Brief Communication: ~~Investigating trends in European hailstorm damage using CMIP6-DAMIP climate models~~Drivers of the recent warming of the Mediterranean Sea, and its implications for hail risk

Stephen Cusack[1], Tyler Cox[2]

[1]Stormwise Ltd, Luton, LU4 9DU, United Kingdom
[2]Inigo Limited, London, EC3A 5AY, United Kingdom

Correspondence to: Stephen Cusack ~~(stephen.cusack@stormwise.co.uk)~~(stephen.cusack@stormwise.co.uk)

Abstract

~~Warming seas around Europe have been driving recent upward trends in hailstorm severity. Therefore, learning more about changes to sea temperatures can give insights into hail climate too. Here, we use~~The Mediterranean Sea has warmed by about 2 K since the early 1980s, and past research has established how this heating intensifies moisture-driven perils such as hailstorms and floods in continental Europe. This study uses the DAMIP (Detection and Attribution Model Intercomparison Project) set of climate model experiments to ~~explore how external forcings have modified Mediterranean temperatures. Climate models indicate external forcings caused most~~identify the drivers of the ~~multidecadal changes in modern times, with~~ recent Mediterranean warming. The models simulate the observed multidecadal variations of Mediterranean Sea temperatures in the modern industrial period accurately, and indicate anthropogenic ~~aerosols explaining the cool~~aerosol forcing was largely responsible for the cooler period from about 1900 to the late 1970s, ~~and~~while rising greenhouse ~~gas increases mainly responsible for~~gases are the ~~rapid 0.5 K/decade~~ main cause of warming ~~of the Mediterranean~~waters since then. ~~Current trends in anthropogenic forcing are expected to continue warming seas which suggests European~~Next, we reviewed the quantitative impact of this heating on hailstorm risk~~.~~, and found hail damages in higher-risk countries have been increasing by around 2% per year since 1980. The rising risk fits with the established mechanism whereby warmer waters moisten low-level air and intensify thunderstorms. Anthropogenic forcings will ~~keep rising.~~ continue warming the Mediterranean for the next couple of decades at least, indicating further increases to hail damages in central and southern Europe.

1 Introduction

~~Europe has experienced unusually large hailstorm losses in recent times. Thunderstorms in 2023 caused over five billion euros of insured loss, mostly in Italy (Swiss Re, 2024) which is all the more remarkable given very low insurance uptakes (e.g. Fitch Ratings article at https://www.fitchratings.com/research/insurance/european-insurers-more-exposed-to-weather-losses-as-reinsurers-retreat-17-11-2023). In 2022, French property and automobiles suffered five billion euros of loss due to hail (France~~

Assureurs, 2023). A series of thunderstorms in June 2021 caused 4.5 billion USD of losses spread across a few countries (Swiss Re, 2021), though their effects may have been much greater by saturating soils prior to the immense damages from the storm Bernd flood in July 2021. In 2013 and 2014, hailstorms Andreas and Ela caused multi-billion euro losses, mainly to Germany and France respectively (Swiss Re, 2014 and 2015). This frequency of severe annual losses is in sharp contrast to the preceding 30 years with just one loss of a similar magnitude, namely the Munich hailstorm in 1984 (e.g. Climate impacts from anthropogenic forcings have regional variations, caused by factors such as dynamical feedbacks and spatial inhomogeneities of some drivers such as aerosols (e.g. Seneviratne et al., 2021). The Mediterranean region has been a notable climate hotspot over the past few decades (e.g. MedECC, 2020; Ali et al., 2022). For example, sea surface temperatures warmed by 0.41 K/decade over the 1982-2023 period according to the Copernicus Marine Service (Roquet et al., 2016; Mulet et al., 2018) which is almost double the rate of the global oceans. Further, its warming is projected to continue outpacing the global mean in the future (e.g. Lionello and Scarascia, 2018).

One of the main effects of a warming sea is the humidification of the lower levels of the atmosphere. The warming sea surface is accompanied by similar increases in temperature of the overlying air, increasing its water-holding capacity, and as a result more water is evaporated into the atmosphere. In general, greater amounts of low-level water vapour in the atmosphere act to raise the severity of weather perils such as heavy precipitation events (reviewed in Seneviratne et al., 2021) and large hail (e.g. Raupach et al., 2021; Chen and Dai, 2023). More specifically to central and southern Europe, moisture amounts from the Mediterranean Sea have been a key ingredient in many of the most damaging floods (e.g. James et al., 2004; Volosciuk et al., 2016; Krug et al., 2022; Tradowsky et al., 2023) and hailstorms ((e.g. Heimann and Kurz, 1985; Kunz et al., 2018; Piper et al., 2019; Kunz et al., 2020; Kopp et al., 2023) in recent decades.

Given how research has established low-level Mediterranean air masses as an important component of past major weather disasters, and that these air masses are moistening due to sea surface warming, it would be prudent to learn more about the Mediterranean Sea warming trend, and its consequences on severe weather risk. The main aim of this study is to use modelling results from thePucik et al., 2019). Looking further back, there is no evidence of multi-billion hailstorm losses for a couple of decades prior to 1980, either from higher-quality loss records (e.g. VKG, 2022), or more anecdotally.

A variety of evidence indicates the recent spate of severe losses was part of an upward trend in hail risk over the past few decades. Raupach et al. (2021, hereafter R21) reviewed past hail trends, and found mixed results depending on the quantity (thunderstorms, any hail, or larger hail) and the geographic region being studied. However, if we confine our attention to studies of annual hail damage in the European area using longer datasets, then they tend to agree on a rising risk in recent decades, as now summarised.

R21 describe how large groups of long hailpad records are a highly valued source of ground-truth hail in Europe, and two major studies show signs of rising trends. Berthet et al. (2011) studied 457 hailpad stations in south and southwest France covering the period 1989-2009 and found annual hail kinetic energy growing by almost +3% p.a. over the period, while Eccel et al. (2012) analysed records from around 250 hailpad stations in the central-eastern Alpine area of Italy spanning 1975 to 2009, and reported an increase of about 1.5% p.a. in the mean kinetic energy of events. Positive trends in annual aggregate hail damage from earlier to later in the 20th century were documented in various early studies: tree-ring data from 1939 to 1996 in Switzerland (Hohl et al., 2002), crop insurance from 1920 to 1993 also in Switzerland (Willemse, 1995), and crop-hail insurance data in France from 1946 to 1992 (Dessens, 1995). A significant upturn in activity from about 1980 seems to be a main factor in these trends, as highlighted by Dessens (1995). More recently, Kunz et al. (2009) analysed insured losses to buildings in southwest Germany over the period 1986-2004 and found positive trends exceeding 5% p.a. in total hail losses, which was supported by significant increases in annual number of days with claims. More recently, some studies have examined how the hail-relevant environmental conditions evolved over the past few decades, and find that the basic atmospheric ingredients for large hail have become increasingly common since the 1970s (e.g. Mohr and Kunz, 2013; Radler et al., 2018; Taszarek et al., 2021). The hail model developed by Radler et al. (2018) indicated the annual amount of hail ≥ 2 cm increased at around 2.4% p.a. over 1979-2015 in a region covering Germany and the Alps, and up by 1.4% p.a. over the greater area of western and central Europe.

More evidence of rising trends in European hail have been uncovered since the review by R21. Battaglioli et al. (2023) described a model which had been calibrated to observed lightning and large hail reports, and indicated increasing trends of large hail throughout most of the western and central European mainland. They highlighted how hail ≥ 5 cm is now three times more likely than in the 1950s in northern Italy. Research within the insurance industry (Stormwise Ltd., at https://stormwise.co.uk/climate-change-and-hail and Partner Re, at https://www.partnerre.com/perspectives/the-contribution-of-climate-change-to-europes-increasing-hail-losses/), using models similar to those of Radler et al. (2018) and Battaglioli et al. (2023), find increases in annual hail risk of 1 to 1.5% p.a. over much of mainland Europe.

Insurance losses are also a valuable source of information on damaging hail in Europe. Insurance associations often monitor losses to their national market, and some records now extend to a few decades. The German Insurance Association (GDV) issue annual losses for combined wind and hail perils, all indexed to 2023 inventory and prices (available at https://www.gdv.de/gdv/statistik/datenservice-zum-naturgefahrenreport). Figure 1a shows the annual losses in the 1973-2023 period for automobiles, the vast majority of which are due to hail, and an annual growth rate of 3.1% is found over the past 50 years, or 2.2% p.a. since 1980. Figure 1b presents annual hail losses to all insured buildings in France, using data from France Assureurs (2023), with an indexation to 2023 values using the standard FFB Index (at https://www.outils.ffbatiment.fr/federation-francaise-du-batiment/le-batiment-et-vous/en_chiffres/indices-index/Chiffres_Index_FFB_Construction.html). The best-fitting annual growth rate of +6.0% p.a. in hail losses from 1990 to 2022 drops to +4.8% p.a. when excluding the final year with its huge hail losses. Figure 1c shows annual hail loss costs in Switzerland for the 1980 to 2023 period for all buildings in the 19 Swiss cantons covered by public insurance. In Fig. 1c, historical data are transcribed from Fig. 15 in VKG (2022), with more recent data from https://cms.vkg.ch/media/tutg0vgg/elementarschaeden-an-gebaeuden-2004-2023_de.pdf. The best-fitting annual growth rate of loss is 2.8% p.a. over the past 44 years.

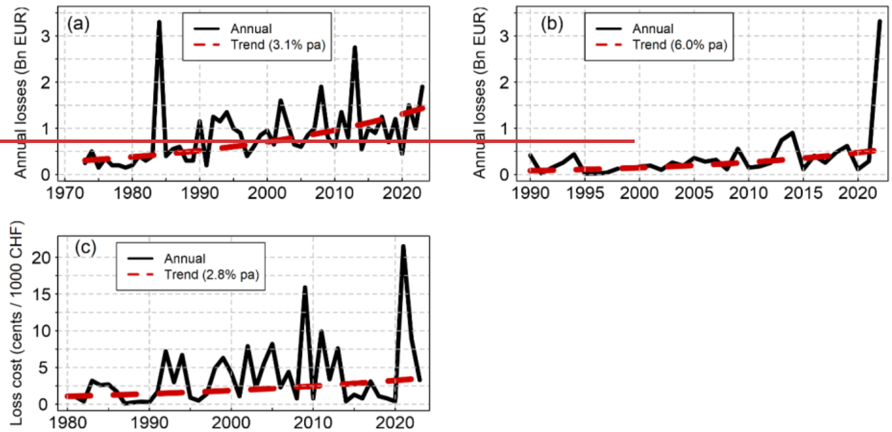


Figure 1: timeseries of insured hail damages for (a) automobiles in Germany, (b) buildings in France, and (c) buildings in Switzerland.

In general, national insurance losses trending upward at 2 to 5% per year over the past few decades. This is faster than the 1 to 2% range suggested by hazard-based studies. Both methods contain uncertainties: repair costs may be inflating faster than industry estimates, while those hazard methods trained to point occurrences of hail may not fully capture slow trends. Future investigation of the errors in both methods would help reduce uncertainty in how fast hail damage is increasing.

The causes of the rising hail risk in Europe have been investigated too. Dessens (1995) described a strong relation between annual hail loss in France and summertime minimum temperatures, which suggested rising wet-bulb temperatures in a warming climate were responsible for increasing hail risk. Berthet et al. (2011) found rising trends in hail kinetic energy from their hailpad network were mainly associated with nighttime warming, and dominated by trends in April and May. Kunz et al. (2009) found the growing hail risk over southwest Germany was accompanied by rising wet-bulb temperatures, while more accurate measures of convective instability such as CAPE were also increasing. Mohr and Kunz (2013) analysed CAPE values based on radiosonde observations in 1978-2009 and reported significant upward trends in CAPE throughout most of Europe. Further, they identified a positive trend in low-level moisture as the main driver of intensifying CAPE and thunderstorms over Europe. More recent research using modern weather reanalyses calibrated to improved datasets of hail reports (e.g. Radler et al., 2018; Taszarek et al., 2021; Battaglioli et al., 2023) also implicate the humidification of low-level air in the rising trends of large hail.

Past research points to a warming climate causing more damaging hail in Europe. The key area is the Mediterranean Sea (the Med), because it is the main source of the high dewpoints which produce damaging hail (e.g. Kunz et al., 2020). Therefore,

~~more knowledge of temperature anomalies in the Med can provide insights into hail trends too. This article explores drivers of past Med warming using climate models. The~~ DAMIP (Detection and Attribution Model Intercomparison Project; Gillett et al., 2016) sub-project of CMIP6 ~~was created to estimate how various external forcings, both natural and anthropogenic, force the climate system. DAMIP results from a set of climate models will be analysed to find how Med temperatures~~for information on how sea surface temperatures in the Mediterranean respond to different forcings of the climate system. Section 2 contains a description of the data and ~~its processing, followed by the main results from DAMIP in Section 3. A discussion and summary are presented in Section 4~~processing used in this study, followed by an analysis in Section 3 which identifies the key drivers of Mediterranean heat changes over the industrial period based on DAMIP results. A secondary aim was to quantify the link from Mediterranean Sea warming to its impacts on hailstorm risk in Europe, using hazard and insurance loss information from recent decades. This investigation is presented in Section 4. A summary of the main findings is presented in Section 5.

2 Data and methods

~~The~~2.1 Mediterranean temperatures

This study uses data from the DAMIP sub-project, which is one of 23 sub-projects that formed part of the sixth version of the Coupled Model Intercomparison Project (CMIP6; Eyring et al., 2016~~)~~). DAMIP was ~~a huge effort by the global climate community to understand and quantify climate change both in the past and future. CMIP6 contains 23 independent sub-projects targeting specific questions covering a wide range of climate topics. In particular, the DAMIP sub-project (Gillett et al., 2016) was created~~designed to investigate the impacts of various external forcings on global and regional climate. ~~In the main, its tests~~Its experiments explore the modern industrial period from 1850 to 2014, and its Tier 1 model simulations ~~set~~consist of setting one type of forcing to suitable values for the historical period, with all others fixed at pre-industrial values. Initial conditions are taken from pre-industrial control runs (from the main CMIP6 model experiments), and Tier 1 historical forcings are split into three distinct types: natural forcings (solar and volcanic, hereafter Nat), greenhouse gases (GHG), and anthropogenic aerosols (Aero). ~~This study used climate models~~We analyse results from six different modelling centres providing monthly-mean near-surface temperature diagnostics~~,~~ (variable ‘tas’) for at least five different ensemble members, for all three forcing tests. In addition, the Historical experiments with all forcings (Hist) performed as part of the central CMIP project are also analysed. Table 1 summarises the simulations analysed in this study. More information on the climate models is provided in CMIP (2025).

Table 1: summary details of the DAMIP climate model simulations.

Formatted: Space After: 6 pt

the CMIP webpage: https://wcrp-cmip.org/cmip-model-and-experiment-documentation/.

Model	**Reference ID in text**	**No. of ensemble members**	**Release year**	**Atmosphere resolution (km)**	**Ocean resolution (km)**
CNRM-CM6-1	1	10	2017	250	100
CanESM5	2	15	2019	500	100
GISS-E2-1-G	3	5	2019	250	100
HadGEM3-GC31-LL	4	15	2016	250	100
MIROC6	5	10	2017	250	100
MPI-ESM1-2-LR	6	15	2017	250	250

Observed sea surface temperatures are taken from the Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST; Rayner et al., 2003), a global dataset of monthly sea surface temperature values at 1° x 1° resolution from January 1870 and continually updated to the present day.

Table 1: summary details of the DAMIP climate model simulations.

Model	**Reference ID in text**	**No. of ensemble members per 1850-2014 forcing test**
CNRM-CM6-1	1	10
CanESM5	2	15
GISS-E2-1-G	3	5
HadGEM3-GC31-LL	4	15
MIROC6	5	10
MPI-ESM1-2-LR	6	15

Both observed and modelled data are processed similarly. Monthly mean values are initially area-averaged over the northern halfa region of the Mediterranean Sea (referred to as the northern Med, seeshown in Figure 2),1, then combined to form an extended summertimesummer half-year average (May-SeptemberOctober) corresponding to the annual peak of Mediterranean influence on flood and hail risk, and ensuringin order to focus on the most relevant seasonal warming trends are used (García-Monteiro et al., 2022). Observed and model values Anomalies were converted into anomaliesdefined using the climate from the common baseline period of 1870-2014. Anomalies for all model forcing simulations were computed with respect to the climatology for observed and modelled values. The climate of the Hist experiment oversimulations in this common 1870-2014 period. has been used to define all model anomalies, for consistency with how observed anomalies are defined. Finally, a second-order low-pass Butterworth filter (Butterworth, 1930) with a 5-year cutoff was applied to all timeseries to reduce large

Formatted: Space After: 6 pt

amounts of interannual noise obscuring longer-term trends. The 5-year cutoff was chosen to retain potential signals from Nat forcings such as 11-year solar cycles and major volcanoes, as well as the slower changes from GHG and Aero.

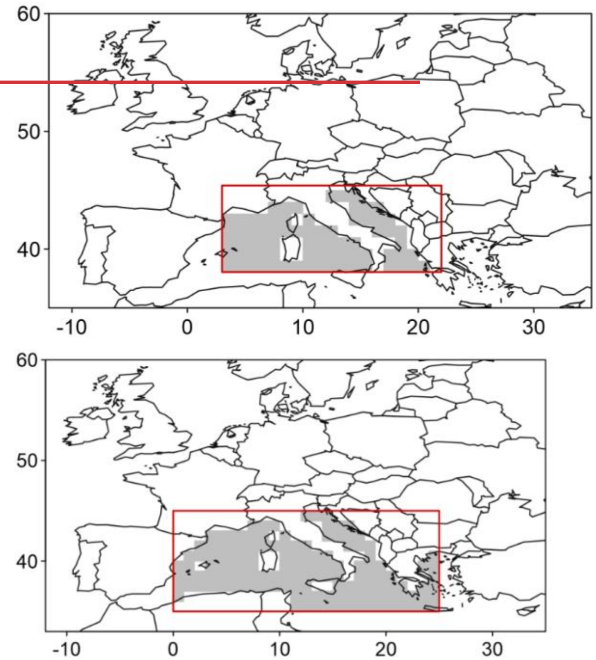


Figure ~~2: the region~~ 1: map of a part of Europe, with shaded area denoting the Mediterranean Sea region used in the analysis.

2.2 European hail losses

National insurance associations often monitor losses to their market, and some of their records extend to the past few decades. Three publicly available historical records of hail losses are explored in Section 4 for guidance on trends in the risk from this weather peril. These data are now described.

The German Insurance Association (GDV) issue annual losses indexed to 2023 inventory and prices using data on numbers of insured vehicles, and the cost of automobile parts and repair from the Federal Statistical Office of Germany (GDV, 2024).

The second dataset comprises annual hail losses to all insured buildings in France, based on information from France Assureurs (2023). Their annual data consists of the ratio of all insured risks making a hail claim (a frequency ratio) and the average hail claim size indexed to 2022 values using the standard FFB Index, which is based on costs for various elements of a standard apartment in Paris and specifically designed to index insurance policies (FFB, 2025). We have computed total industry losses by multiplying these two quantities together, then scaling them by the total number of industry risks (N). The total industry loss in 2022 was used to define N, then we apply this value of N to all other years to obtain annual industry losses for all years based on the number of risks in 2022. This approach ensures indexation captures both the growth in claim severity, and how claim numbers increase with changes in number of insured risks.

The third national loss dataset contains annual hail loss costs in Switzerland for the 1980 to 2023 period for all buildings in the 19 Swiss cantons covered by public insurance, from VKG (2022, 2024). The loss cost is defined as the ratio of the total cost of repair to the total exposure value. It is a useful loss metric in insurance, because total exposure value in the denominator is usually defined to reflect the same growths in insurance claim size and number which are present in the numerator, hence socio-economic trends are absent from the ratio: loss costs are indexed (aka normalised) by design.

Trends in losses over the past few decades are derived from a regression of log(loss quantity) with year, providing best-fit estimates of the growth in units of % per year.

3 Results

3.1 Past changes in Mediterranean SST

Figure 2 displays timeseries of SST anomalies in both the global (60°S to 60°N) and Mediterranean regions for summer half-years in 1940 to 2024. The Mediterranean region cooled from roughly 1950 to 1980, then warmed rapidly since then. Changes in the global mean have been more muted, with anomalies near zero from 1940 to the mid-1970s, and a more gradual warming since then. Figure 2 also contains the best-fitting linear trend for SST in these two areas from 1980 to 2024, and it was found that average SSTs over each area have been warming at rates which are significantly different from zero at the 1% level (p-values are below 1e-10 in both cases). However, the most notable feature is the summertime Mediterranean SSTs trending upward at more than three times the global-mean warming rate since 1980. The Mediterranean Sea has been an oceanic hotspot over the past four decades.

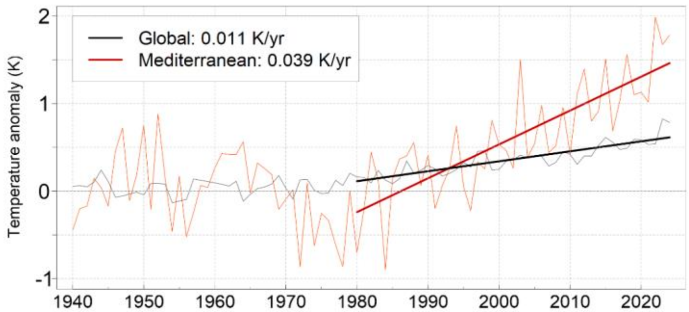


Figure 2: timeseries of global (black) and Mediterranean (red) SST anomalies in the summer half-year (May to October), with associated best-fitting linear trends in the 1980-2024 period. Data are from HadISST, anomalies are computed with respect to the 1870 to 2014 period, and global data are from 60°S to 60°N.

3.2 Drivers of past changes in DAMIP experiments

The causes of the more rapid warming of the Mediterranean Sea are now explored using DAMIP modelling results. Figure 3a shows the timeseries of ~~northern Med~~Mediterranean temperature anomalies over the extended historical period for observed and multi-model ensemble means for the Historical and three ~~distinct~~ DAMIP single-forcing experiments.

~~The most notable feature in HadISST observations (solid black) is the recent sharp upward trend from a near-minimum coolness in the late 1970s to a maximum in the present day which greatly exceeds earlier temperatures. Prior to this rapid warming, the timeseries contains a multidecadal variation, with minima around 1910 and the late 1970s, and a local maximum from about 1930 to the early 1960s.~~

The multi-model ensemble mean signal from all forcings (Hist – solid red line) is similar to observed values (solid black line) over the whole period. Specifically, the modelled rate of Mediterranean warming ~~in the northern Med~~ since the 1970s closely follows HadISST data, and the earlier multidecadal oscillation in observations, consisting of minima around 1910 and the late 1970s, and a local maximum from about 1930 to the early 1960s, is replicated in Hist, albeit with reduced amplitude. Control simulations with forcings fixed at preindustrial levels (part of the main CMIP6 protocol) have an interannual standard deviation ~~(□)~~(σ) of 0.38 K, hence a 70-member mean ~~has □=~~is expected to have σ=0.046 K~~, and~~ (from the Central Limit Theorem), therefore the simulated multidecadal oscillation in Hist with amplitude of 0.5 K is ~~significant. Therefore, the 20th century~~ very unlikely to be caused solely by internal climate variability. Research in nearby regions also find a role for external forcing in the multidecadal cycle ~~in northern Med warmth is a feature caused in some part by external forcing, according to climate models. Research by~~ over the first seven decades of the 20th century, such as Booth et al. (2012) in the broader North Atlantic, and Aizawa et al. (2022) in the Arctic~~, also concluded that external forcing contributed substantially to pronounced~~

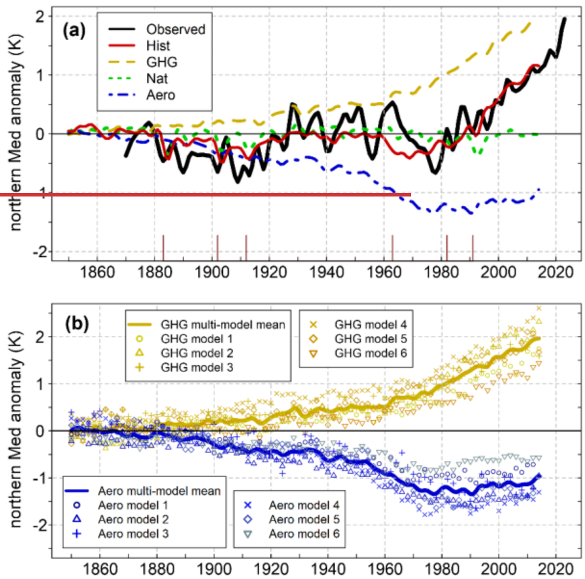
multidecadal variations in near-surface heat in their study areas in the 20th century. We note how the sum of responses to individual forcings are consistent with Hist signals, suggesting Med warmth has a mostly linear response to forcings. .

Having established the validity of CMIP6 climate models to simulate temperature anomalies in the northern MedMediterranean, we now discuss the contribution of individual forcings to the total signal.

Nat forcing (green dotted line in Figure 3a) of northern Med temperatures is near-zero over the long-term. However, volcanic eruptions exert influence on northern Med anomalies at timescales shorter than about 10 years in DAMIP simulations. Six of the largest climate-changing eruptions in the simulation period are indicated as long red tick-marks on the x-axis (Krakatoa 1883; Santa Maria 1902; Novarupta 1912; Mount Agung 1963; El Chichon 1982; Pinatubo 1991), and their occurrences coincide with anomalies of up to -0.5 K for a few years. This size of perturbation is smaller than the recent GHG and Aero forcings, and of much shorter duration, hence Nat forcing is a minor consideration in the modern industrial period, according to DAMIP results.

GHG (gold dashed) acts to warm the northern Med throughout the period. The magnitude of its forcing was small up to around 1920, then it has grown continuously since then. DAMIP models indicate GHG has caused almost 2 K of warming by the end of simulations in 2014. This large forcing has overwhelmed the Med in recent times, leading to GHG being the main cause (almost three-quarters) of the total modelled warming from 1975 to 2014.

The northern Med cools in response to Aero forcing (blue dash-dotted line in Figure 3a). This driver dominated total climate forcing up to 1920, and outweighed GHG forcing for much of the 20th century. Its peak impact on the Med was reached in the late 1970s, then stabilised for a short time before reducing in magnitude from about 1990 onwards, in line with aerosol emissions (e.g. Lund et al., 2019). The net warming from 1990 to 2014 due to lowered aerosol burdens caused about one-quarter of the total modelled warming in this recent period. Given the coupling between northern Med temperatures and thunderstorm severity, these results suggest Aero forcing led to significant reductions in hail damage during most of the 20th century, while the recent trend to cleaner, healthier air has raised hail risk. Anthropogenic aerosols have been found to drive substantial multidecadal changes in the climate of other perils, such as tropical cyclones (Murakami, 2022), and the profound multidecadal peak in European windstorm damages in the late 20th century (Cusack, 2024).


(a)
Observed
Hist
GHG
Nat
Aero
northern Med anomaly (K)
2
1
0
-1
-2
1860
1880
1900
1920
1940
1960
1980
2000
2020
(b)
GHG multi-model mean
GHG model 1
GHG model 2
GHG model 3
GHG model 4
GHG model 5
GHG model 6
Aero multi-model mean
Aero model 1
Aero model 2
Aero model 3
Aero model 4
Aero model 5
Aero model 6
northern Med anomaly (K)

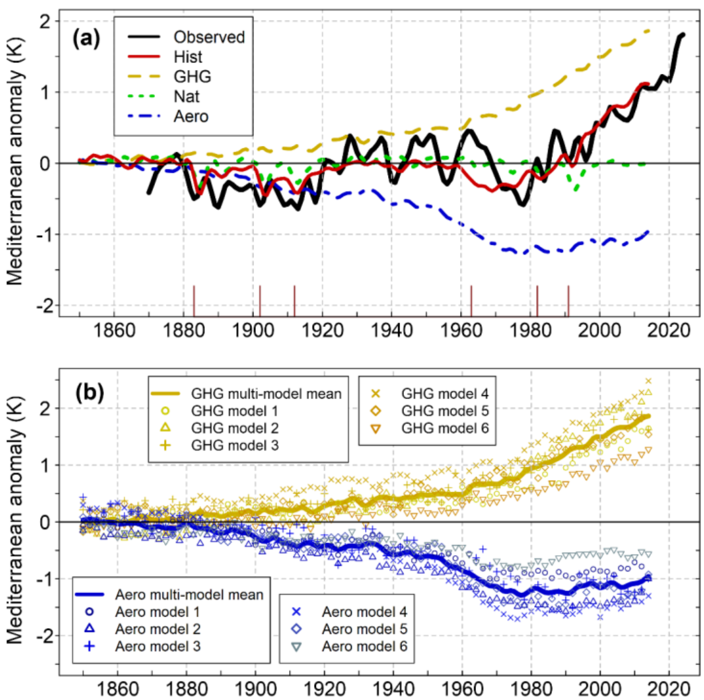


Figure 3: timeseries of ~~northern Med~~Mediterranean temperature anomalies. (a) observed (solid black line) and multi-model mean anomalies for the various forcing experiments, with major volcanic eruptions indicated by the long ~~ticks~~red tick marks on the time axis. (b) DAMIP multi-model mean (solid lines), and the mean of each of the six models (various symbols), for the Aero (blue) and GHG (gold) experiments.

The impact of Nat forcing (green dotted line in Figure 3a) on Mediterranean temperatures is simulated to be near-zero over the long-term. However, volcanic eruptions exert influence on temperature anomalies at timescales shorter than about 10 years in DAMIP simulations. Six of the largest climate-changing eruptions in the simulation period are indicated as long red tick-marks on the x-axis (Krakatoa 1883; Santa Maria 1902; Novarupta 1912; Mount Agung 1963; El Chichon 1982; Pinatubo 1991), and are associated with anomalies of up to -0.5 K for a few years following the eruption. Such a size of perturbation is smaller than the recent GHG and Aero forcings, and of much shorter duration, hence DAMIP model results indicate Nat forcing is a minor consideration in the modern industrial period.

GHG (gold dashed line) acts to warm the Mediterranean throughout the period. The magnitude of its forcing was small up to around 1920, and has grown continuously since then. DAMIP models indicate GHG had caused almost 2 K of warming by the end of the simulations in 2014, and caused almost three-quarters of the total modelled warming from 1975 to 2014.

The Mediterranean cooled in response to Aero forcing (blue dash-dotted line in Figure 3a). This forcing dominated total climate forcing up to 1920, and outweighed GHG forcing for much of the 20th century. Its peak impact on the Mediterranean was reached in the late 1970s, then stabilised for a short time before reducing in magnitude from about 1990 onwards, in line with aerosol emissions (e.g. Lund et al., 2019). DAMIP models suggest slow variations in the warmth of the northern Med during the modern industrial period was largely governed by the strengths of GHG and Aero forcings. In earlier times, aerosol cooling effects were dominant, and the northern Med dipped to a nadir in the late 1970s, then GHG forcing grew to become dominant and warm the Med, along with declining aerosol burdens adding a little to this warming. We can be quite sure that recent trends will persist into the near future (at least), with continued rises in GHG forcing, together with more clean-air policies implemented around the world. A continuation of the warming trend in the Med corresponds to further increases in European hail damage.

The net warming from 1990 to 2014 due to reduced aerosol burdens caused almost one-quarter of the total modelled warming in this recent period.

Finally, we note how the sum of responses to individual forcings are consistent with Hist signals (not shown), suggesting Mediterranean warming is largely explained as a linear response to external forcings. Confidence in these DAMIP signals was also assessed using the inter-model spread. Figure 3b contains mean signals for each of the six climate models, for the two main forcings of GHG and Aero. All six models agree on the respective sign of the two forcings, and signal amplitudes are similar too. We conclude that GHG and Aero forcings of northern MedMediterranean temperatures are a robust feature of DAMIP models and that these two forcings are the primary drivers of recent Mediterranean Warming.

4 Conclusions

Evidence clearly points to a rising trend in the European hail climate over the past few decades, from hailpad observations, insured losses, and raw weather ingredients for large hail. Here, we presented new evidence of increasing hail damage in Europe, based on national insurance association surveys of building and automobile losses over the past few decades, and indexed to the present day. The largest remaining uncertainty concerns how positive this upward trend in hail damage has been in western and central Europe over the past few decades. Most of the hazard-based estimates are around 1 to 2% per year, whereas loss-based estimates contain steeper rises from about 2% to 5% per year.

Warming of the European area over the past few decades has driven the upward trend in hail risk. Rising temperatures of local seas humidify the low-level air, which intensifies thunderstorms leading to more severe hail. Therefore, knowing more about sea temperature variations would inform on the hail climate too. We found how climate models participating in the set of CMIP6-DAMIP experiments replicate most of the variations in observed northern

4 Trends in hail risk

In this section, we review past research showing a link between the Mediterranean Sea and damaging hail events in the higher risk parts of Europe, and how rising low-level moisture amounts are implicated in increasing trends of hail in these areas, thus connecting the warming Mediterranean to rising hail risk. Next, we provide quantitative estimates of trends in damaging hail, based on both published results and a new analysis of hail losses provided by national insurance bodies, to quantify how the warming Mediterranean may be impacting this peril.

It is difficult to quantify the fraction of all hail damage across the continent which involves a Mediterranean moisture source, since hail damage records are spatially and temporally incomplete. However, past research has linked many of the most damaging events in Europe to low-level Mediterranean air masses (e.g. Heimann and Kurz, 1985; Kunz et al., 2018; Piper et al., 2019; Kunz et al., 2020; Kopp et al., 2023). Meanwhile, Kunz et al. (2020) performed a more comprehensive analysis of hailstorms in their study area (Germany, France, Belgium, Luxembourg) and noted that the typical case involves a trough drawing moist Mediterranean air northwards over Europe on its eastern flank, while the increased shear and lifting processes from the trough produce conditions conducive for organised thunderstorm development. Other sources of low-level moisture may also cause damaging hail in some parts of Europe, such as the Cantabrian Sea (e.g. de Pablo Dávila et al., 2021) and the Black Sea (e.g. Piper et al., 2019), but it is clear that the warmest body of water in the region, the Mediterranean Sea, is the main source of the high dewpoints in the damaging hail events in the higher risk, central and southern parts of Europe.

A number of studies identify increases in low-level moisture as being the main cause of rising hailstorm risk across Europe over the past few decades. Low-level moistening increases the severity of hail in two ways. First, moisture drives convective instability hence greater amounts of water vapour will tend to intensify thunderstorms and produce more severe hail (e.g. Kunz et al. 2009; Mohr and Kunz, 2013; Púčik et al., 2017; Taszarek et al., 2021; Wilhelm et al., 2024). Second, Schemm et al. (2017) found more frequent strong fronts over the bulk of Europe from 1979 to 2014 due to rising humidity, and Kunz et al. (2020) described how hail associated with fronts were more damaging, due to larger hailstones and longer hail swathes. Severe hail occurrence depends on other quantities such as deep layer shear, steep mid-level lapse rates and the low-level cap, and Taszarek et al. (2021) show these ingredients have quite steady, or even slightly inhibiting recently, implying low-level moisture amounts are the dominant driver of upward trends in hail risk over the past few decades.

The full picture of trends in hail risk at all European locations will require consideration of other moisture source such as the Black Sea, and other environmental ingredients such as the warmer, drier air that inhibits convective initiation, and future research into their contributions would be valuable. At the present time, it is clear that a warming Mediterranean is a primary contributor to the trends in hail risk in key parts of Europe. We now seek to quantify the trend in hail risk in the higher-risk areas, for guidance on the impacts of the warming Mediterranean on this peril.

Measurements of recent trends in hail damage fall into two broad types: those reflecting hailstone occurrence, and those based on observed hail damages. The former type has the benefit of more homogeneous hazard data over time, but are often based on models of hail occurrence at a location given the atmosphere conditions, with uncertainty as to whether the models accurately capture the relative roles of all hailstorm ingredients over the past few decades. In contrast, evaluations based on damages reflect hail occurrence at the ground, however, there is some uncertainty in estimated losses at the time of older events, and in how the losses are indexed to represent the total damages if the events occurred in the present day. Given these uncertainties, we will consider estimates of trends from both methods.

Hazard-based studies generally find that large hail has become increasingly common across most of Europe since the 1970s. For instance, extensive hailpad networks indicate a trend toward more intense hail in both southern France over the 1989-2009 period (Berthet et al., 2011), and the central-eastern Alpine area of Italy over the 1975-2009 period (Eccel et al., 2012). A second type of hazard-based study provides more spatially complete and longer hail reconstructions, based on weather ingredients from reanalyses and calibrated to observations such as damaging hail on the ground (e.g. Mohr and Kunz, 2013; Rädler et al., 2018; Battaglioli et al., 2023). The hail model developed by Rädler et al. (2018) indicated the annual amount of hail ≥ 2 cm increased at around 2.4% p.a. over 1979-2015 in a region covering Germany and the Alps, and up by 1.4% p.a. over the greater area of western and central Europe. More recently, Battaglioli et al. (2023) described a model which had been calibrated to observed lightning and large hail reports, then estimated linear trends in damaging hail occurrence from 1950 to 2021, and found it had been rising generally across Europe, with relatively bigger changes for larger hail. They highlighted how hailstones ≥ 5 cm are now three times more likely than in the 1950s in northern Italy, though the trend was not uniform throughout the whole period, with most of the increase occurring since the 1980s, hence linear trends since 1950 are likely to underestimate trends over the past four decades. Some insurance industry research used models similar to those of Rädler et al. (2018) and Battaglioli et al. (2023): Stormwise Ltd. (2024) studied linear trends over 1960-2023 while Partner Re (2024) examined 1950-2022, and both report increases in annual hail risk of around 1 to 1.5% p.a. over much of mainland Europe. The trends from Rädler et al. (2018) are higher than others, however, they base their trends on the more recent 1979-2015 period hence more synchronised with the period of Mediterranean warming, which began around 1980.

There are various sources of property losses due to hail and they all show an upward trend in recent decades. Many in the insurance industry get their impression of rising hail severity in Europe from publicly issued industry loss estimates. There have been some notable events in the past few years, with 4.5 billion USD of insured losses from severe thunderstorms in Europe during summer 2021 (Swiss Re, 2021), then in 2022, French property and automobiles suffered five billion euros of insured loss due to hail (France Assureurs, 2023), while in 2023, hail storms caused over five billion euros of insured loss, mostly in Italy (Swiss Re, 2024). These loss severities were rarer in earlier times: while storms Andreas (2013) and Ela (2014) caused multi-billion euro insured losses, mainly to Germany and France respectively (Swiss Re, 2014 and 2015) and were the first major events since the multi-billion loss in the Munich hailstorm of 1984 (e.g. Pucik et al., 2019). While the sudden spate of multi-billion euro events is impactful, it is viewed as weak evidence of rising hail risk, due to significant errors in estimates of damages from older storms and statistical uncertainty from small sample sizes.

Consideration of other data sources and analysis provides a more robust view on hail loss trends. Early work included a study by Dessens (1995) which found an upward trend in crop-hail insurance losses in France after 1980, while Kunz et al. (2009) examined damage to buildings in southwest Germany over the period 1986-2004, and found the number of severe hail days had increased significantly, by around 3.5% per year.

We supplement earlier damage studies with a new analysis of annual hail losses published by national insurance associations, which were described in subsection 2.2. These industry bodies often monitor losses to their market, and some of their records extend to the past few decades. Figures 4a-c show timeseries of hail losses in Germany, France and Switzerland respectively. The timeseries of annual losses in the 1973-2023 period for automobiles due to the combined wind and hail perils (the vast majority of which are due to hail) contains an annual growth rate of 3.1% over the past 50 years, while more modern data since 1980 grow by 2.2% per year, and both trends are significantly different from zero at the 1% level. Figure 4b presents annual hail losses to all insured buildings in France, containing a +5.8% annual growth rate of hail losses from 1990 to 2022, which drops to +4.7% p.a. when excluding the final year with its huge hail losses. Both of these trends are different from zero at the 1% level. Finally, Figure 4c shows annual hail loss costs in Switzerland for the 1980 to 2023 period for all buildings in the 19 Swiss cantons covered by public insurance, and the best-fitting trend is 2.7% per year over the past 44 years, and *not* different from zero at the 1% level (p-value = 0.058).

In summary, the datasets shown in Figure 4a-c indicate losses have been trending upward at 2 to 5% per year over the past few decades, and consistently faster than the 1 to 2% range suggested by the above-mentioned hazard-based studies. Losses from national bodies are based on accurate information from surveys of reported losses combined with careful indexation methods using data widely regarded as suitable for its purpose, and represent the industry's best estimates of loss growth. However, hazard-based estimates use hail models based on our best understanding of atmospheric processes, and calibrated to observed hail on the ground, and they represent the best estimates from meteorology. The cause of their different growth rates is unclear, and future investigation into how fast hail damage has been increasing would be useful. In the meantime, we suggest the best estimate of rising hail risk to property is around 2% per year for mainland Europe.

In practice, a 2% per year trend in hail risk may accumulate and harm the insurance industry. Their risk pricing is often based on models calibrated to past experience of hazard or loss, and they will have lower risk than the present day due to the hail trends. As an example, if a model is calibrated to a time period with a midpoint of 10 years ago, and the risk has been increasing at 2% per year, then this translates to a 1.02^{10} = 21.9% underestimate of the present-day risk. This is material in the context of larger companies typically aiming for annual profits of around 5 to 10%.

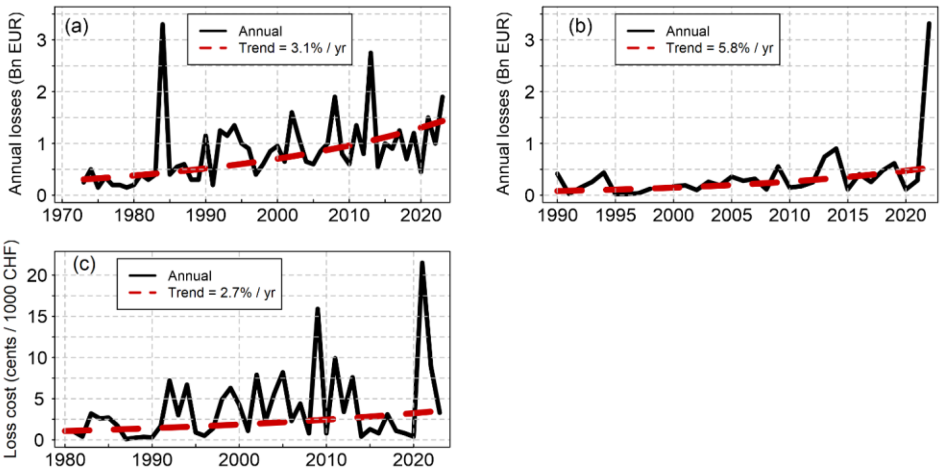


Figure 4: timeseries of national hail damages for three countries. Insurance industry hailstorm losses are shown for (a) automobiles in Germany (GDV, 2024), (b) buildings in France (France Assureurs, 2023), and (c) buildings in Switzerland (VKG, 2022, 2024).

5 Conclusions

The Mediterranean Sea has been warming at three times the rate of global mean SSTs over the past 45 years, and its drivers were investigated using results from the CMIP6-DAMIP experiments. The DAMIP climate models were found to simulate most of the variations in observed Mediterranean temperatures at multidecadal timescales since 1870, building confidence in the realism of ~~their simulations.~~these models. They indicate anthropogenic forcings from greenhouse gases (GHG) and aerosols (Aero) ~~dominate~~have had the ~~slower~~greatest influence on multidecadal changes in Mediterranean temperatures~~ over the northern Med. The Aero effect~~. Anthropogenic aerosols dominated ~~from 1850~~up to the late 1970s to produce a ~~slight cooling~~slightly cool period on average, then clean-air acts reduced their impacts while GHG forcing continued to grow, resulting in a rapid warming of the ~~Med~~Mediterranean of about 0.5 K / decade since 1980. GHG rises were responsible for about three-quarters of ~~the~~this warming ~~in the northern Med~~ over the past four decades, ~~and~~with the remaining portion ~~is~~ mostly due to ~~reducing~~declining aerosol burdens. Major volcanoes ~~can also change temperatures in the northern Med, but~~modify Mediterranean SSTs, though their peak temporary cooling of -0.5 K~~, lasting for just~~ over a few years~~, suggests this forcing~~ is minor compared to ~~ongoing GHG and Aero forcing~~anthropogenic forcings.

~~We can develop an outlook for hail climate in Europe based on the model results, and it is not encouraging. It is very likely that recent positive trends from rising GHG concentrations and less negative Aero forcing will persist over the next couple of~~

~~decades, hence the current trend toward more severe hail is set to continue. The main unresolved issue is the size of the hail damage response to this ongoing warming of local seas.~~

The temperature trends in the Mediterranean Sea are a concern for hail risk in central and southern Europe. It is known that the Mediterranean is the main source of the high moisture amounts that drive severe hailstorms in the higher risk parts of Europe, and its warming fits with the increases in low-level moisture which are driving hail trends since about 1980. Recent trends in hail damages over these higher-risk parts of Europe were reviewed to measure the impacts due to Mediterranean warming. Two different types of studies produce a similar sign of trend, but different rates of growth in risk over recent decades. First, models of hail based on environmental conditions and calibrated to observed occurrences of larger hail indicate risk across mainland Europe has been rising by 1 to 2% per year since the mid-20th century, and the trend since 1980 may be nearer the upper end of this range. Second, trends in estimates of hail damage to property, indexed to the present-day, show annual hailstorm losses are increasing by 2 to 5% in some key countries (Germany, France and Switzerland). Both methods have strengths and weaknesses, and future work on resolving their different estimates would be useful. We suggest a best estimate of 2% per year growth in hail damage based on current evidence. Uncertainty is large, though large-scale trends in the higher-risk area are positive from almost all studies.

Impacts of rising trends in hail are material to society. For example, if an estimate of hail risk was based on a climate centred on 10 years ago, then a 2% per year growth accumulates to a 22% underestimate of the damages from a peril which causes billions of euros of losses to Europe each year.

While further work is required to precisely measure how much of the increase in hail risk in central and southern Europe is due to the warming Mediterranean, it is clear that it has played an important role, and will continue to do so given the current trajectory of anthropogenic forcings. We recommend including hail trends in our views of risk.

Acknowledgements

The authors are grateful to the reviewers and the public commentator for their feedback which improved this manuscript. SC is very grateful to Inigo Limited for funding ~~most~~part of ~~his contribution to~~ this research.

Code/Data availability

HadISST data are available at https://www.metoffice.gov.uk/hadobs/hadisst/ (accessed on 24th October 2024). CMIP6-DAMIP climate model results were downloaded from the Earth System Grid Federation (ESGF): https://aims2.llnl.gov/search/cmip6/ (accessed July-October 2024).

Author Contribution

SC designed the tests and did the analysis. ~~Both~~ SC and TC prepared the manuscript.

Competing Interests

The authors declare no competing interest.

References

Aizawa T., Oshima N. and Yukimoto S.: Contributions of anthropogenic aerosol forcing and multidecadal internal variability to mid-20th century Arctic cooling—CMIP6/DAMIP multimodel analysis. Geophys. Res. Lett., 49, e2021GL097093. https://doi.org/10.1029/2021GL097093, 2022.

Ali, E., W. Cramer, J. Carnicer, E. Georgopoulou, N.J.M. Hilmi, G. Le Cozannet, and P. Lionello, 2022: Cross-Chapter Paper 4: Mediterranean Region. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2233–2272, doi:10.1017/9781009325844.021.

Battaglioli F., Groenemeijer P., Púčik T., Taszarek M., Ulbrich U. and Rust H.: Modeled Multidecadal Trends of Lightning and (Very) Large Hail in Europe and North America (1950–2021), J. Appl. Meteorol. Clim., 62, 1627–1653, https://doi.org/10.1175/JAMC-D-22-0195.1, 2023.

Berthet C., Dessens J. and Sanchez, J. L.: Regional and yearly variations of hail frequency and intensity in France. Atmos. Res., 100, 391–400, https://doi.org/10.1016/j.atmosres.2010.10.008, 2011.

Booth B. B. B., Dunstone N. J., Halloran P. R., Andrews T. and Bellouin, N.: Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability. Nature, 484(7393), 228–232. https://doi.org/10.1038/nature10946, 2012.

~~Cusack S.: Recent multidecadal European storm variations explained by anthropogenic aerosols and natural internal variability in CMIP6-DAMIP climate models. Manuscript submitted, 2024.~~

Butterworth S., "On the Theory of Filter Amplifiers," Experimental Wireless and the Wireless Engineer, Vol. 7, pp. 536-541, https://www.changpuak.ch/electronics/downloads/On_the_Theory_of_Filter_Amplifiers.pdf, 1930,

Chen, J., & Dai, A. (2023). The atmosphere has become increasingly unstable during 1979–2020 over the Northern Hemisphere. Geophysical Research Letters, 50, e2023GL106125. https://doi.org/10.1029/2023GL106125.

CMIP: CMIP Model and Experiment Documentation, https://wcrp-cmip.org/cmip-model-and-experiment-documentation/, 2025.

de Pablo Dávila, F., Soriano, L.J.R., Alonso, C.J., García, M.M. and Martín, J.R.: Synoptic patterns of severe hailstorm events in Spain. Atmospheric Research, 250, 105397. https://doi.org/10.1016/j.atmosres.2020.105397, 2021.

Dessens J.: Severe convective weather in the context of a nighttime global warming. Geophys. Res. Lett., 22, 1241–1244, https://doi.org/10.1029/95GL00952, 1995.

Eccel E., Cau P., Riemann-Campe K. and Biasioli F.: Quantitative hail monitoring in an alpine area: 35-year climatology and links with atmospheric variables. Int. J. Climatol., 32, 503–517, https://doi.org/10.1002/joc.2291, 2012.

Eyring V., Bony S., Meehl G. A., Senior C. A., Stevens B., Stouffer R. J. and Taylor K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geosci. Model Dev., 9, 1937–1958, https://doi.org/10.5194/gmd-9-1937-2016, 2016.

FFB: FFB Construction Cost Index, https://www.outils.ffbatiment.fr/federation-francaise-du-batiment/le-batiment-et-vous/en_chiffres/indices-index/Chiffres_Index_FFB_Construction.html, 2025

France Assureurs:. L'Assurance des Événements Naturels en 2022, Fédération Française de l'Assurance, https://www.franceassureurs.fr/wp-content/uploads/lassurance-des-evenements-naturels-en-2022.pdf, 2023.

García-Monteiro S., Sobrino J., Julien Y., Sòria G., and Skokovic D.: Surface Temperature trends in the Mediterranean Sea from MODIS data during years 2003–2019. Regional Studies in Marine Science, 49:102086, https://doi.org/10.1016/j.rsma.2021.102086, 2022.

GDV: Data service for the natural hazards report, https://www.gdv.de/gdv/statistik/datenservice-zum-naturgefahrenreport, 2024.

Gillett N. P., Shiogama H., Funke B., Hegerl G., Knutti R., Matthes K., Santer B. D., Stone D. and Tebaldi C.: The Detection and Attribution Model Intercomparison Project (DAMIP v1.0) contribution to CMIP6, Geosci. Model Dev., 9, 3685–3697, https://doi.org/10.5194/gmd-9-3685-2016, 2016.

~~Hohl R., Schweingruber F. H. and Schiesser H.-H.: Reconstruction of severe hailstorm occurrence with tree rings: a case study in central Switzerland. Tree-Ring Res., 58, 11–22, https://repository.arizona.edu/handle/10150/262541, 2002.~~

Heimann D., and Kurz M.: The Munich hailstorm of July 12, 1984. A discussion of the synoptic situation. Beitr. Phys. Atmos. 58: 528–544, https://elib.dlr.de/64721/1/85-heimann.pdf, 1985

James P., Stohl A., Spichtinger N., Eckhardt S., and Forster C.: Climatological aspects of the extreme European rainfall of August 2002 and a trajectory method for estimating the associated evaporative source regions, Nat. Hazards Earth Syst. Sci., 4, 733–746, https://doi.org/10.5194/nhess-4-733-2004, 2004.

Kopp J., Schröer K., Schwierz C., Hering A., Germann U. and Martius O.: The summer 2021 Switzerland hailstorms: weather situation, major impacts and unique observational data. Weather, 78: 184-191. https://doi.org/10.1002/wea.4306, 2023.

Krug, A., Aemisegger, F., Sprenger, M., and Ahrens, B.: Moisture sources of heavy precipitation in Central Europe in synoptic situations with Vb-cyclones, Clim. Dynam., 59, 3227–3245, https://doi.org/10.1007/s00382-022-06256-7, 2022.

Kunz M., Sander J. and Kottmeier C.: Recent trends of thunderstorm and hailstorm frequency and their relation to atmospheric characteristics in southwest Germany. Int. J. Climatol., 29, 2283–2297, https://doi.org/10.1002/joc.1865, 2009.

Formatted: French (France)

Formatted: French (France)

Formatted: French (France)

Kunz, M., Blahak, U., Handwerker, J., Schmidberger, M., Punge, H. J., Mohr, S., Fluck, E., and Bedka, K. M.: The severe hailstorm in southwest Germany on 28 July 2013: characteristics, impacts and meteorological conditions, Q. J. Roy. Meteorol. Soc., 144, 231–250, https://doi.org/10.1002/qj.3197, 2018.

Kunz M., Wandel J., Fluck E., Baumstark S., Mohr S. and Schemm S.: Ambient conditions prevailing during hail events in central Europe, Nat. Hazard Earth Sys., 20, 1867–1887, https://doi.org/10.5194/nhess-20-1867-2020, 2020.

Lionello, P. and L. Scarascia, 2018: The relation between climate change in the Mediterranean region and global warming. Reg. Environ. Change, 18(5), 1481–1493, https://doi.org/10.1007/s10113-018-1290-1.

Lund M. T., Myhre G. and Samset B. H.: Anthropogenic aerosol forcing under the Shared Socioeconomic Pathways, Atmos. Chem. Phys., 19, 13827–13839, https://doi.org/10.5194/acp-19-13827-2019, 2019.

MedECC (2020) Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report [Cramer, W., Guiot, J., Marini, K. (eds.)] Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, 632pp. ISBN: 978-2-9577416-0-1 / DOI: 10.5281/zenodo.7224821

Mohr S. and Kunz M.: Recent trends and variabilities of convective parameters relevant for hail events in Germany and Europe. Atmos. Res., 123, 211–228, https://doi.org/10.1016/j.atmosres.2012.05.016, 2013.

Murakami, H.: Substantial global influence of anthropogenic aerosols on tropical cyclones over the past 40 years. Sci. Adv., 8, eabn9493. https://doi.org/10.1126/sciadv.abn9493, 2022.

PucikMulet, S., Buongiorno Nardelli, B., Good, S., Pisano, A., Greiner, E., Monier, M., Autret, E., Axell, L., Boberg, F., Ciliberti, S., Drévillon, M., Droghei, R., Embury, O., Gourrion, J., Høyer, J., Juza, M., Kennedy, J., Lemieux-Dudon, B., Peneva, E., Reid, R., Simoncelli, S., Storto, A., Tinker, J., Von Schuckmann, K., Wakelin, S. L., 2018. Ocean temperature and salinity. In: Copernicus Marine Service Ocean State Report, Issue 2, Journal of Operational Oceanography, 11:sup1, s5–s13, DOI: 10.1080/1755876X.2018.1489208

Partner Re: The Contribution of Climate Change to Europe's Increasing Hail Losses, https://www.partnerre.com/perspectives/the-contribution-of-climate-change-to-europes-increasing-hail-losses/, 2024

Piper, D. A., Kunz, M., Allen, J. T., and Mohr, S.: Investigation of the temporal variability of thunderstorms in Central and Western Europe and the relation to large-scale flow and teleconnection patterns, Q. J. Roy. Meteor. Soc., 145, 3644–3666, https://doi.org/10.1002/qj.3647, 2019.

Púčik, T., Groenemeijer, P., Rädler, A. T., Tijssen, L., Nikulin, G., Prein, A. F., van Meijgaard, E., Fealy, R., Jacob, D., and Teichmann, C.: Future changes in European severe convection environments in a regional climate model ensemble, J. Climate, 30, 6771–6794, https://doi.org/10.1175/JCLI-D-16-0777.1, 2017.

Púčik, T., Castellano C., Groenemeijer P., Kuhne T., RadlerRädler A. T., Antonescu B. and Faust E.: Large hail incidence and its economic and societal impacts across Europe. Mon. Weather Rev., 147, 3901–3916, https://doi.org/10.1175/MWR-D-19-0204.1, 2019.

Rädler A. T., Groenemeijer P., Faust E. and Sausen R.: Detecting severe weather trends using an additive regressive convective hazard model (AR-CHaMo). J. Appl. Meteorol. Clim., 57, 569–587, https://doi.org/10.1175/JAMC-D-17-0132.1, 2018.

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, Nat. Rev. Earth Environ., 2, 213–226, https://doi.org/10.1038/s43017-020-00133-9, 2021.

Rayner N. A., Parker D. E., Horton E. B., Folland C. K., Alexander L. V., Rowell D. P., Kent E. C. and Kaplan A.: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, J. Geophys. Res., 108, 4407, https://doi.org/10.1029/2002JD002670, 2003.

SDES: Key figures for natural hazards, edition 2023, The data service and statistical studies (SDES) in partnership with the National Observatory of natural risks (ONRN), https://www.statistiques.developpement-durable.gouv.fr/edition-numerique/chiffres-cles-risques-naturels-2023/pdf/chiffres-cles-des-risques-naturels-edition-2023.pdf, 2024.

Roquet, H., Pisano, A., Embury, O., 2016. Sea surface temperature. In: von Schuckmann et al. 2016, The Copernicus Marine Environment Monitoring Service Ocean State Report, Jour. Operational Ocean., vol. 9, suppl. 2. doi:10.1080/1755876X.2016.1273446.

Schemm, S., Sprenger M., Martius O., Wernli H., and Zimmer, M.: Increase in the number of extremely strong fronts over Europe? A study based on ERA-Interim reanalysis (1979–2014), Geophys. Res. Lett., 44, 553–561, https://doi.org/10.1002/2016GL071451, 2017.

Seneviratne S., Zhang X., Adnan M., Badi W., Dereczynski C., Luca A. D., Ghosh S., Iskandar I., Kossin J., Lewis S., Otto F., Pinto I., Satoh M., Vicente-Serrano S., Wehner M., and Zhou, B.: Weather and Climate Extreme Events in a Changing Climate. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, https://doi.org/10.1017/9781009157896.013, 2021.

Stormwise Ltd.: Climate Change impacts on hail, https://stormwise.co.uk/climate-change-and-hail, 2024.

Swiss Re: Natural catastrophes and man-made disasters in 2013, Swiss Re Institute, Sigma No.1/2014, https://www.swissre.com/institute/research/sigma-research/sigma-2014-01.html, 2014.

Swiss Re: Natural catastrophes and man-made disasters in 2014, Swiss Re Institute, Sigma No.2/2015, https://www.swissre.com/institute/research/sigma-research/sigma-2015-02.html, 2015.

Swiss Re: Global insured catastrophe losses rise to USD 112 billion in 2021, the fourth highest on record, Swiss Re Institute estimates, https://www.swissre.com/media/press-release/nr-20211214-sigma-full-year-2021-preliminary-natcat-loss-estimates.html, 2021.

Swiss Re: Natural catastrophes in 2023: gearing up for today's and tomorrow's weather risks, Swiss Re Institute, Sigma No.1/2024, https://www.swissre.com/dam/jcr:c9385357-6b86-486a-9ad8-78679037c10e/2024-03-sigma1-natural-catastrophes.pdf, 2024.

Taszarek M., Allen J. T., Brooks H. E., Pilguj N. and Czernecki B.: Differing trends in United States and European severe thunderstorm environments in a warming climate. B. Am. Meteorol. Soc., 102, E296–E322, https://doi.org/10.1175/BAMS-D-20-0004.1, 2021.

Tradowsky, J. S., Philip, S. Y., Kreienkamp, F., Kew, S. F., Lorenz, P., Arrighi, J., Bettmann, T., Caluwaerts, S., Chan, S. C., De Cruz, L., De Vries, H., Demuth, N., Ferrone, A., Fischer, E. M., Fowler, H. J., Goergen, K., Heinrich, D., Henrichs, Y., Kaspar, F., Lenderink, G., Nilson, E., Otto, F. E. L., Ragone, F., Seneviratne, S. I., Singh, R. K., Skålevåg, A., Termonia, P., Thalheimer, L., Van Aalst, M., Van Den Bergh, J., Van De Vyver, H., Vannitsem, S., Van Oldenborgh, G. J., Van Schaeybroeck, B., Vautard, R., Vonk, D., and Wanders, N.: Attribution of the heavy rainfall events leading to severe flooding in Western Europe during July 2021, Clim. Change, 176, 90, https://doi.org/10.1007/s10584-023-03502-7, 2023.

VKG: Analyse langfristiger Gebäudeschadendaten, published by Vereinigung Kantonaler Gebäudeversicherungen VKG, https://cms.vkg.ch/media/at1kb01p/vkf_analyse-schadendaten_de.pdf, 2022.

Willemse S.: A statistical analysis and climatological interpretation of hailstorms in Switzerland. Thesis, ETH Zürich, https://doi.org/10.3929/ethz-a-001486581, 1995. VKG: Elementar: Übersicht 2004-2023 – Elementarschäden an Gebäuden (20-Jahresvergleich) https://cms.vkg.ch/media/tutg0vgg/elementarschaeden-an-gebaeuden-2004-2023_de.pdf, 2024.

Volosciuk, C., Maraun, D., Semenov, V. et al. Rising Mediterranean Sea Surface Temperatures Amplify Extreme Summer Precipitation in Central Europe. Sci Rep 6, 32450 (2016). https://doi.org/10.1038/srep32450.

Wilhelm, L., Schwierz, C., Schröer, K., Taszarek, M., and Martius, O. (2024). Reconstructing hail days in Switzerland with statistical models (1959–2022), Nat. Hazards Earth Syst. Sci., 24, 3869–3894, https://doi.org/10.5194/nhess-24-3869-2024.

Formatted: German (Germany)

Formatted: German (Germany)

Formatted: German (Germany)