Answer to **RC1**: 'Comment on nhess-2023-40', Anonymous Referee #1, 09 Jun 2023

The manuscript describes the application of AR-ChaMo, being an additive logistic regression model, to forecast large hail and lightning over Europe. The additive logistic regression model predicts the probability of lightning (hence also of a thunderstorm) and the probability of the occurrence of large hail given a thunderstorm forms. The observational data stem from lightning observations and hail reports from the ESWD. The authors show the performance of their model using a case study and also consider the AUROC-score as a verification metric. They also compare their model to two other classical indices and find their model to give equal or better guidance.

The manuscript touches on a very important topic and I find the use of the additive logistic models to predict lightning and hail very interesting. However, I think that the presentation should be improved and some major aspects should be clarified before the manuscript can be accepted.

General comments:

- Lines 14-15: Where do you show the model's ability to reproduce the climatological distribution and the seasonal cycle?

Authors: Thank you for pointing this out. The mention of the model's ability to reproduce the climatological distribution and the seasonal cycle refers to results from Battaglioli et al. 2023. For this reason, it was decided to remove these statements from the abstract since they don't belong to the main results of this paper.

- Section 2.1: I think the model should be described in more detail in this section. Although you refer to another article that should contain all the details, I advocate to repeat the main aspects here to provide the reader a self-contained article. In addition, I have some further remarks/questions

Authors: The section has been significantly extended to account for the reviewer comment. We expanded on the different training regions for the lightning and hail model, on the rationale behind these areas and on how lightning and hail reports are connected to the corresponding grid points. See next points for a more detailed description.

(i) Training of the hail-model is based on the hail reports from the ESWD and obviously not all hail occurrences are reported there hence your training data contains many cases where hail occurred but no report was issued. Does this pose a severe problem for the training? How do you mitigate the effect of these non-reported but true hail events?

Authors: Good point. Indeed not all reports are reported within the ESWD and the underreporting of hail in the dataset is a known limitation (Groenemeijer and Kühne 2014; Taszarek et al. 2020a) especially across certain regions. To minimize the impact of underreporting on the model training, we selected a specific region (Central Europe) and period (2008-2019) as done by Rädler et al. (2018) to train our hail models. For this region/period, the underreporting is the lowest. To best display the different training regions for the lightning and the hail model, we added a figure (Figure 1), adapted from Battaglioli et al. 2023, to the manuscript.

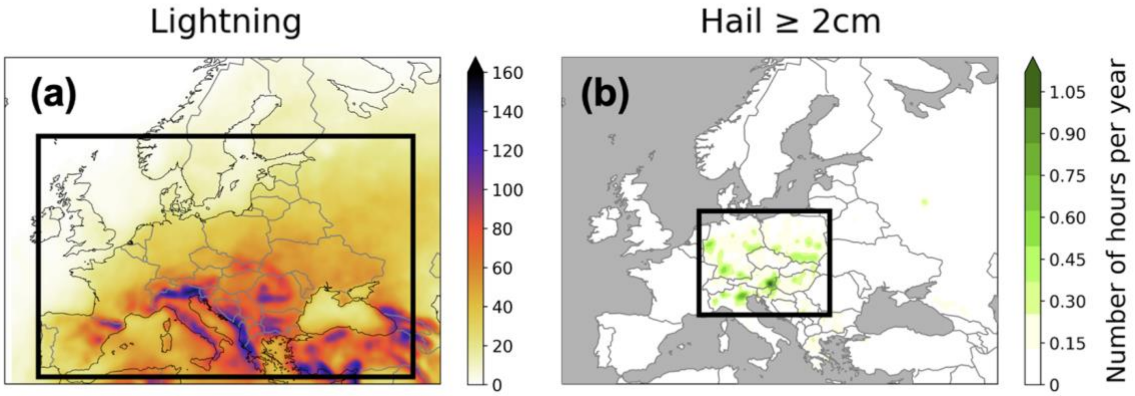


Figure 1: Annual mean distribution of lightning (a) and hail ≥ 2 cm (b) for the period 2008-2019. The black squared in (a) and (b) indicate the training regions for lightning (34.5° – 63.5°N, -9.0° – 46.0°W) and hail ≥ 2 cm (45.0° – 54.0°N, 5.0° – 22.0°W). Adapted from Battaglioli et al. (2023).

The rationale behind the different training regions for the lightning and the hail models has been added to the text as well: "The model training area for large hail was limited to Central Europe (Fig. 1) where reporting of severe weather in the ESWD is the highest (Groenemeijer and Kühne 2014; Taszarek et al. 2020a). This was done to limit sampling of situations in our training dataset that could have affected the model development, namely when hail occurred but was not reported to the ESWD. The lightning model training region covered a much larger area since the detection efficiency of ATDnet is comparatively stable throughout the domain".

(ii) If a hail report is within the ESWD, how do you connect the report to the corresponding gridpoints (in space and time)?

Authors: Thank you for raising this point. We now clarified how reports are connected to the surrounding grid box and associated temporarily with the ERA5 reanalysis. A new paragraph has been added to the manuscript:" Lightning and hail reports were gridded on a 0.25° x 0.25° grid box, the same horizontal resolution of the ERA5 reanalysis. In addition, the time of reports was rounded down to the nearest full hour. This allowed to best sample the pre-convective environment associated with each lightning observation or hail report as done by Rädler et al. (2018) and Taszarek et al. (2021b).".

(iii) Judging from the figures in other sections, you apply AR-ChaMo per ensemble member. This should be stated explicitly.

Authors: Yes we do so. See section (v) of the review document.

(iv) Given that you also refer to a "Ensemble mean probabilistic forecast" (e.g. captions of figures 3 and 4 and also line 51 or line 170), how do you compute this mean forecast? Is it the mean of the forecasted probabilities of AR-ChaMo on the individual ensemble members?

Authors: Yes it is. This has now been clarified at the beginning of section 5 in the manuscript.

(v) What exactly would your forecast-product look like, i.e. what should a forecaster see? Do you want to forecast a probability per member or a single probability that is a combined/mean probability derived from all ensemble members? If it is the latter, I suggest to add a figure of that combined probability.

Authors: The purpose of this section is exclusively to present the AR-CHaMo as the conceptual base for our probabilistic forecasts, its framework and the way it was developed. The application of the model (to different ensemble members or to the ensemble mean) is presented in Section 3 and 4 where we add more explanation regarding the points being raised here e.g., applying it to each ensemble member. In section 3 and 4 we display both the forecast per ensemble member and the ensemble mean.

- Section 2.2: Does the ECMWF model change from 46r1 to 47r1 (as mentioned in line 71) have an impact on the training of AR-ChaMo?

Authors: No we don't expect this to have had an impact on training or application of AR-CHaMo. To clarify in the text we added the following: "Such change in IFS cycle is not expected to have caused discontinuities in convective parameters calculation (e.g., in CAPE) since the convection scheme was not modified from 46r1 to 47r1."

- Section 2.3: How many hail reports are within your trainingset?

Authors: Good point! We added a sentence mentioning the amount of lightning and hail reports: "In total, 10872890 lightning observations and 5493 reports of large hail were considered within the verification dataset."

- Section 3:

(i) Why do you adapt the model based on ERA5 with this complicated process and not retrain it on the reforecast-data?

Authors: That is not possible, since reforecasts are run only twice a week. To sample the conditions associated with large hail well, we would need a forecast time close to the *analysis time, and the forecasts are available only every 6 hours. This leaves very few times at which we would have both a reasonably accurate and temporally nearby estimate of the state of the atmosphere to any hail report, and definitely too few cases to train the model on.*

A paragraph detailing these limitations and the reasons for the chosen approach has been added to the Section.

(ii) Where do all these adaptation-formulas come from, i.e. how are they derived?

Authors: Thank you for pointing this out. We clarified this in the text: "following Eq. (3), based on the assumption that each hour probability is independent of that in another hour". Eq. 3 simply regards the probability of each hour being independent of that in another hour. We know that this is not necessarily true, but we wanted to keep the approach simple rather than additionally considering the correlations between probabilities between adjacent hours.

With Eq. 3 we want to transform the 1 hour probability output from the model to a 3 hour equivalent. To clarify this, let's take an example: If we have 10% chance in the first hour and 10% in a second hour, we can have these possibilities:

*event in first hour and event in second hour: P = 0.1 * 0.1 = 0.01. Event in first hour but not in second hour P = 0.1 x 0.9 = 0.09. Event in second hour but not in first hour P = 0.9 x 0.1 = 0.09. Event not in first and not in second hour: P = 0.9 x 0.9 = 0.81. So, chance of one or more events = 0.01 + 0.09 + 0.09 = 0.19. The chance of zero events = 0.81. The formula generalized this to three probabilities.*

The same concept applies for Eq. 2 with the difference that instead of the hourly periods it uses the ratio of the surface areas.

(iii) Please clearly state the quantities that your lightning model and your hail model try to forecast, e.g.: The probability of occurrence of at least two lightnings within 3 hours and an area of 0.2°x0.2°.

Authors: We modified the last sentence of Section 3 to the following: "With these adaptations, we applied the AR-CHaMo based on ERA5 to ECMWF reforecasts yielding 3 hourly ensemble lightning and hail probabilistic forecasts at 0.2° x 0.2° spatial resolution for the period 2008-2019 and the whole of Europe" adding mentions about the probabilistic nature of the forecast, the temporal and spatial resolution.

- Line 96: You state that the probabilities are calibrated. Please add some reliability plots.

Authors: Thank you for pointing this out. "Calibrated" is indeed the wrong choice of word here. No calibration of modeled output to the observations was performed here. For "calibrated" here we mean that the probabilities had to be adapted from an ERA5 grid

(0.25° x 0.25°) to an ECMWF reforecast one (0.2° x 0.2°). In this regard, please refer to equation 2. To clarify this, we modified “calibrated” to “adapted”.

- Line 108: Did you also upscale the observations?

Authors: The observations were also accumulated at 3 hourly intervals for verification purposes. The procedure is explained at lines 172-175: “Ensemble mean probabilistic forecasts were systematically verified against … hail reports from the ESWD in the three hours following the forecast time (00– 03UTC, 06–09UTC, 12–15UTC, 18–21UTC).

- Line 123: How did you upscale the probabilities?

Authors: The probabilities were upscaled using equation 2 but instead of an ECMWF and ERA5 grid size we converted the ECMWF grid size to the equivalent of a 25 miles grid box. Effectively the forecasts were adapted to an ECMWF grid (from an ERA5 one) and then upscaled to yield the equivalent probability over a 25 miles grid. To clarify this in the text we added a reference to Equation 2.

- Lines 166-167: To be more precise, you showed that for this case the forecast was skilful up to 108h in advance but a single case study cannot support such a conclusion in general.

*Authors: Thank you for the comment. Indeed we agree one case study is not enough to say that our forecasts are skillful at a certain lead time. With lines 166-167 we want to point out that “**For** this case study … the logistic model provided a skillful forecast up to 108 hours”, not that the model is always skillful up to 108 hours. To provide a more objective and general validation of the AR-CHaMo models we systematically evaluated their performance throughout the whole period 2008-2019 using AUC scores in Section 5.*

To highlight the fact that we are not drawing conclusions on the performance of the model only on the base of a case study, a sentence at the beginning of Section 5 has been added to the manuscript: “In order to provide an evaluation of the model’s skill not tied to a single case study, the ensemble mean probabilistic forecasts were systematically verified …”

- Section 5: Please add a few sentences that clarify the quality aspect that is covered by the AUROC-score.

Authors: Yes, good point. We added a sentence describing the role of the AUC scores in our study, namely measuring: “the ability of the hail (lightning) model to discriminate between hail (lightning) and non-hail (non-lightning) situations. AUC values can range from 0 to 1: a model that has an AUC of 0.5 has the same skill of random guessing, the closer the AUC is to 1 the better the model can classify observations into classes. More specifically, an AUC of 0.8 to 0.9 is considered excellent, and more than 0.9 is considered outstanding (Hosmer et al. 2013). “

- Line 172: In section 2.3 you define a lightning case as a one-hour period. Now you consider a three-hour period. What is the final product? Mixing of both products is misleading.

Authors: Thank you for the comment. Indeed there is a lack of consistency between section 2.3 and line 172. A lightning case is defined as a three-hour period with at least two lightning strikes per grid box. This has now been modified in the text in section 2.3.

- Line 183: Are the 1-dimensional logistic regression models trained on the same trainingset (where the appropriate quantities are computed) as AR-ChaMo?

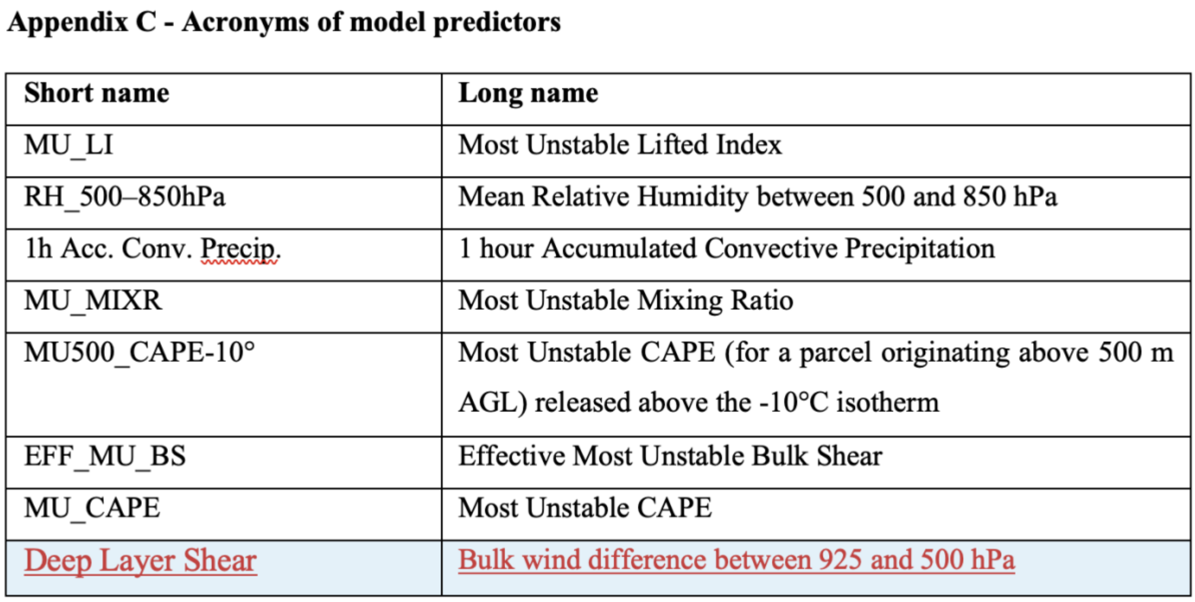
Authors: Yes, they were trained on the same dataset. To clarify this in the text we added a sentence to this section: "The performance of ARhail was compared with that of 1-dimensional logistic models trained using CAPE-shear and SHP as predictors and the same training dataset as for ARhail".

- Appendix B: Maybe I missed it but I think there is no reference to appendix B suggesting that this appendix is not needed.

Authors: There is a reference to Appendix B in lines 164-165: "The T-108-hour lightning forecast (Appendix B) was also in good agreement with the T-12-hour forecast"

- Appendic C: The caption of the table says that this is the list of parameters that enter AR-ChaMo based on ERA5. I suggest to extend that table to also give a list of parameters that enter the AR-ChaMo model used in present study.

Authors: Good point. The new predictors that entered AR-CHaMo model used in the present study are: Deep Layer Shear, Specific humidity at 925 and Wet Bulb Zero height. We have added them to the table. Since specific humidity and wet bulb are explicitly mentioned in the text without acronyms they were not included in Appendix C. Deep Layer Shear was included with its definition: "Bulk wind difference between 925 and 500 hPa".

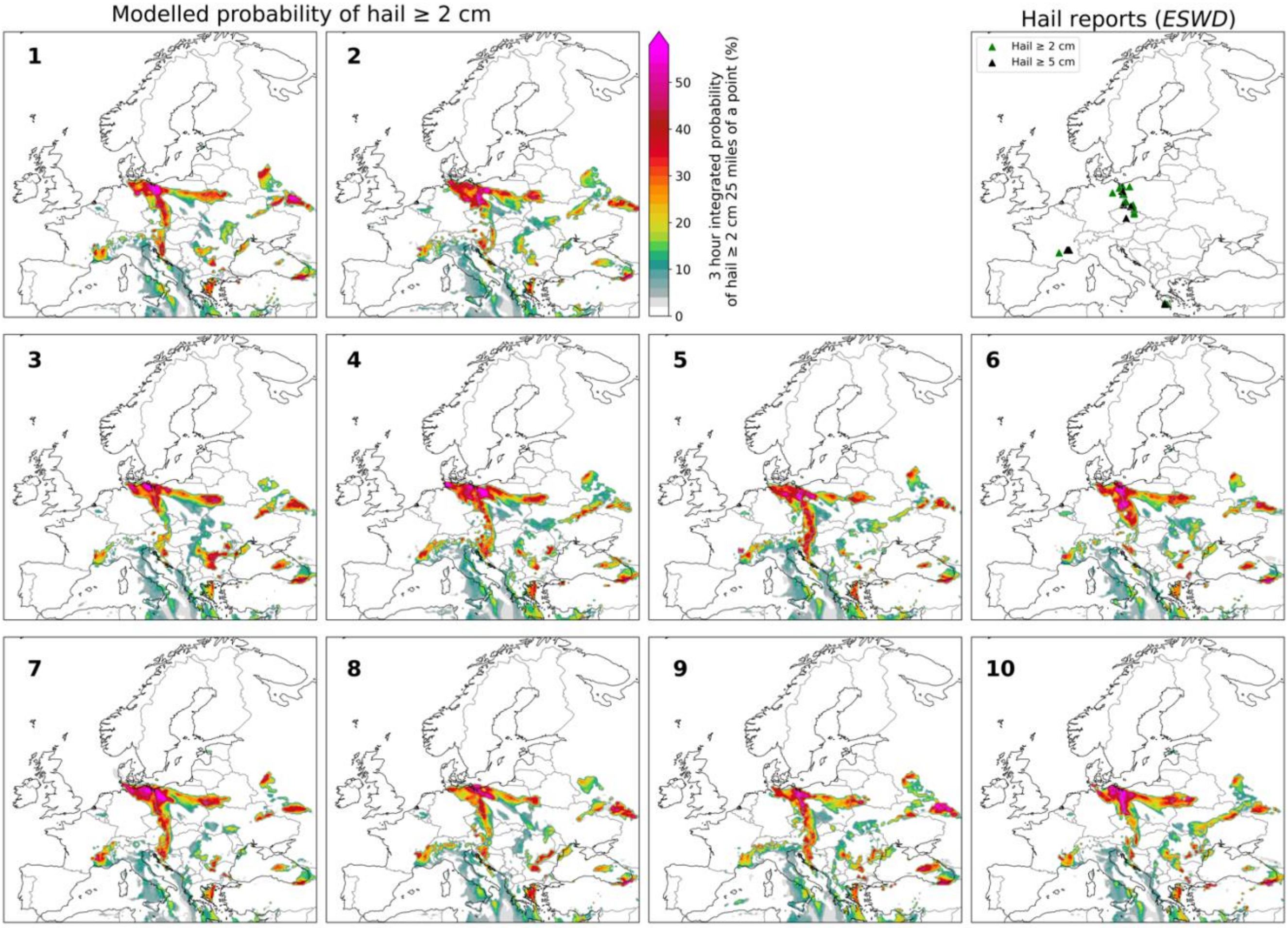


Appendix C - Acronyms of model predictors

Short name	Long name
MU_LI	Most Unstable Lifted Index
RH_500–850hPa	Mean Relative Humidity between 500 and 850 hPa
1h Acc. Conv. Precip.	1 hour Accumulated Convective Precipitation
MU_MIXR	Most Unstable Mixing Ratio
MU500_CAPE-10°	Most Unstable CAPE (for a parcel originating above 500 m AGL) released above the -10°C isotherm
EFF_MU_BS	Effective Most Unstable Bulk Shear
MU_CAPE	Most Unstable CAPE
Deep Layer Shear	Bulk wind difference between 925 and 500 hPa

- Figures 1, 4, 5: I suggest to add a panel that contains the guidance from the other composite indices for comparison.

Authors: Thank you for pointing this out. To take this comment in consideration we produced forecasts for the 15th of June 2019 and three initialisation times (T-12h, T-108h, T-180h) - as for AR-CHaMo - but for the 1-dimensional logistic models based on SHP and CAPESHEAR. The 12 hour forecasts plots (now Figure 3 and Figure 4) have been added to the main text along with a discussion of the main differences with the AR-CHaMo output in Section 4.1: "To compare the AR-CHaMo forecast with that of existing composite parameters, we produced probabilistic hail forecasts for the same timestep and initialization time based on two 1-dimensional logistic models trained using SHP (Figure 3) and CAPESHEAR (Figure 4). The SHP model is in agreement regarding the Germany-Poland-Czechia and south-eastern France regions, but compared to AR-CHaMo, yields high hail probabilities also across regions where no hail was reported e.g., the Balkans and Eastern Europe. The CAPESHEAR model, on the other hand, identifies well the south-eastern France region but places the highest probability of hail across northern Germany and northern Poland away from the highest density of hail reports to the south.“ The plots for the longer lead times have been added to the Appendix.



Modelled probability of hail ≥ 2 cm
Hail reports (ESWD)
Hail ≥ 2 cm
Hail ≥ 5 cm
3 hour integrated probability of hail ≥ 2 cm 25 miles of a point (%)
0
10
20
30
40
50
1
2
3
4
5
6
7
8
9
10

Figure 3: Probabilistic ensemble forecast of hail occurrence based on a 1D logistic SHP model for the 15th of June 2019 at 12:00 UTC (initialized on the 15th of June 2019 at 00:00 UTC). Hail reports between 12:00 UTC and 15:00 UTC are shown as triangles (green for hail ≥ 2 cm but ≤ 5 cm, black for hail ≥ 5 cm) in the right-top panel.

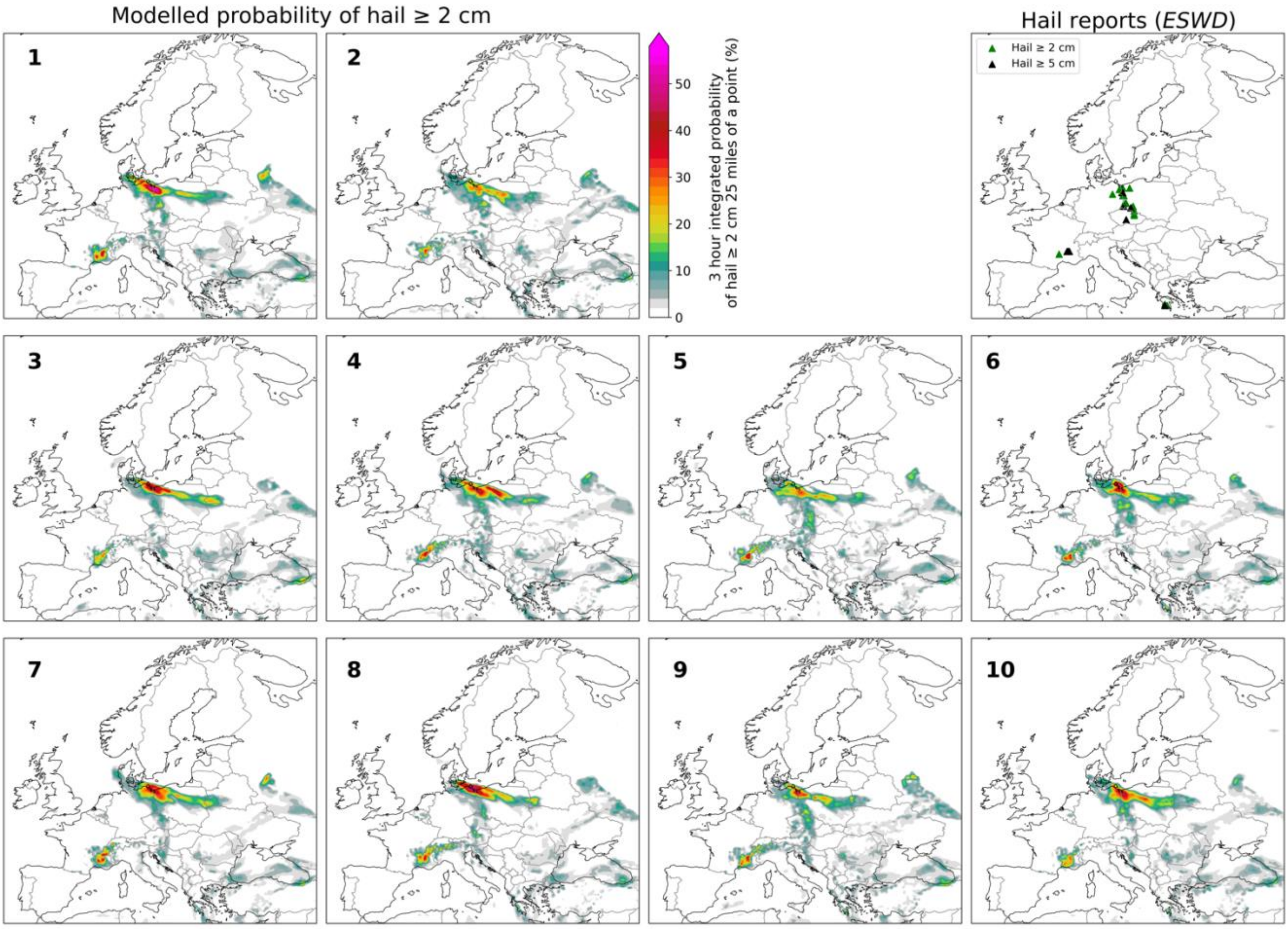

Modelled probability of hail ≥ 2 cm
Hail reports (ESWD)
Hail ≥ 2 cm
Hail ≥ 5 cm
1
2
3
4
5
6
7
8
9
10
50
40
30
20
10
0
3 hour integrated probability of hail ≥ 2 cm 25 miles of a point (%)

Figure 4: Probabilistic ensemble forecast of hail occurrence based on a 1D logistic CAPESHEAR model for the 15th of June 2019 at 12:00 UTC (initialized on the 15th of June 2019 at 00:00 UTC). Hail reports between 12:00 UTC and 15:00 UTC are respectively as triangles (green for hail ≥ 2 cm but ≤ 5 cm, black for hail ≥ 5 cm) in the right-top panel.

Technical comments:

- Lines 66, 89: I think it should read "Table C1"?

Authors: Thank you for pointing this out. The reference to Table 1 is correct. We noticed that Table 1 was not correctly copied in the preprint, hence the confusion about the reference. The comment was addressed by adding Table 1 in the text.

- Line 88: It should read "Battaglioli et al. (2023)".

Authors: Thank you. I added the parentheses.

- Lines 92, 94: There is no Table 2.

Authors: Thank you for pointing this out. For some reason both Table 1 and Table 2 did not make it in the preprint. Both tables have been added at the bottom of the manuscript before Figure 1.

- Line 129: It should read "...France. This...".

Authors: Yes, thank you for pointing this out. I added a full stop between "France" and "This".

- Line 138, 139: It should read: "...probabilities for lightning...".

Authors: Modified to "probabilities of lightning".

- Line 191: I think it should read "Section 4.3"?

Authors: Yes indeed, it should read "Section 4.3". This has been corrected in the text.

- Lines 194, 197: Prior to this section you used the British version "skilful" instead of "skillful".

Authors: True, in order to keep consistency, all "skillful" in text have been modified to "skilful".

- Line 194: I think it should read "based on the period" instead of "for the period".

Authors: In this case we mean "for the period" meaning that we are applying the models to all available ensemble forecasts between 2008 and 2019. The comment probably refers to the fact that the logistic models were also trained "based on the period" 2008-2019 but in this case that is not what we are referring to. For this reason, we left "for the period" in the text.

References:

1. Groenemeijer, P., and T. Kühne, 2014: A Climatology of Tornadoes in Europe: Results from the European Severe Weather Database.Mon. Wea. Rev., 142, 4775-4790, doi:10.1175/mwr-d-14-00107.1.

2. Rädler, A. T., P. Groenemeijer, E. Faust, and R. Sausen, 2018: Detecting Severe Weather Trends Using an Additive Regressive Convective Hazard Model (AR-CHaMo). J. Appl. Meteor. Climatol., 57, 569–587, https://doi.org/10.1175/JAMC-D-17-0132.1

3. Taszarek, M., J. Allen, P. Groenemeijer, R. Edwards, H. Brooks, V. Chmielewski, and S. Enno, 2020(a): Severe Convective Storms across Europe and the United States. Part I: Climatology of Lightning, Large Hail, Severe Wind, and Tornadoes. J. Climate, 33, 10239- 10261, doi:10.1175/jcli-d-20-0345.1.

4. Taszarek, M., N. Pilguj, J. Allen, V. Gensini, H. Brooks, and P. Szuster, 2021b: Comparison of convective parameters derived from ERA5 and MERRA2 with rawinsonde data over Europe and North America. J. Climate, 1-55, doi:10.1175/jcli-d-20-0484.1.