Brief Communication: Drivers of the recent warming of the Mediterranean Sea, and its implications for hail risk

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Abstract

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 identify the drivers of the recent Mediterranean warming. The models simulate the observed multidecadal variations of Mediterranean Sea temperatures in the modern industrial period accurately, and indicate anthropogenic aerosol forcing was largely responsible for the cooler period from about 1900 to the late 1970s, while rising greenhouse gases are the main cause of warming waters since then. 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 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

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 the DAMIP (Detection and Attribution Model Intercomparison Project; Gillett et al., 2016) sub-project of CMIP6 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 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

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 designed to investigate the impacts of various external forcings on global and regional climate. Its experiments explore the modern industrial period from 1850 to 2014, and its Tier 1 model simulations 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). 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.

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.

Both observed and modelled data are processed similarly. Monthly mean values are initially area-averaged over a region of the Mediterranean Sea shown in Figure 1, then combined to form an extended summer half-year average (May-October) corresponding to the annual peak of Mediterranean influence on flood and hail risk, in order to focus on the most relevant seasonal warming trends (García-Monteiro et al., 2022). Anomalies were defined using the climate from the common baseline period of 1870-2014 for observed and modelled values. The climate of the Hist simulations 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 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.

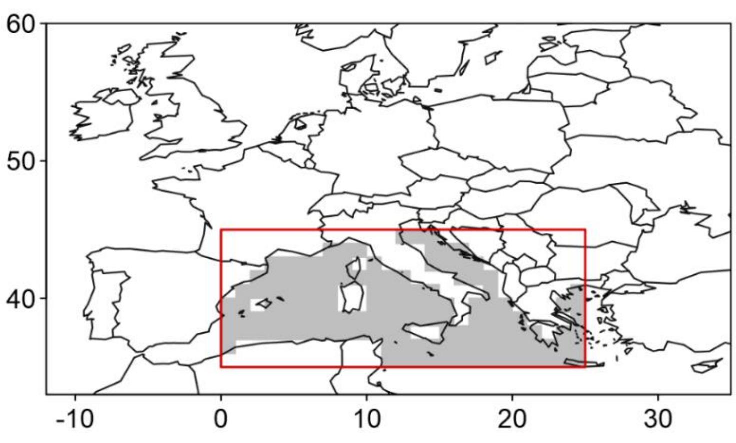

Figure 1: map of a part of Europe, with shaded area denoting the Mediterranean Sea region used in the analysis.

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.

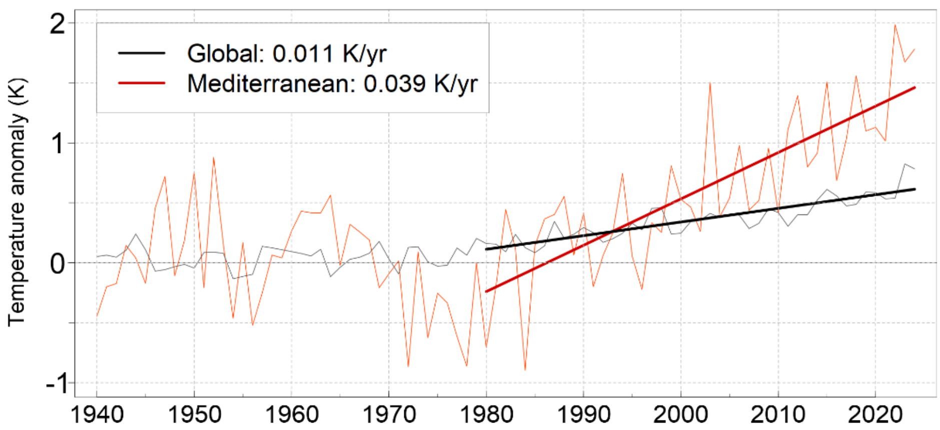

Figure 2: timeseries of global (black) and Mediterranean (red) SST anomalies in the summer half-year (May to October), with associated best-fitting linear trends in the 1980-2024 period. Data are from HadISST, anomalies are computed with respect to the 1870 to 2014 period, and global data are from 60°S 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 Mediterranean temperature anomalies over the extended historical period for observed and multi-model ensemble means for the Historical and three DAMIP single-forcing experiments.

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 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 is expected to have σ=0.046 K (from the Central Limit Theorem), therefore the simulated multidecadal oscillation in Hist with amplitude of 0.5 K is 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 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.

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

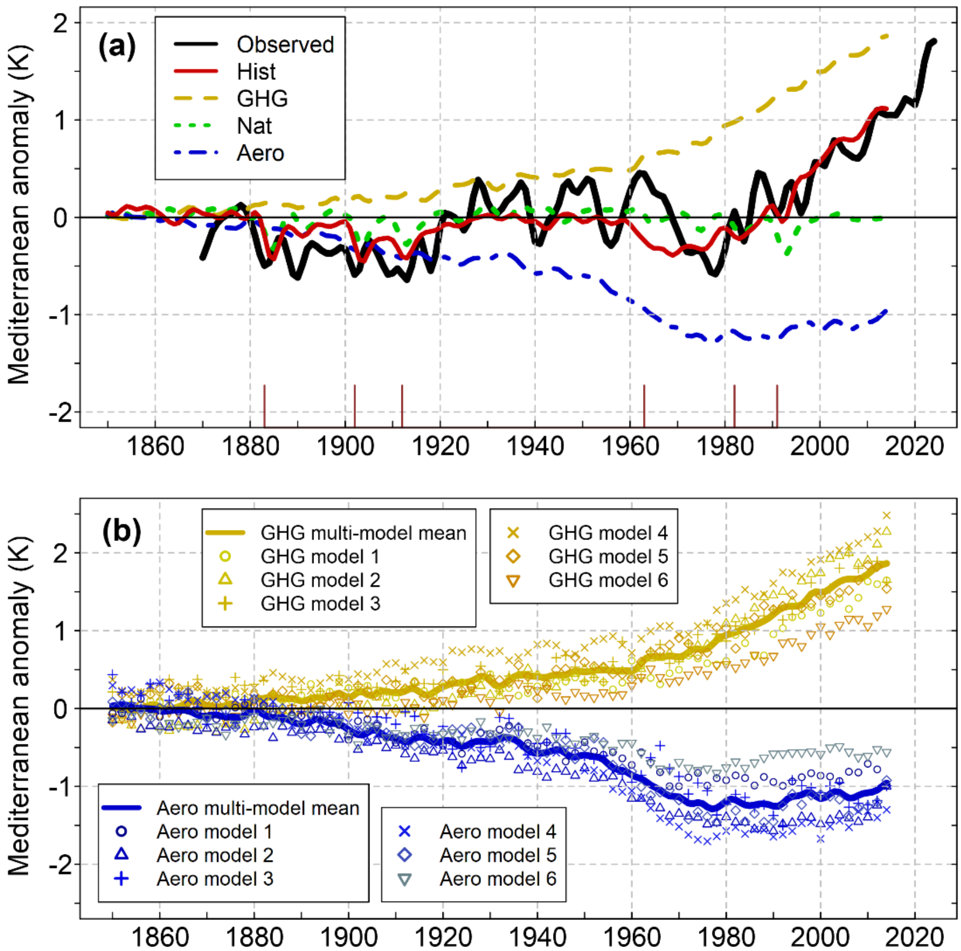

Figure 3: timeseries of Mediterranean temperature anomalies. (a) observed (solid black line) and multi-model mean anomalies for the various forcing experiments, with major volcanic eruptions indicated by the long red tick marks on the time axis. (b) DAMIP multi-model mean (solid lines), and the mean 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). 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 Mediterranean temperatures are a robust feature of DAMIP models and that these two forcings are the primary drivers of recent Mediterranean Warming.

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%.

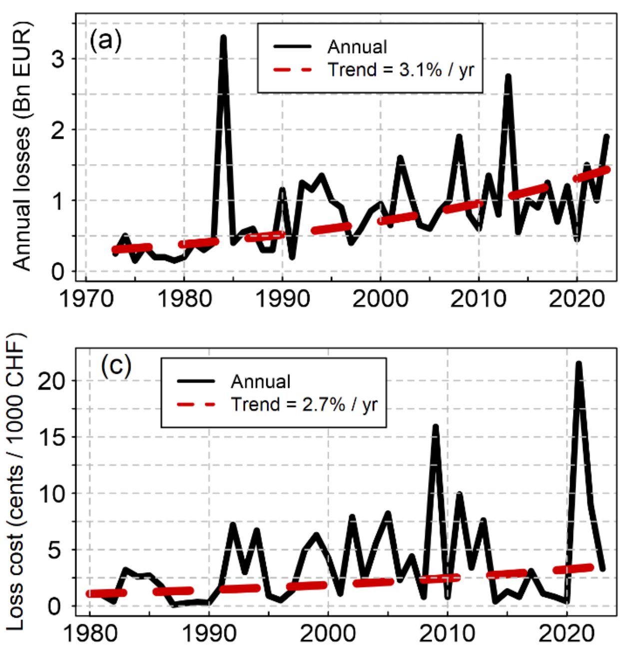

Figure 4: timeseries of national hail damages for three countries. Insurance industry hailstorm losses are shown for (a) automobiles in Germany (GDV, 2024), (b) buildings in France (France Assureurs, 2023), and (c) buildings in Switzerland (VKG, 2022, 2024).

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 these models. They indicate anthropogenic forcings from greenhouse gases (GHG) and aerosols (Aero) have had the greatest influence on multidecadal changes in Mediterranean temperatures. Anthropogenic aerosols dominated up to the late 1970s to produce a 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 Mediterranean of about 0.5 K / decade since 1980. GHG rises were responsible for about three-quarters of this warming over the past four decades, with the remaining portion mostly due to declining aerosol burdens. Major volcanoes modify Mediterranean SSTs, though their peak temporary cooling of -0.5 K over a few years is minor compared to anthropogenic forcings.

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.

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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. SC and TC prepared the manuscript.

Competing Interests

The authors declare no competing interest.

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