Reviewer 2

I suspect the sentence on line 188 is missing an object.

Thanks for finding this error. This sentence was missing a word and is corrected in the new version of the manuscript.

Reviewer 3

Re-review of NHESS-2024-210. I thank the authors for their responses to my comments from my first review and for the significantly refocused and much improved article.

The authors thank Reviewer 3 for their time and effort on this manuscript. Their comments highlight aspects that may cause confusion, and we appreciate this opportunity to revise and clarify details in the manuscript.

In my last review I suggested that the authors a) consider changes in exposure and vulnerability in concert with changes in damages when performing trend analysis, and b) thoroughly link rising Mediterranean Sea temperatures to hailstorm activity (specifically, as compared to overall thunderstorm activity) in Europe. The authors have better explained how their loss estimates are normalised for exposure and vulnerability changes, which is helpful for part a). For part b), the authors have relied on a review of previous studies that show the importance of low-level moisture for convection-prone (not always hail) environments. The importance of low-level moisture is now well established, but the link from rising Mediterranean temperatures to severe hail trends is still not thoroughly made.

The connection from Mediterranean moisture to rising hail trend is queried multiple times by the reviewer, so we revised the manuscript to highlight the evidence on this important topic. Section 4 contained a lot of information on multiple subjects, and quite monolithic, and has been re-structured into two subsections, with modified text, in the new version of the manuscript. In particular, subsection 4.1 contains a review of studies showing the Mediterranean is the main source region for the high values of low-level moisture that are a key ingredient of damaging hail events, then reviews past research which found that rising amounts of low-level moisture were the main cause of upward trends in damaging hail. The revised manuscript presents the published evidence connecting Mediterranean heat to damaging hail in key parts of Europe more clearly to the reader.

The secondary aim of the paper is to "quantify the link from Mediterranean Sea warming to its impacts on hailstorm risk in Europe". The authors have not succeeded in this aim. There is no quantification in the paper; rather the two trends are analysed in parallel. At a minimum, I suggest that the authors quantify the correlation between Mediterranean temperatures and hail damage or hail-prone environments in the historical period. Do years in which the Mediterranean is warmer produce more severe hail? How much of the variability in hail losses is (statistically) explained by variability in Mediterranean temperatures? Plotting the two timeseries together would also help show a relationship.

The study consists of three parts:

1. Identifying the drivers of multidecadal changes in Mediterranean Sea temperatures over past decades
2. Review of past studies establishing how recent trends in Mediterranean Sea temperatures drive trends in damaging hail over higher-risk parts of western and central Europe
3. Reviewing trends in damaging hail, including new analysis of losses from national insurance associations

Parts 2 and 3 above were described inaccurately in the manuscript, and we thank the reviewer for identifying the weakness in the sentence they highlight. We replaced this sentence with the following text in the revised version: "Section 4 begins with a review of the robust evidence linking multidecadal trends in Mediterranean Sea temperatures to damaging hail over the higher-risk parts of Europe, then we provide estimates of trends in damaging hail over recent decades, based on previous studies and a new analysis of insurance loss data."

Note how the study establishes the connection from Mediterranean warming to damaging hail in high-risk parts of Europe using past research findings. It is not possible to precisely quantify such a link due to limitations of hail damage records (as noted in first sentence of subsection 4.1), but past research has established a strong connection. The contributions of this Brief Communication are to identify the drivers of the Mediterranean warming, and to review trends in damaging hail from other studies, and loss datasets, and we use the findings from past research to highlight how both trends are connected.

We considered the request from the reviewer to analyse the correlation between Mediterranean heat and hail at annual timescales. This study concerns the connection of their multidecadal trends rather than interannual variability. There are substantial differences between behaviours at these two timescales, which means correlations at annual timescales do not reflect the strength of connection at multidecadal scales. For example, damaging hail is rare and the sampling error at annual scales naturally reduces correlation, whereas a multidecadal analysis has much

smaller sampling error. Further, the interannual variations of other hailstorm ingredients will reduce correlation between Mediterranean heating and damaging hail at annual timescales, but researchers have found these other ingredients have very little multidecadal trend. Therefore, the inter-annual correlation has little relevance to a study of multidecadal trends. Note that the manuscript provides the timeseries of multidecadal trends in Mediterranean temperatures and hail losses: the red solid line in Figure 2, versus the red dashed lines in Figures 4a-c.

Secondly, the authors should take great care in their wording of conclusion statements so that the uncertainties inherent in this study are well explained – I show specifics below. While I do not doubt that the warming Mediterranean plays a role in the trends in severe hail in Europe, this study does not yet show a convincing link. I hope that my comments below will help to improve the manuscript.

Your comments have improved the clarity and accuracy of the manuscript, and the authors are very grateful.

We reviewed the conclusions in section 5 to ensure they accurately reflect uncertainties in the coupling between Mediterranean Sea temperatures and damaging hail occurrence in this higher-risk parts of western and central Europe. Several independent studies conclude that the trends in low-level moisture are the main driver of the trends in damaging hail in high-risk parts of Europe (subsection 4.1). Other studies show how low-level Mediterranean air masses are the typical source of the high moisture values which are key to damaging hail events in the high-risk parts of Europe (subsection 4.1). These studies combine to provide confidence in a strong connection between Mediterranean Sea temperatures and damaging hail occurrence at multidecadal scales. There is some remaining uncertainty, referred to in the first sentence of the final paragraph in section 5, and this would be a good avenue for future work.

Specific comments

1. *Lines 32: The cited article by Kunz et al. (2018) does not show a direct link between Mediterranean moisture and hailstorms.*

Subsection 4.1 of Kunz et al. (2018) show the link between Mediterranean moisture and the hailstorm that caused major damage in southwest Germany on 28th July 2013. The authors describe how a low pressure off the east coast of Scotland was connected to a secondary low near the Gulf of Lyon, and their Figure 3 includes surface pressure contours (white lines) indicating low-level airflow from the Mediterranean to southwest Germany.

2. *Line 54: The authors analyse the variable "tas", or near-surface atmospheric temperature, rather than model variables for sea surface temperature which may be different. They compare these data to historical sea surface temperature in Figure 3. The authors should mention this difference and explain their choice.*

This point was raised in the first round of review too. The revised manuscript includes the following sentences in the second paragraph of subsection 2.1:

"These SST data are used to assess the validity of near-surface air temperature variations in DAMIP simulations. Anomalies in both quantities are very similar at the large spatial and temporal scales analysed in this study. For example, Rubino et al. (2020) described their close correspondence at interdecadal timescales (their Figure 4), and the two quantities are often used interchangeably in long climate reconstructions (e.g. Morice et al., 2012). "

In Figure 3, the agreement of the historical simulations with observations is not particularly strong, with observations showing much more variability. The authors should comment on this discrepancy in variability.

We assume the reviewer is referring to the interdecadal variations from 1850 to about 1980. Reviewer 2 asked about this in the first round of review, and a detailed reply was provided. The manuscript was modified to include a brief discussion of these smaller, earlier variations. Specifically, the first two paragraphs of subsection 3.2 were replaced with the following text:

"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. Earlier multidecadal variations in observations, consisting of minima around 1910 and the late 1970s, and a local maximum

from about 1930 to the early 1960s, are replicated in Hist, albeit with reduced amplitude. To our knowledge, there are no published results on the relative roles of internal climate variability and external forcing toward the observed multidecadal variations in the Mediterranean basin prior to 1980. However, these earlier fluctuations are similar to those in the North Atlantic sector analysed by Booth et al. (2012), and those authors found they were caused by both anthropogenic and volcanic aerosol forcing, in addition to internal climate variability. The observed warming since about 1980 is of greater concern since it has four times larger amplitude than the mid-20th century peak. Notably, the multimodel ensemble mean simulates this recent rapid warming accurately. This comparison to observed variations bolsters confidence in the fidelity of CMIP6-DAMIP climate model simulations of surface temperature anomalies in the Mediterranean, particularly its dominant feature of rapid warming in recent decades. We now use the validated model ensemble to assess the contribution of individual forcings to the total signal."

3. *Line 181: The authors write "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" – but no references are given. The authors should cite exactly which studies show this, because not all the studies they cite in the following paragraph show that low-level moisture is the main driver of increases in hailstorm risk – rather some show the importance of low-level moisture in more-general convective environments, of which hail environments are a specific subset.*

The reviewer quotes the first sentence to the second paragraph of subsection 4.1. This sentence is intended to introduce the reader to the topic of the link between low-level moisture to damaging hail, and the fact that there are two pathways. The remainder of the paragraph describes the two pathways, and provides several references to studies which link greater moisture specifically to more damaging hail.

One of the references in the reviewed manuscript (Púčik et al., 2017) concerned convective environments rather than observed hail hazard or losses. While there is much evidence linking their convection proxy (high instability, shear and precipitation) to severe hail, this reference was removed because several other studies are referenced to help avoid doubts that moisture trends are connected to damaging hail trends.

4. *Line 191: The authors write that "it is clear that a warming Mediterranean is a primary contributor to the trends in hail risk in key parts of Europe". The authors have shown that moisture increases are often linked to increases in convective storm environments, but the link to trends in hail risk is not clear. Other factors such as changes in melting of hailstones and local changes in convective inhibition may affect hail hazard, while risk changes are also affected by changes in vulnerability and exposure. I would suggest allowing for more uncertainty by replacing this line with "At the present time, it is likely that a warming Mediterranean is a primary contributor to the trends in the occurrence of convective environments in some parts of Europe".*

The second paragraph in subsection 4 was re-written, for clarity.

- Subsection 4.1 refers to a number of studies showing moisture increases are the main driver of upward trends in *damaging hail* in the high-risk parts of central and western Europe
- The third paragraph in subsection 4.1 discusses how hail hazard events depend on other ingredients, then mentions past investigations which conclude that these ingredients have mostly flat or even slightly inhibiting trends, which strengthens the case for rising moisture driving upward trends in damaging hail
- Past research, and this study, take account of changing exposure when assessing damage trends

As a result, we use a version of the reviewer's suggested sentence which is adapted to fit with the evidence presented in subsection 4.1: "Though it is very likely that a warming Mediterranean is the main contributor to the recent trends in damaging hail across the higher-risk parts of Europe."

5. *Around line 215: The authors use "hail risk" when they may be referring to hail hazard. I suggest only using the word "risk" when exposure and vulnerability are also taken into account in these reported results.*

Thanks, this has been changed to "…both report hazard driving changes in hail risk…".

6. *Line 238: "both trends are significantly different from zero at the 1% level" and similar lines – which statistical test is used for significance statements?*

The revised manuscript has extra text inserted at the first mention of significance testing (in the second last paragraph of subsection 4.2): "…both trends are significantly different from zero at the 1% level based on a standard two-sided t-test (used in all significance testing of trends)."

7. *Line 275: "are driving hail trends since about 1980" – there is not sufficient evidence for this claim. Trends in hail are highly uncertain and complex, with large geographical inhomogeneity...*

Trends in damaging hail at local scales are spatially inhomogeneous, mainly due to the relative rarity of damaging hail at a location leading to large sampling error. However, there is a large body of evidence showing robust positive trends when damaging hail occurrences are analysed over aggregate spatial scales. The new subsection 4.2 describes the evidence from past research leading to the conclusion that damaging hail has been trending upward since about 1980 across the main high-risk areas of central and western Europe. In more detail, subsection 4.2 refers to many different hazard-based studies, using a variety of input data and methods, and all find a rising trend in damaging hail in the higher-risk parts of western and central Europe. Further, subsection 4.2 refers to past studies showing an upward trend in insured losses in France and Germany, and this study provides a new analysis of data from the French, German and Swiss insurance associations, and all three countries show positive trends in national hail losses. In summary, there is much evidence of rising trends in damaging hail across the higher-risk parts of western and central mainland Europe.

- *… and there is not one single driver*

Past research indicates low-level moisture amounts are the main driver of the multidecadal, large-scale trends in damaging hail in the higher-risk parts of western and central mainland Europe. The research consists of a range of different studies all converging on the conclusion that rising low-level moisture has been the main cause of upward trends in damaging hail in recent decades. These past studies are mentioned in the new subsection 4.1, which also describes studies investigating other ingredients of damaging hail events, such as winds and cap strength, and how these other drivers explain little of the trend in damaging hail occurrence. The final paragraph of subsection 4.1 describes how other drivers may be responsible for some of the rising trend, and that further research would be valuable.

8. *Lines 275–278: "Recent trends in hail damages over these higher-risk parts of Europe were reviewed to measure the impacts due to Mediterranean warming." This study does not measure the impact on hail due to Mediterranean warming – there is no quantification.*

Please see our reply in the General Comments section, on the scope of this work:

1. Identifying the drivers of multidecadal changes in Mediterranean Sea temperatures over past decades
2. Review of past studies establishing how recent trends in Mediterranean Sea temperatures drive trends in damaging hail over higher-risk parts of western and central Europe
3. Reviewing trends in damaging hail, including new analysis of losses from national insurance associations

We have re-written the final paragraph of the Introduction for clarity on the scope of this Brief Communication. Specifically, the study uses the results and conclusions from past research to establish the connection from Mediterranean warming to upward trends in damaging hail across the higher-risk parts of central and western Europe. The studies which have established this connection are reviewed in subsection 4.1, and also discussed in reply to the second part of question 7, above.

Given how past research has established the link from Mediterranean warming to damaging hail in the higher-risk parts of Europe, then the synthesis of trends in damaging hail in subsection 4.2 is quantifying the impact on hail due to Mediterranean warming. Though we recommend further analysis of the link from Med warming to damaging hail in two key parts of the manuscript: the final paragraph of subsection 4.1, and the final paragraph of the Conclusions.

Rather, the study shows that a) the Mediterranean has warmed, b) low-level moisture from the Mediterranean is important for convection, c) other published severe hail trends show increases over Europe, and d) hail damages have also increased over Europe.

The revisions to the manuscript may clarify the first two parts of the study: (a) the study investigates the drivers of the Mediterranean warming (as described in the Title, Abstract, Introduction, the entirety of Section 3, and the

Conclusions), and (b) low-level moisture from the Mediterranean is important for damaging hail occurrence rather than general convection. This focus on severe hail is mentioned in the Introduction, and reviewed in section 4, and mentioned again in the Conclusions. We are confident most readers will be able to describe what this study has done with regards to parts (a) and (b), since they are described multiple times in the revised manuscript.

> *The link between a) and c) and d) needs to be made stronger and it is not shown whether the Mediterranean temperatures are the key driver amongst many influences on severe hail production.*

The link from (a) to (c)+(d) is made in the new subsection 4.1 in the revised manuscript. Also, please see our replies in the General Comments section, and to Specific Comments numbers 3, 4, and 7 above, for more details on this same point.