	Romania
Estonia	Republic of Moldova
Finland	Russian Federation
France	Serbia
Georgia	Slovakia
Germany	Slovenia
Greece	Spain
Hungary	Sweden
Iceland	Switzerland
Ireland	Syrian Arab Republic
Israel	Turkey
Italy	Ukraine
Jordan	United Kingdom of Great Britain and Northern Ireland
Kazakhstan	

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