

1

TABLE OF CONTENTS FOR THIS DOCUMENT

2

3

1. Authors response to referee #1

4

2. Authors response to referee #2

5

3. Additional changes to the revised manuscript

6

4. A marked-up version of the manuscript

AUTHORS' RESPONSE TO REFEREE #1

Research article:

Comparing an insurer's perspective on building damages with modelled damages from pan-European winter windstorm event sets: a case study from Zurich, Switzerland (Nat. Hazards Earth Syst. Sci. Discuss., <https://doi.org/10.5194/nhess-2020-115>, in review; submitted on 07 April 2020)

Authors:

Christoph Welker, Thomas Röögli, David N. Bresch

We thank the referee Dr. Alexandros Georgiadis for his comments, which have improved the quality of the manuscript.

The original comments from the referee are listed below directly followed by our responses in blue and italic and changes to the manuscript in blue and bold.

The main objective of the paper is to demonstrate the value of catastrophe modelling analysis in respect of estimating the frequency of high intensity storms, compared to a pure statistical analysis of the claims history from a portfolio that has a limited record of a few decades. Two catastrophe models with different vulnerabilities and exposures are used to calculate the losses, GVZ's proprietary model and the open source CLIMADA platform. Both models perform very well in calculating the losses of a numbers of historical storms (e.g. Vivian, Lothar, Burglind) so are clearly appropriate tools for the stated job. The selected hazard inputs include the: (i) WISC historical set of 75 years with 142 events and (ii) a probabilistic perturbation of the above event set, where every storm has 29 altered offsprings, thus the set is extended to have 4,260 storms covering 2,250 years. On the other hand, the insured claims dataset consists of about 40 years of losses that provides 18 storms which are available in the WISC historical set. Overall, I think that the presented work is of high quality: there are no obvious methodological errors and the findings are robust regarding the stated purpose, to complement claims-based risk assessment with a modelling approach. The conclusion that the return period of intense storms (like Lothar) cannot be determined sufficiently from a simple analysis of claims history is robust, but also well

established in the Insurance industry. The proposed approach to produce a probabilistic event set by perturbing/expanding the WISC historical events, then calculate the losses using one or more damage models is technically correct and appropriate but it is not novel. Focusing on the results, I think that risk assessment at the tail will benefit from an attempt to build a more focused estimation of the uncertainty associated with the WISC probabilistic exceedance probability curves in Figure 2. The confidence interval based on the WISC historical set (CHF 19M to 33000M) is very conservative and negates much of the fundamental advantage of complementing risk assessment with probabilistic catastrophe modelling. I think that this is the major point to be addressed in the analysis, thus I would recommend publishing the article conditionally the authors provide a substantial response to this question (see below, bullet points: 2.a-c).

In the eyes of both referees, the uncertainty of the probabilistic event set “WISC probabilistic extension” should be discussed in more detail. Nonetheless, they have different opinions about the uncertainty estimations: While Referee #1 writes that “the confidence interval based on the WISC historical set [...] is very conservative and negates much of the fundamental advantage of complementing risk assessment with probabilistic catastrophe modeling”, Referee #2 writes that “the authors correctly state in their discussion [...], the ‘WISC probabilistic’ dataset does not reduce uncertainty compared to ‘WISC historic’ because they’re based on the same data”.

The opposing ways of interpretation of both referees show that there are obviously different ways of interpretation about whether the uncertainty of risk assessment can be reduced by a probabilistic event set based on the same data. In a way, we represent the “conservative” way of interpretation in our paper, i.e. that the uncertainty cannot be reduced by statistical perturbation, and we would like to continue to support this way of interpretation. We will discuss this further below.

In this response, we will show that the illustration of uncertainty, as requested by Referee #1, partly ignores the parameter uncertainty and that is why the full uncertainty cannot be illustrated easily. We will mention the uncertainty more often as requested by Referee #2.

In the following, we would like to briefly clarify our way of interpretation of the uncertainty associated with historic and probabilistic event sets in general and in the case of this paper:

(1) *Historic event sets:*

Regarding the risk from rare events, an important source of uncertainty is the sampling uncertainty. In this paper, we illustrate the sampling uncertainty of both insurance claims data and modelled damages based on “WISC historic” by showing the 90-% confidence interval derived by resampling (see Fig. 2).

(2) *Probabilistic event sets:*

As Referee #1 summarises, a probabilistic event set can be generated by statistical perturbation and by using dynamical models. The sources of uncertainty are different for both approaches. In the following, we only want to discuss statistical perturbation, as this was the subject of the paper. We used statistical perturbation with two parameters with the aim of representing the distribution of pan-European windstorm severity. By doing this for the best-fit distribution, we transformed the sampling uncertainty of the severity of historic windstorm events into parameter uncertainty of our model. However, as our statistical approach does not add any additional information, the uncertainty is finally not reduced. In our opinion, only if the process of generating a probabilistic event set does include additional information one could argue in favour of the probabilistic event set reducing uncertainty.

As this interpretation and argumentation needs to be clarified in the manuscript, we will incorporate it at different points throughout the revised manuscript.

Also suggestions to further expand the work (beyond the scope of the current article) are available in the end of bullet point 1.

More specifically, I will address the following scientific question/issues:

- (1) The proposed approach to produce a probabilistic event set by perturbing/expanding the WISC historical events is technically correct and appropriate given the scope of the analysis. Having said that, although acceptable, the approach is not novel. Several (re)insurers have proprietary cat models that follow similar methodologies. A limited historical ‘seeding’ data-set (often based on reanalysis data, e.g. 20C_R, ERA-Int, ECMWF_R) is extended either by a statistical perturbation/resampling approach (e.g. Swiss Re) or extensive use of dynamical modelling (usually regional climate modelling-RCM) outputs (e.g. Weather Predict/Renaissance Re, Partner Re) to produce a realistic

probabilistic event set. The advantage of the latter is the physical consistency of each individual stochastic event due to the physics-based simulation of the RCM. Furthermore, the main catastrophe model vendors in the market (RMS, AIR, AON Impact forecasting and more) tend to provide probabilistic windstorm solutions based on outputs extracted for a variety of long global climate model (GCM) runs, calibrated (often fitted) against the available historical record. The advantage of this approach is that the simulation generates physically realistic storms that are not constrained by the attributes/parameters of the seeding historical windstorms.

As the referee rightly states, there are many different ways to assess the risks from European winter windstorms. We show two possible approaches in this paper, i.e. a methodology implemented in a proprietary model and one in an open source model, and discuss which uncertainties have to be considered with these two approaches. Furthermore, we check the reliability of the open source impact model CLIMADA with both GVZ's claims data and output from their proprietary damage model. Those kinds of proprietary data are usually not available for scientific publications.

The paper was not necessarily about showing a new methodology. In our view, the recent development of freely accessible data on windstorm footprints (WISC) in combination with an open source damage model (CLIMADA) opens up new opportunities for applied research and provides a straightforward entry point for insurance companies to model the risks associated with winter windstorms in Europe – thus providing an additional / alternative perspective compared to inhouse or commercial models (as listed by the referee above). The application example we give is something new because of the open source concept presented.

Such methodologies directly address the main limitation of the WISC probabilistic expansion approach used by the authors that results to almost identical AAD values in Tables 2 (1.4M CHF) and A1(1.1M-1.2M CHF) for the WISC historic and probabilistic sets. The probabilistic expansion adds very little further risk hazard information compared to the seeding historical set. A possible avenue for the authors to continue the current work would be to look into calibrating the WISC synthetic gusts distribution (in figure A1, lines 793-797) against the WISC historical event set to address the low gust

speed intensity. Then repeat the loss calculation with the ‘enhanced’ WISC synthetic event set.

We thank the referee for his suggestion to calibrate the distribution of the event set "WISC synthetic" against "WISC historic". However, we do not think that this would be successful in the case of "WISC synthetic" for the following reason.

The event set "WISC synthetic" contains wind gust footprints for around 23'000 synthetic windstorms: i.e., three sets of 7'660 events each. In each of the three sets a different approach was applied to carry out a calibration (see https://wisc.climate.copernicus.eu/wisc/#/help/products#eventset_section), which however ultimately did not solve the problem of a generally lower severity of the synthetic windstorm events compared to the historic ones. It is possible, that such a calibration would be more successful, if applied to hourly wind gust data, before the aggregation to 72-hour events is done. This is analogous to the conclusion about correcting WISC wind gust data for higher altitudes in Marseille et al. (2017).

We agree with the referee, that in general, a probabilistic event set originating from dynamical modelling could provide new information and would allow to reduce the uncertainty, which is the main limitation of our WISC probabilistic expansion approach. We think this is an important statement, that we would like to include as an outlook in the revised manuscript. We suggest to add the following sentence at L495:

“In future studies, the information from dynamical models, which are run for many model years, would help to further reduce this uncertainty.”

- (2) The approach to expand the WISC historical events and determine the frequencies of the offspring probabilistic storms (GEV distribution fitted to the historical SSI values) has merit, and the concluding results in paragraphs 3.2 and 3.3, also provided in table 2, are realistic. I am not surprised the two WISC-based analyses reduce the calculated AAD value between 1.1 and 1.4M CHF. Also, Lothar/Martin’s return period is (correctly) positioned at and above 75 yrs, potentially beyond 125 yrs. Considering the disproportional yet uncertain impact of the extreme event Lothar/Martin on the claims data analysis, the above results are plausible, yet the authors do not follow with a narrower estimation of the uncertainties. I understand why the authors prefer to retain the

confidence interval based on the WISC historical set (CHF 19M to 33,000M), yet this reduces somewhat the functionality of the probabilistic expansion model. It's main objective is to provide a tail view. Here are a few suggestions:

- a. The 4,260 storms in the WISC probabilistic set provide the equivalent of 2,250 years of storm activity (based on the analysis assumptions). You may sample randomly the equivalent of 250 or 500 years of storms and build multiple exceedance frequency curves for each sample. A spaghetti plot of the 'secondary' exceedance frequency curves will enable a reviewed estimation of the uncertainty around the curve. Essentially the idea is not dissimilar to the re-sampling approach described in paragraph 2.4.3 for the Pareto Pricing.
- b. Estimate multiple probabilistic extensions of the WISC historic event set with different initial assumptions including (but not limited to) fitting different extreme distributions (e.g. Weibull, Pareto), inclusion/exclusion of Lothar/Martin in the seeding WISC historic set to quantify the sensitivity of the methodology in the most extreme event in the set, for both damage models (GVZ & CLIMADA). This will produce an ensemble of exceedance frequency curves that can be visualized as a spaghetti plot.
- c. A combination of the above two ideas can work as well.

We thank the referee for his suggestions. We have implemented all of them and discuss the results in the following. As a conclusion, we would still argue, that the yellow ribbon in Fig. 2 (i.e., the sampling uncertainty of the modelled damages based on "WISC historic") is the best illustration of the uncertainty for "WISC probabilistic extension". We will include this argumentation in the manuscript, alongside the arguments already provided in this response.

Following the referee's suggestion 2a and based on our data sample of total damages modelled based on the hazard event set "WISC probabilistic extension" and the GVZ damage model (red diamonds in Fig. 2), we sampled randomly the equivalent of 500 years of windstorms and built an exceedance frequency curve for each sample (number of samples = 1'000). Accordingly, the red shading in Fig. R1-1 shows the 90-% confidence interval as a result of the random resampling.

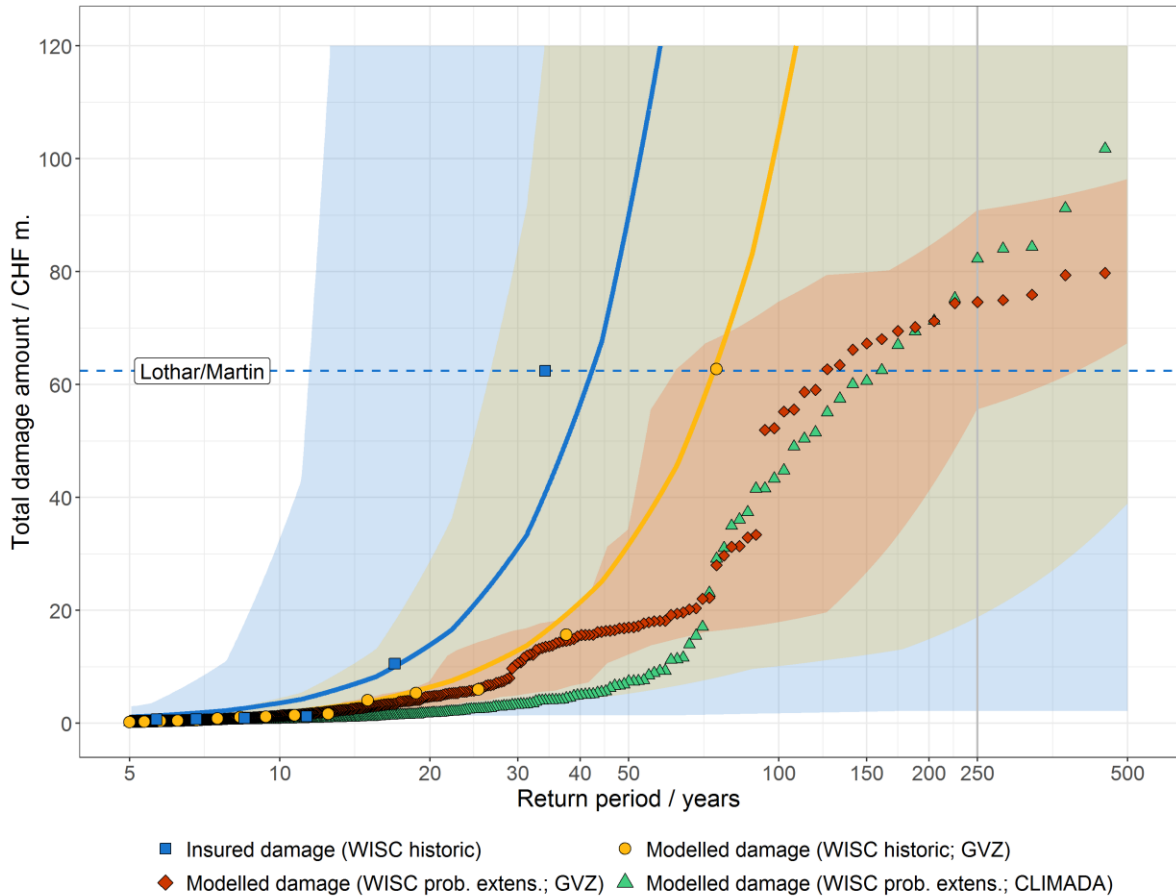


Figure R1-1: Modified Fig. 2. New is the red shading, which shows the 90-% confidence interval for the modelled damages based on “WISC probabilistic extension” and the GVZ damage model computed by applying the referee’s suggestion 2a.

We are aware that the parameter uncertainty regarding the event set “WISC probabilistic extension” is important, especially in comparison with “WISC historic”. However, in our opinion this source of uncertainty is not fully estimated and sufficiently illustrated with such a resampling methodology.

Following the referee’s suggestion 2b, to include / exclude Lothar/Martin in the seeding, we tried a more systematic approach. We resampled (choice with replacement) the historic events (same number of events in each sample; choosing with replacement means some events are missing, whilst others are double). Then we created a probabilistic event set for each of these samples. The 90-% confidence interval is again given by the 5th and 95th percentiles of all samples. This is the best possible way we achieved to illustrate at least part of the uncertainty that originates from the fact that the best-estimate of the

distribution of the pan-European Storm Severity Index is unknown and thusly the parameters for the creation of the probabilistic sets can only be chosen with a certain degree of uncertainty. The uncertainty estimation up until a 30-year return period follows approximately the uncertainty estimation for “WISC historic”; at higher return periods the uncertainty estimation is levelling off, probably due to the limited ability of our probabilistic approach to create very different (e.g., much stronger) events from the seeding historic set. Therefore, we argue that the shown difference between the yellow ribbon and the red ribbon could be misleading.

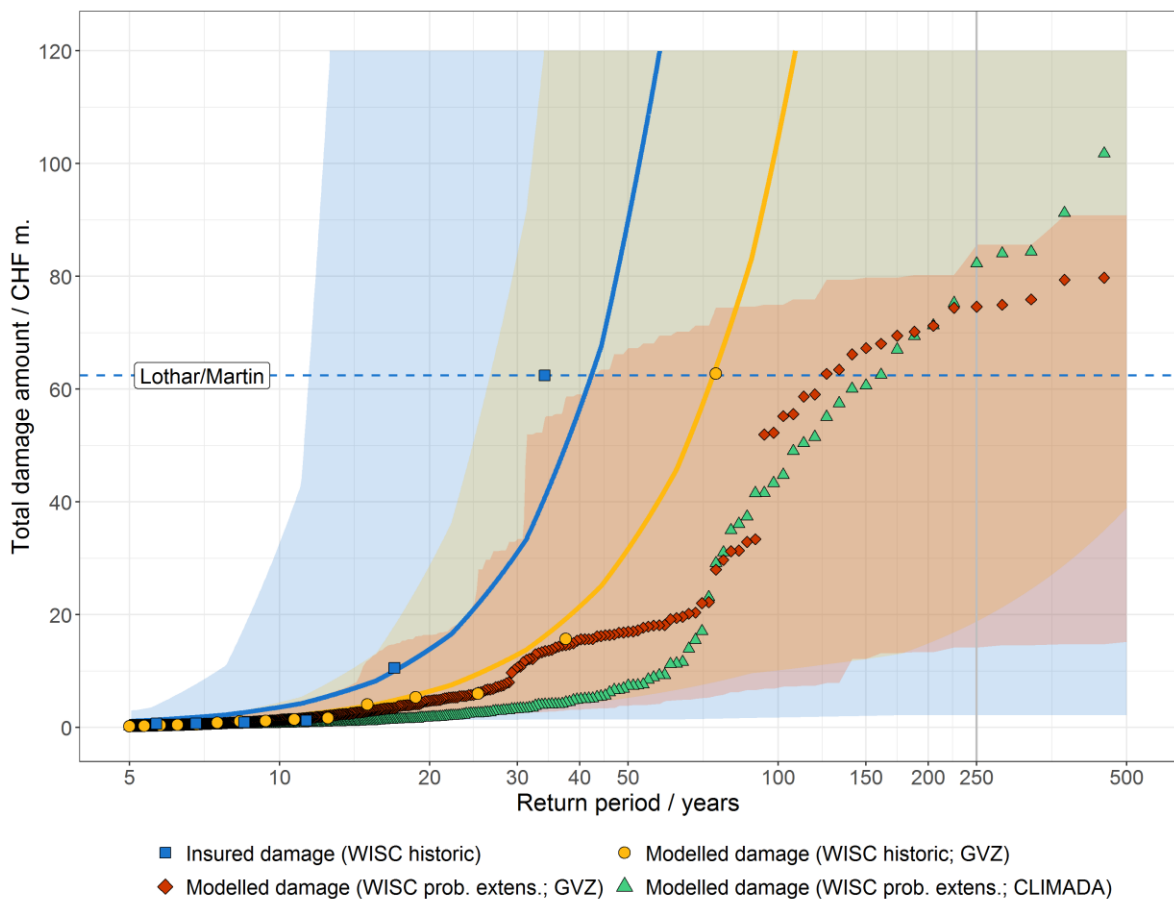


Figure R1-2: Analogous to Fig. R1-1 but here the red shading shows the 90-% confidence interval for the modelled damages based on “WISC probabilistic extension” and the GVZ damage model computed by applying the referee’s suggestion 2b.

The results for the referee’s suggestion 2c, which is a combination of his suggestions 2a and 2b, are given in Fig. R1-3. Firstly, we resampled (number of samples = 100) the historic events and then used these different historic samples to create an ensemble of probabilistic damage event sets (as suggested in 2b). Secondly, for each new

probabilistic damage event set, we sampled (number of samples = 20) randomly the equivalent of 500 years of windstorm events and built an exceedance frequency curve for each sample (as suggested in 2a). From this set of resampled and bootstrapped damage event sets (total number of samples = 2000), we then calculated the 90-% confidence interval. Whereas this combination provides a smooth illustration of the resampling uncertainty, it still suffers from the same problem as the illustration in Fig. R1-2. Therefore, we would still argue that the yellow ribbon in Fig. 2 is the best illustration of the uncertainty for “WISC probabilistic extension”.

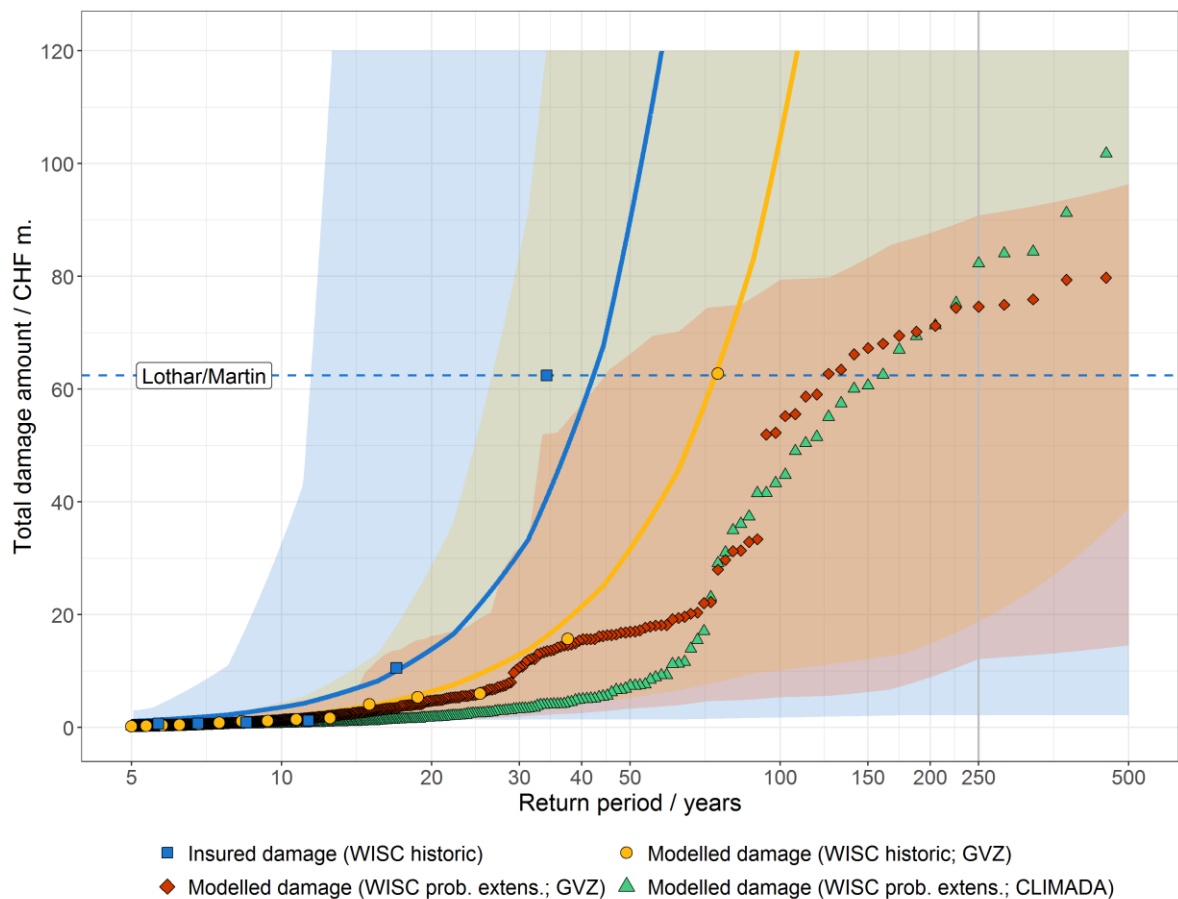


Figure R1-3: Analogous to Fig. R1-1 but here the red shading shows the 90-% confidence interval for the modelled damages based on “WISC probabilistic extension” and the GVZ damage model computed by applying the referee’s suggestion 2c.

- (3) One aspect which is underrepresented in the discussion is the role of the loss uncertainty due to the vulnerability (and exposure) components. GVZ’s damage model has a stochastic component as seen in figure 4, also described in the text (lines 443 to 449), yet it is unclear whether the damage (given by the red bars in figure 4) informs the process of

building the exceedance frequency curve of the modeled damage based on the WISC probabilistic extension of figure 2. Please clarify.

The range of the modelled damages through the stochastic component in GVZ's damage model (represented by red bars in Fig. 4) is not directly included in the calculation of the exceedance probabilities in Fig. 2. Rather, we use the median of the damage range modelled for each event to calculate the exceedance probabilities.

Additionally, we suggest to include the uncertainty related to vulnerability and exposure in the following sentences at L510:

“A disadvantage of the used vulnerability curve is that it does not implicitly provide a quantification of the uncertainty as a probabilistic vulnerability curve would (e.g., Heneka et al., 2006; Prahl et al., 2012). The quantification of the uncertainty of exposure and vulnerability information was generally omitted in this study to focus on the comparison of the claims and hazard datasets. But of course, for comparison of the presented risk numbers with other studies the uncertainty of the vulnerability and exposure information play a bigger role.”

The two references used have also been included at L659 and L688:

“Heneka, P., Hofherr, T., Ruck, B., and Kottmeier, C.: Winter storm risk of residential structures – model development and application to the German state of Baden-Württemberg, Nat. Hazards Earth Syst. Sci., 6, 721–733, doi:10.5194/nhess-6-721-2006, 2006.”

“Prahl, B. F., Rybski, D., Kropp, J. P., Burghoff, O., and Held, H.: Applying stochastic small-scale damage functions to German winter storms, Geophys. Res. Lett., 39, L06806, doi:10.1029/2012GL050961, 2012.”

- (4) The two modelling approaches (GVZ damage model & CLIMADA impact model) use different input exposures as described in lines 272 for GVZ's model and 303 for CLIMADA. Is it possible to get a feeling regarding the difference between the two input exposures (e.g. 10%, 50%)?

The GVZ damage model uses an exposure information (i.e., insured value of the buildings in the canton of Zurich) which sums up to approximately 480 billion CHF. The exposure used in the CLIMADA impact model sums up to 80 % of that value.

In this context, it is important to emphasise that differences in the total exposure values, compared to the GVZ damage model, were partially compensated by calibrating the damage functions in the CLIMADA impact model, in order be able to reproduce event damages comparable to those from the insurance claims database. We used publicly available exposure information in CLIMADA and not GVZ's proprietary portfolio information because of the open source concept presented in this paper. This way the presented methodology can be easily applied to other regions.

References used in this response

- Heneka, P., Hofherr, T., Ruck, B., and Kottmeier, C.: Winter storm risk of residential structures – model development and application to the German state of Baden-Württemberg, *Nat. Hazards Earth Syst. Sci.*, 6, 721–733, doi:10.5194/nhess-6-721-2006, 2006.
- Marseille, G. J., Stoffelen, A., van den Brink, H., and Stepek, A.: WISC Bias Derivation and Uncertainty Assessment, [https://wisc.climate.copernicus.eu/wisc/documents/shared/\(C3S_441_Lot3_WISC_SC2-D3.3-CGI-RP-17-0071\)%20\(Final%20Bias%20Derivation\)%20\(v1.0\).pdf](https://wisc.climate.copernicus.eu/wisc/documents/shared/(C3S_441_Lot3_WISC_SC2-D3.3-CGI-RP-17-0071)%20(Final%20Bias%20Derivation)%20(v1.0).pdf), 2017.
- Prahl, B. F., Rybski, D., Kropp, J. P., Burghoff, O., and Held, H.: Applying stochastic small-scale damage functions to German winter storms, *Geophys. Res. Lett.*, 39, L06806, doi:10.1029/2012GL050961, 2012.

AUTHORS' RESPONSE TO REFEREE #2

Research article:

Comparing an insurer's perspective on building damages with modelled damages from pan-European winter windstorm event sets: a case study from Zurich, Switzerland (Nat. Hazards Earth Syst. Sci. Discuss., <https://doi.org/10.5194/nhess-2020-115>, in review; submitted on 07 April 2020)

Authors:

Christoph Welker, Thomas Röögli, David N. Bresch

We thank the referee for comments, which have improved the quality of the manuscript.

The original comments from the referee are listed below directly followed by our responses in blue and italic and changes to the manuscript in blue and bold.

General comments

This paper compares windstorm risk estimations (such as annual average damage, exceedance frequency curves) in the canton of Zurich, Switzerland, using insurance claims data, and modelled damages with two models (GVZ and CLIMADA) using various hazard inputs ('WISC historic' and 'WISC probabilistic extension'). They find that the claims data is skewed by the extreme event Martin/Lothar, leading to a shorter return period for that storm and higher average annual damages compared to the results from the longer modelled datasets.

The paper is well written and the results are worthy of publication. My main issue is that I feel the conclusions about return periods derived from 'WISC probabilistic' may have been overstated. The authors correctly state in their discussion (L486-499), the 'WISC probabilistic' dataset does not reduce uncertainty compared to 'WISC historic' because they're based on the same data, but in some instances I think it is important to emphasise the uncertainty (I include examples in the 'specific comments' below).

Referee #2 raised as main issue the uncertainty of the results derived from the hazard event set “WISC probabilistic extension”. This is the same issue as raised by Referee #1. We would like to pick up the suggestions by Referee #2 and emphasise the uncertainty of our estimation more. We have also expanded our interpretation of the uncertainty in more detail in the response to Referee #1 and aim to clarify our interpretation of the uncertainty more clearly at different points throughout the manuscript.

Specific comments

1. Abstract L20: “Additionally, the probabilistic modelling approach allows assessing rare events, such as a 250-year return period windstorm causing CHF 75 million damages” – please emphasise the uncertainty here.

We now emphasise the uncertainty in L20:

“Additionally, the probabilistic modelling approach allows assessing rare events, such as a 250-year return period windstorm causing CHF 75 million damages, **including an evaluation of the uncertainties.**”

Please consider the given word limit for the abstract of a maximum of 200 words.

2. Section 2.2.2: I don’t think it’s necessary to describe ‘WISC operational’ and ‘WISC stochastic’ as they are not used. It is already mentioned in the introduction why you can’t use ‘WISC stochastic’ (L102; perhaps you could refer to fig A1 here), and the reasons for not using ‘WISC operational’ could also be discussed here.

To overcome the shortcomings of the event set “WISC synthetic”, we propose in addition the probabilistic windstorm hazard event set “WISC probabilistic extension”. We briefly describe “WISC synthetic”, since we used “WISC synthetic” for a comparison with “WISC probabilistic extension” in Fig. 1 and Fig. A1. We also think that readers are asking themselves about calibrating the wind gust information from “WISC synthetic” as suggested by Referee #1. We would therefore like to provide this information in a structured way, for which the data and methods section is suitable for.

“WISC operational” is described, basically to explain why we didn't use this event set in the context of the paper. We think that readers might ask themselves this question.

We would therefore like to keep this structure. Is that understandable?

3. Section 2.2.3 L209: please could you mention here that you describe how alpha and beta are chosen later in the section?

Yes, thank you for the hint. We suggest the following change to L207-209:

“The wind gust speeds were intensified and weakened by no more than 3 m/s (normally much less) according to the probabilistic alteration of wind speeds in Eq. (1), with a scale parameter $\alpha=0.0225$ and a power parameter $\beta=1.15$ (**choice explained further below**): [...].”

4. Equations (1) (L209-210): I presume this transformation is applied at each grid point, so that a wind speed from a grid point i becomes the $\text{windspeed}_{\text{original}}$ at grid point j in the shifted footprint? If so, how do you account for different properties of grid points i and j – for example, they could have very different roughness and altitudes (in an extreme case i could be over open water and j could be in a sheltered area, so would have much lower expected wind speeds).

WISC wind gust footprints are available at a spatial resolution of 4.4 km. Small-scale changes in both topography and ground cover can indeed strongly influence the characteristics of wind gusts. However, those small-scale changes cannot be resolved sufficiently well in a model with a horizontal resolution of approximately 4 km. In general, the canton of Zurich is characterised by a gentle to moderate topography (see Fig. A2a). For these reasons, we decided not to make a correction regarding the topography (and the ground cover) in our current model setup.

Nonetheless, we think the referee touches on an important point and a refinement of our methodology would be interesting for a follow-up study. It is conceivable that the quality of the windstorm footprints from “WISC probabilistic extension” could be improved by using a correction method, which takes account of at least the topography.

In general, we think that the referee's comment is most relevant for those countries and regions in Europe which are characterised by a complex and pronounced topography or which border large water surfaces with a lower roughness compared to the land surface.

82 *In the computation of the event set “WISC probabilistic extension”, the spatial*
83 *displacement was undertaken by shifting the respective windstorm footprint by about*
84 *20 km to the north, south, west, or east. For different regions and countries in Europe, we*
85 *determined the difference in wind gusts, which results from this spatial displacement of*
86 *the windstorm footprints. In total, there are 3'408 windstorm events that result from the*
87 *spatial displacement of either the original windstorm footprints or of altered windstorm*
88 *footprints (according to Eq. (1)).*

89 *Figure R2-1 shows for the canton of Zurich, the whole country of Switzerland, and the*
90 *UK boxplots of all changes due to spatial displacement that occurred on any point in any*
91 *event. Here, Switzerland and the UK were chosen as examples because Switzerland is a*
92 *country which is characterised by a pronounced topography with high mountains and the*
93 *UK is characterised by pronounced land-sea contrasts.*

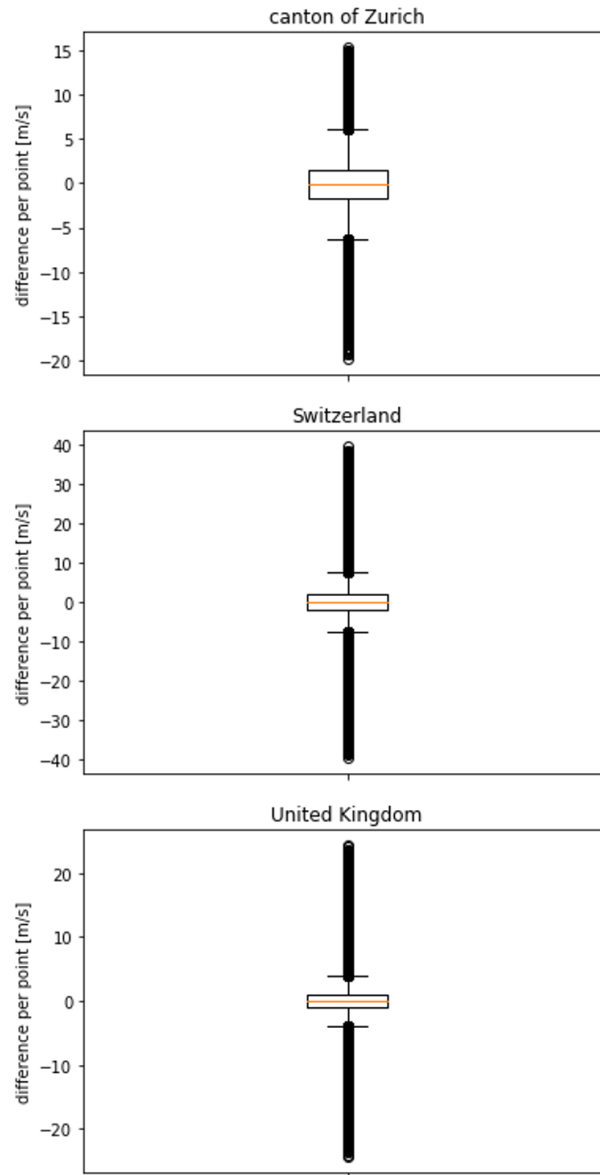


Figure R2-1: Boxplots of all differences due to spatial displacement that occurred on any point in any event for the canton of Zurich, the whole country of Switzerland, and the UK.

Figure R2-1 shows that the spatial displacements in windstorm footprints made can result in quite extreme changes in wind gust speed as one can see from changes of up to plus 16 m/s in the case of the canton of Zurich. These extremes are however very rare: 50 % of all points in all events are not changed by more than 2 m/s, and 90 % of all points are changed by no more than 5 m/s. The extremes are even higher in the case of Switzerland with up to 40 m/s and 25 m/s in the case of the UK. However, 50 % of all points in all events are not changed by more than 2 m/s in the case of Switzerland and

1 m/s in the case of the UK; 90 % of all points are changed by no more than 6 m/s in the case of Switzerland and 4 m/s in the case of the UK.

To be more precise in the paper, we have added this sentence to L211:

“In countries close to the sea or with a pronounced and high topography, the methodology for creating the probabilistic events might need adaptation to better incorporate the difference in surface roughness and altitude.”

5. L215/216: The references given for the storm severity index all have different definitions. Which formula did you use here?

We used the formula described by Dawkins et al. (2016). We now emphasise this more strongly in L214-216:

“In an effort to assign reasonable frequency estimates to the probabilistic windstorm footprints, we considered the distribution of the historic, pan-European Storm Severity Index (SSI; formula used by Dawkins et al., 2016; further information in Lamb and Frydendahl, 1991; Leckebusch et al., 2008).”

6. L282-287: This paragraph is a bit confusing. I guess you mean to say that MDD is calculated from the vulnerability curve of Schwierz et al, and you use this same vulnerability curve in CLIMADA?

We have clarified the language in L282-287:

“To estimate the damage in monetary terms, the value of each individual building (i.e., its insured value) was multiplied by the factor “Mean Damage Degree” (MDD, a number between 0 and 1) calculated from the vulnerability curve of Schwierz et al. (2010); where the gust speeds at building level computed in the first step were converted into the corresponding MDD factors. The MDD factors are a non-linear function of the maximum wind gust speed during a windstorm event and are diagrammed in Welker et al. (2016). The same vulnerability curve of Schwierz et al. (2010) is also implemented in the open source impact model CLIMADA (Aznar-Siguan and Bresch, 2019a).”

7. L348/349: How many data points did you have above the threshold in each case? When you do the re-sampling, is the number of re-sampled points (200) equal to the number of points you used for the original fit?

The threshold defines how data points are used for the original fit. In the case of the insured damages, the threshold of CHF 0.4 million resulted in 9 data points above the threshold. In the case of the modelled damage event set based on “WISC historic”, the threshold of CHF 0.1 million resulted in 19 data points above the threshold. As expressed in L346-347, these thresholds result “in a parameterised GPD with similar exceedance frequencies for the largest damage amount in the event set”. Additionally, the number of data points per observation year is reasonably similar between these two damage event sets. The number of resampled points is equal to the number of data points we used for the original fit.

As mentioned in the “Code availability and data availability” section (L575-576), the code used for this analysis is published here: https://github.com/CLIMADA-project/climada_papers.

8. Section 3.3: L386-391: I think you need more emphasis on the uncertainty in the return period of Lothar/Martin. Although the value from the claims is much smaller (34yrs), it’s still within the 90% confidence interval from WISC historic (25yrs to > 500yrs)

Thanks for the hint. We want to emphasise the uncertainty in our estimate of the return period of Lothar/Martin more and therefor suggest to insert the following sentences at the end of L391:

“These estimates represent the best guess for each damage event set. It is important to note that the quantified uncertainty of the estimate for the return period of Lothar/Martin based on “WISC historic” (yellow ribbon, 25 years to > 500 years) incorporates both the estimate for the insurance claims data (blue ribbon) as well as the estimate based on “WISC probabilistic extension”.”

Additionally, we would add the following sentence to the discussion at L458:

“We argue that the return period based on the historic windstorm footprints (75 years) is much more reliable than the return period based on the insured damage record (34 years).

Well knowing that the two estimates each have overlapping uncertainties, the estimates do not contradict each other. Rather the estimates, as best guesses, can inform varying deterministic risk views. Other information, like [...].”

In addition to this, we have made the following illustration, which we however do not show in the paper: Figure R2-2 shows in addition to the 90-% confidence interval the 50-% confidence interval, in order to show more clearly the change in the uncertainty range from the insurance claims data (blue ribbon) to the modelled damages based on "WISC historic" (yellow ribbon). As one would expect from the larger sample of windstorm events considered, the area of uncertainty is smaller in the case of the modelled damages based on "WISC historic" compared to the insured damages. Considering the 50-% confidence interval, the return period for the damage event Lothar/Martin is between approximately 25 and 250 years based on the claims data. For comparison, the estimate based on modelled damages using "WISC historic" provides a narrower uncertainty range between approximately 45 and 175 years. Based on the insurance claims data only, the return period for the damage event Lothar/Martin was estimated to be 34 years. Figure R2-2 shows that although this value is within the 90-% confidence interval it is not within the 50-% confidence interval from modelled damages using "WISC historic".

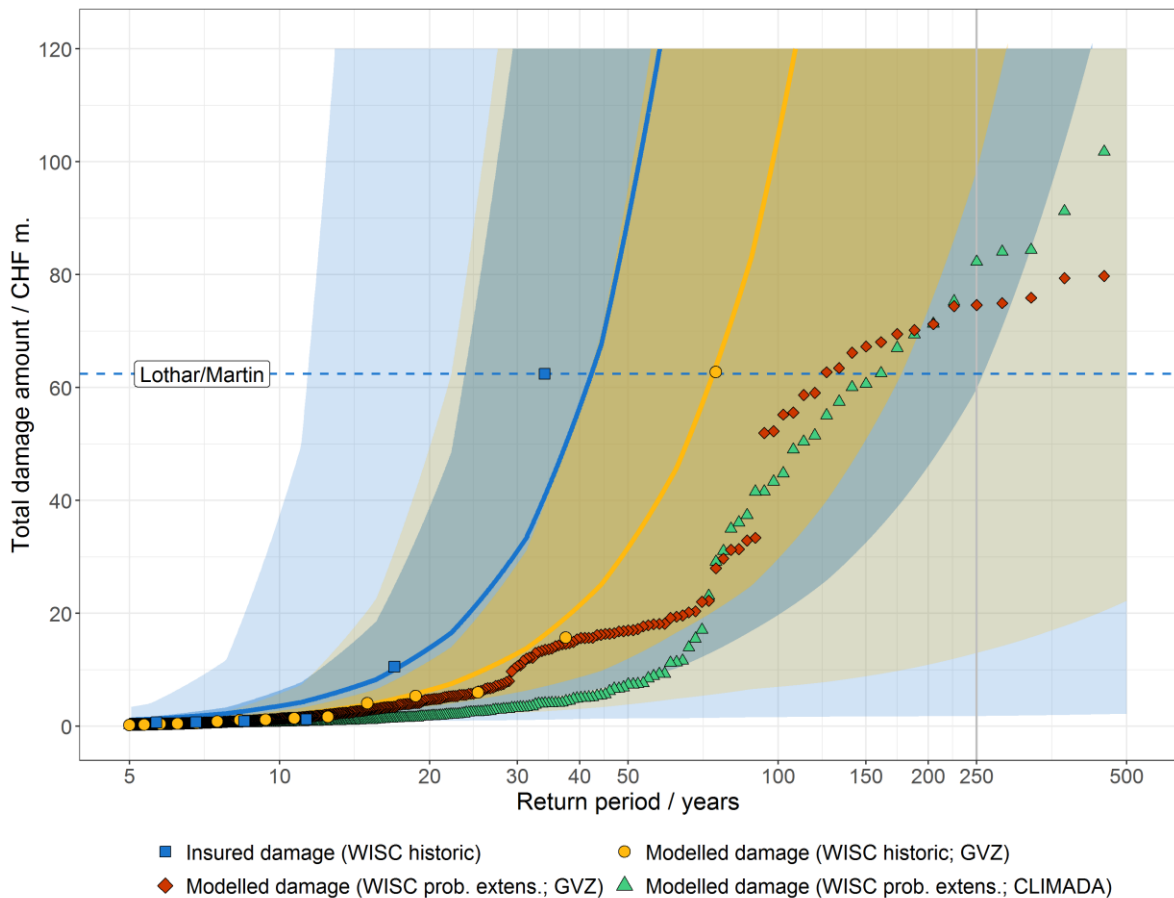


Figure R2-2: Modified Fig. 2. New is the darker blue and yellow inner shading, which shows the 50-% confidence interval for the insured damage and the damage modelled on the basis of "WISC historic".

9. L398: Again, I think you should mention that the 250yr RP from the claims data is within the range estimated from WISC historic.

Thanks for the hint. We suggest to add the following sentence to the end of L399:

“At a return period of 250 years, the quantified uncertainty of the estimate based on “WISC historic” incorporates both the estimate for the insurance claims data as well as the estimate based on “WISC probabilistic extension”.”

Compare our answer to the referee’s comment #8.

10. L400-404: Since the ‘WISC probabilistic extension’ and ‘WISC historic’ 250yr RPs are well within the 90% confidence intervals of one another, can you really conclude anything about the difference in return periods?

We would like to clarify the language in L400-402:

“An interesting feature illustrated in Fig. 2 is that at higher return periods the modelled damages on the basis of “WISC probabilistic extension” increase less strongly compared to the two extrapolations based on the fitted distributions.”

11. Section 3.5 L439-440: “In total, “WISC probabilistic extension” contains 17 events which are potentially more damaging than Lothar/Martin”: I assume the 17 events referred to in the text are the 17 red dots in Fig 4 with damages > Martin/Lothar damage, rather than the events with P95 gusts speed > P95 gust speed of Martin/Lothar, so shouldn't the grey area in Fig 4 be bounded by a horizontal line at damage \approx CHF 62m, rather than the vertical line at P95 gust speed \approx 133km/h?

That's right, thanks for the hint. We have adjusted the figure accordingly (see also Fig. R2-3). We agree that this adjustment better connects the text and the figure.

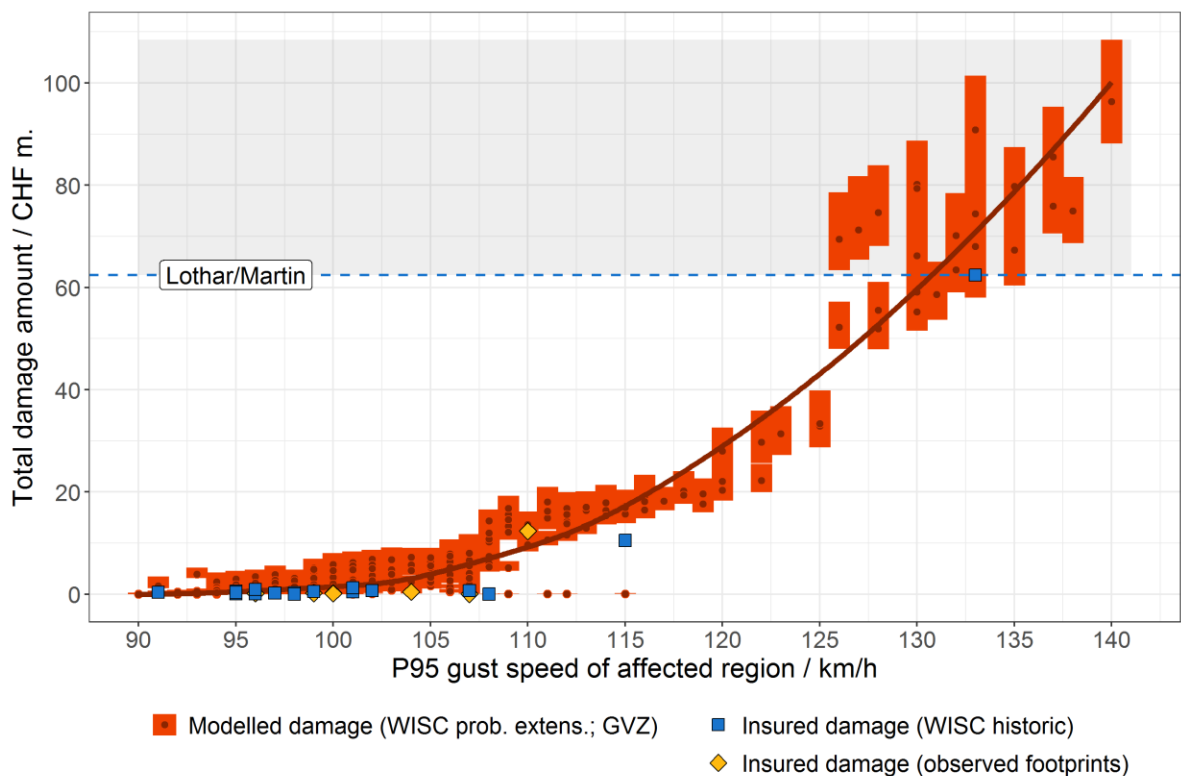


Figure R2-3: Modified Fig. 4. New are the horizontal shading instead of the vertical one and the label of the x-axis (see our response to the referee's comment #14).

12. L441: “A (modelled) total damage amount of more than CHF 96 million is associated with the most extreme windstorm event in “WISC probabilistic extension”: In Fig 2 it looks like the highest damage storm in “WISC probabilistic extension” has a damage amount of approximately CHF 80m. Why is the maximum damage in Fig 4 higher? Aren’t they the same storms?

For plotting reasons, the range of the y-axis in Fig. 2 was reduced in comparison to Fig. 4, since the area of uncertainty is very large in the case of large return periods > 500 years.

13. Fig 4: Please could you clarify if the insured damages (blue squares and yellow diamonds) are the values from the claims dataset (after normalising), or the damage amounts estimated from the GVZ model on the historical events?

In Fig. 4, the blue squares are the values from the claims dataset after normalising to present-day exposure levels for the period 1981-2014. The corresponding wind gust speeds on the x-axis are from the hazard event set “WISC historic”. The yellow diamonds are also values from the claims dataset but for the period 2017-2018; the corresponding wind gust speeds on the x-axis are from the additional hazard event set “observed footprints for current windstorms” (see Sect. 2.2.4).

14. Fig 4: Please could you explain why there are quite a few footprints from WISC probabilistic with zero damage despite having P95 gust speeds of 107-115 km/h? Is it because they mainly hit unpopulated areas?

Yes, that’s true. In GVZ’s damage modelling approach, damage is possible from a wind gust speed of more than 90 km/h, and only buildings affected by such wind gusts were considered in the damage model. In the case of the four points that protrude in Fig. 4, the area with wind gust speeds > 90 km/h is only limited to a small region in the south of the canton of Zurich (see Fig. R2-4), with relatively few buildings potentially at risk. The modelled damage sums are not zero, but rather small (see Table R2-1).

In the case of the modelled windstorm footprints shown in Fig. R2-4, it is maybe not immediately obvious why the 95th percentile of the few buildings affected was calculated and shown in Fig. 4. The reason is as follows: When the GVZ damage model was developed and calibrated, this was done almost exclusively with observed windstorm

236 *footprints that affected the entire canton of Zurich and, in principle, every building in the*
237 *canton was potentially affected – the “classic” so to speak, large-scale winter*
238 *windstorms. The 95th percentile of all potentially affected buildings turned out to be*
239 *suitable for this selection of windstorms to categorise them in a subsequent modelling*
240 *step. Based on this categorisation, a random sample of m buildings was selected*
241 *thereafter, with the number m depending on the windstorm’s severity category and giving*
242 *a percentage of total affected buildings. Only those buildings with potential damage > 0*
243 *were considered in the following modelling steps. The model approach is therefore not*
244 *necessarily intended / calibrated for small-scale and modelled wind gust footprints.*

245 *To be more precise in Fig. 4, we have changed the labelling of the x-axis to:*

246 *“P95 gust speed of **affected region** [...]”*

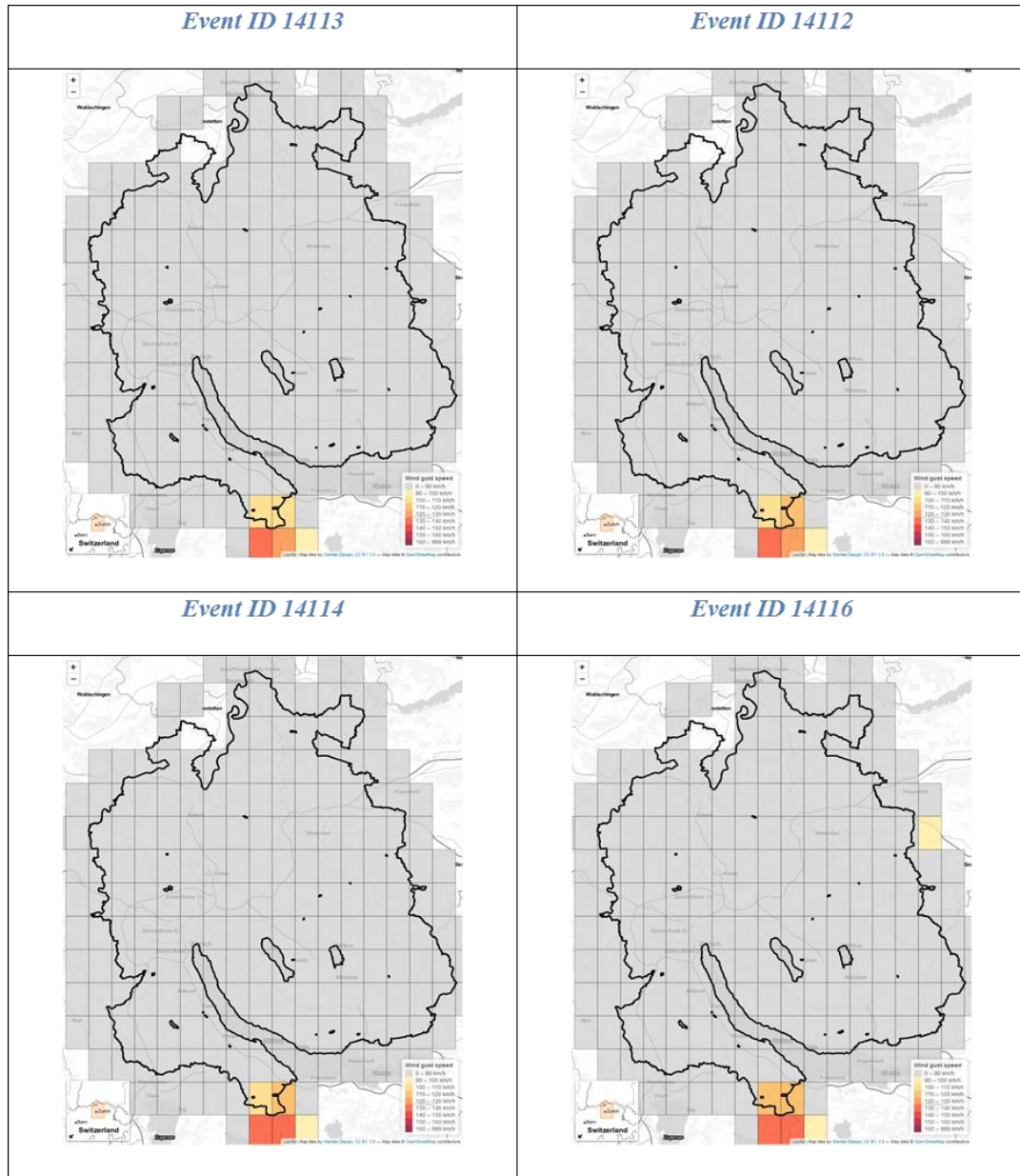


Figure R2-4: Maximum wind gusts for every grid cell in the canton of Zurich for the events with IDs 14113, 14112, 14114, and 14116 in the dataset “WISC probabilistic extension”. Wind gust speeds < 90 km/h are plotted in grey.

Table R2-1: For the same events as in Fig. R2-4, total damage modelled using the GVZ damage model (median of 1'000 random damage modelling) and the 95th percentile of the corresponding gust speeds.

<i>Event ID</i>	<i>P95 wind gust speed / km/h</i>	<i>Median total damage amount / CHF m.</i>
14113	109	0.07
14112	111	0.08
14114	112	0.08
14116	115	0.09

Additional changes to the manuscript

While editing the referee's comment #4, we noticed an error in Eq. (1) in the paper and we would like to correct it in the revised manuscript. The correction ensures consistency between the manuscript and the code used for the calculations. In the case of the definition of $wind_{scenario\ 5}$, the sign of change was incorrectly reversed; two plus signs in the last line are now corrected to two minus signs.

Eq. (1) is correctly defined as follows (L209-210):

$$\begin{aligned}
 wind_{scenario\ 1} &= wind_{original} + \alpha * wind_{original}^{\beta} \\
 wind_{scenario\ 2} &= wind_{original} - \alpha * wind_{original}^{\beta} \\
 wind_{scenario\ 3} &= wind_{original} + \alpha * \sqrt{\beta} wind_{original}^{\beta} \\
 wind_{scenario\ 4} &= wind_{original} - \alpha * \sqrt{\beta} wind_{original}^{\beta} \\
 wind_{scenario\ 5} &= wind_{original} - \frac{\alpha}{2} * wind_{original}^{\beta} - \frac{\alpha}{2} * \sqrt{\beta} wind_{original}^{\beta}
 \end{aligned} \tag{1}$$

ADDITIONAL CHANGES TO THE REVISED MANUSCRIPT

Research article:

Comparing an insurer's perspective on building damages with modelled damages from pan-European winter windstorm event sets: a case study from Zurich, Switzerland (Nat. Hazards Earth Syst. Sci. Discuss., <https://doi.org/10.5194/nhess-2020-115>, in review; submitted on 07 April 2020)

Authors:

Christoph Welker, Thomas Rössli, David N. Bresch

During the preparation of the revised manuscript, we introduced additional changes which are not mentioned in the authors' responses to Referee #1 and #2. Changes to the manuscript are highlighted in bold below.

We want to further clarify our language regarding the uncertainty of the different risk assessments:

L55-57:

“For risk assessment, solid estimates of the probability of occurrence of such events are absolutely essential and GVZ's claims data of almost 40 years provides a too short observational period **which leads to a large sampling uncertainty.**”

L98:

“**This makes it possible to reduce the sampling uncertainty of the risk assessment.**”

L107:

“**As discussed in this study, such a statistical perturbation is based on the same observational period as the WISC historic hazard event set and therefore cannot reduce the sampling uncertainty.**”

L352:

“To illustrate the statistical uncertainty of the exceedance frequency curve, we undertook a resampling **and thereby show the sampling uncertainty for each damage event set.**”

L357:

“In case of the damage event set computed on the basis of “WISC probabilistic extension”, the uncertainty is best illustrated by the sampling uncertainty of the damage event set based on “WISC historic” for the following reasons. The procedure of computing the hazard event set “WISC probabilistic extension” by statistical perturbation (as described in Sect. 2.2.3) transforms part of the sampling uncertainty of the hazard event set “WISC historic” into an uncertainty of the parameters α and β in Eq. (1). However, this parameter uncertainty is difficult to illustrate, since no combination of α and β could be found which adequately represents the upper and lower boundaries of the sampling uncertainty of the pan-European SSI distribution. Additionally, the sampling uncertainty of “WISC probabilistic extension” no longer represents the same uncertainty as in case of the other damage event sets. Thus, for comparison of the uncertainties of the different damage event sets, we suggest to use the sampling uncertainty of “WISC historic” as best illustration of the uncertainty of “WISC probabilistic extension”. ”

We want to clarify when we mean entire area and when affected region:

L110-112:

“A relationship between wind gust speed in the **affected region** of the canton of Zurich and associated building damages is found, which allows for a rapid, straightforward estimation of damage directly after the occurrence of extreme, unprecedented windstorms.”

L289-291:

“The respective windstorm event was automatically categorised according to its severity (here, according to the 95th percentile of all gust speeds at building level in the **affected region of the** canton of Zurich), from which the assumed degree of impact is derived.”

52 *L434-436:*

53 “The 95th percentile of the wind gust speeds at building level in the **affected region** of the
54 canton of Zurich, which is also used in GVZ’s damage model to categorise windstorm events
55 (Sect. 2.3.1), is used as a rapid indicator of the range of possible damages.”

56 *L776-778:*

57 “Total damage modelled using the GVZ damage model and the hazard event set “WISC
58 probabilistic extension” versus the 95th percentile of the corresponding gust speeds in the
59 **affected region of the** canton of Zurich (median of 1’000 random damage modelling as red
60 points; range of modelled damages indicated as red bars).”

61

62 *In addition, we would like to make a few minor changes and correct typos:*

63 *L14:*

64 “We describe and use two windstorm risk models: **an** insurer’s proprietary model and the open
65 source CLIMADA platform.”

66 *L95-98:*

67 “Similar to the predecessor project Extreme Windstorms Catalogue (XWS; Roberts et al., 2014),
68 the WISC historic hazard event set contains windstorms that hit Europe, but provides the
69 corresponding wind gust footprints at improved spatial resolution and covers more windstorms
70 over a period longer than the **claims database** available to most insurance companies.”

71 *L108-110; we removed the brackets around the last part of this sentence:*

72 “This study shows how GVZ uses both the WISC dataset and the new probabilistic hazard event
73 set for assessing the potential building damage and risk due to extreme windstorm events,
74 including an evaluation of the uncertainties of such assessments.”

75 *L222-224:*

76 “For the probabilistic hazard event set to best represent the tail of the historic distribution, we
77 determined a combination of α and β , that minimises the difference in the cumulative distribution
78 functions for events that **have a return period of** > 75 years.”

79 *L291-293:*

80 “The degree of impact for the different windstorm categories (**i.e.**, a percentage of total affected
81 buildings for the canton of Zurich, m) was derived from proprietary event damage data from
82 GVZ’s database.”

83 *L575-576:*

84 “The scripts reproducing the main results of the paper and the figures **are** available under
85 https://github.com/CLIMADA-project/climada_papers”

86 *L579-582:*

87 “CLIMADA is openly available at GitHub ([https://github.com/CLIMADA-](https://github.com/CLIMADA-project/climada_python)
88 [project/climada_python](https://github.com/CLIMADA-project/climada_python); Bresch and Aznar-Siguan, 2019a) under the GNU GPL license (GNU
89 operating system, 2007). The documentation is hosted on Read the Docs ([https://climada-](https://climada-python.readthedocs.io/en/stable/)
90 [python.readthedocs.io/en/stable/](https://climada-python.readthedocs.io/en/stable/); Aznar-Siguan and Bresch, 2019b) and includes a link to the
91 interactive tutorial of CLIMADA.”

92 *L785-786:*

93 “The domain for unprecedented **windstorm damages** – i.e. beyond Lothar/Martin – is shaded
94 grey.”

95 *L800:*

96 “[...] (**source:** Swiss Federal Office of Topography; Swisstopo DEM, 2019).”

Comparing an insurer's perspective on building damages with modelled damages from pan-European winter windstorm event sets: a case study from Zurich, Switzerland

Christoph Welker¹, Thomas Rösli^{2, 3}, David N. Bresch^{2, 3}

¹ GVZ Gebäudeversicherung Kanton Zürich, Zurich, Switzerland

² Institute for Environmental Decisions, ETH Zurich, Zurich, Switzerland

³ Federal Office of Meteorology and Climatology MeteoSwiss, Zurich, Switzerland

Correspondence to: Thomas Rösli (thomas.roesli@usys.ethz.ch)

Abstract

With access to claims, insurers have a long tradition of being knowledge leaders on damages caused by e.g. windstorms. However, new opportunities have arisen to better assess the risks of winter windstorms in Europe through the availability of historic footprints provided by the Windstorm Information Service (Copernicus WISC). In this study, we compare how modelling of building damages complements claims-based risk assessment. We describe and use two windstorm risk models: [thean](#) insurer's proprietary model and the open source CLIMADA platform. Both use the historic WISC dataset and a purposefully-built, probabilistic hazard event set of winter windstorms across Europe to model building damages in the canton of Zurich, Switzerland. These approaches project a considerably lower estimate for the annual average damage (CHF 1.4 million), compared to claims (CHF 2.3 million), which originates mainly from a different assessment of the return period of the most damaging historic event Lothar/Martin. Additionally, the probabilistic modelling approach allows assessing rare events, such as a 250-year return period windstorm causing CHF 75 million damages-, [including an evaluation of the uncertainties](#). Our study emphasises the importance of complementing a claims-based perspective with a probabilistic risk modelling approach to better understand windstorm risks. The presented open source model provides a straightforward entry point for small insurance companies.

1 Introduction

Severe windstorms are responsible for widespread socio-economic impacts such as damage to buildings, structures, transport networks, forests, and even loss of lives. Windstorms represent one of the most damaging natural hazards in many parts of the world, not least in Switzerland (Imhof, 2011). In the densely populated canton of Zurich, which is located in north-eastern Switzerland, windstorms are among the most destructive natural hazards: building damages due to windstorms amount to 30 % of the total amount of building damage from natural hazard in this region. For comparison, damages due to hailstorms and flooding amount to 41 % and 28 %, respectively (all numbers from 2018; GVZ annual report, 2018; Schadenstatistik VKG, 2020).

In general, the impact of a windstorm in terms of building damages depends on the severity of associated surface winds and gusts as well as on the exposed values and the respective vulnerability (i.e., damage susceptibility) of the buildings being subject to the hazard – with both building stock and vulnerability changing over time. High wind speeds cause large pressure and suction effects, which in turn are responsible for damage to the roof and the building facade. Damaging winds and violent gusts in the canton of Zurich are mainly due to

the passage of large-scale extratropical cyclones and their associated fronts during autumn and winter as well as due to mostly local convective storms during summer. Winter windstorms typically cause widespread minor building damages summing up to large amounts, whereas it is not unusual that summer convective storms cause major damages of only a few buildings due to locally very high wind speeds.

The cantonal building insurance GVZ compulsorily insures all buildings in the canton of Zurich (with a few exceptions) against damage due to natural hazards and fire: i.e. in total around 300'000 buildings with a total sum insured of around Swiss Francs (CHF) 500 billion (in 2018). GVZ is an independent institution of the canton of Zurich under public law (GVZ homepage, 2020).

Windstorm damage events in the canton of Zurich have been recorded in GVZ's database since 1981. For example, windstorm Lothar on 26 December 1999 caused total insured building damages of around CHF 60 million and is by far the most extreme windstorm event in the database. Second largest is windstorm Burglind on 3 January 2018 (Scherrer et al., 2018), which caused total insured building damages of more than CHF 14 million. The most extreme summer damage event in GVZ's record is due to a very local, but extremely intense convective storm on 2 August 2017 with measured maximum gusts of more than 180 km/h in the lowlands, which caused total insured building damages of approximately CHF 4 million. Even though small-scale convective storm events are potentially hazardous, in this study we focus on large-scale winter windstorms only, which were responsible for around three quarters of all insured windstorm damages in the canton of Zurich since 1981.

Extreme damage events such as those caused by Lothar or even stronger windstorms are rare by definition. For risk assessment, solid estimates of the probability of occurrence of such events are absolutely essential and GVZ's claims data of almost 40 years provides a too short observational period- [which leads to a large sampling uncertainty](#). A larger sample of events is needed for which at least quantitative meteorological data and if possible damage data at ideally high spatiotemporal resolution are available (e.g., Haas and Pinto, 2012). Observational damage data are generally sparse and incomplete for historic windstorms in Switzerland (Stucki et al., 2014). Instead, societal actors often use modelled impacts to manage their risk. Insurance and reinsurance companies apply impact models for their pricing and governments use modelled risk for option appraisal (e.g., The Economics of Climate Adaptation Working Group, 2009; Bresch, 2016). Additionally, the information is needed for climate-related financial disclosure (Surminski et al., 2020). However, only very few impact models are available open source and free access for users both in the scientific as well as public or private domain.

Typically, risk is modelled as a combination of hazard, vulnerability, and exposure (IPCC, 2014). The hazard part is the best understood and research culminated in open datasets of historic windstorm events (Roberts et al., 2014; WISC products, 2019), whereas maximum wind gust speeds are frequently used as hazard component to assess windstorm risk (e.g., Klawns and Ulbrich, 2003). Vulnerability has been covered by many studies and reviews (e.g., Della-Marta et al., 2010; Schwierz et al., 2010; Feuerstein et al., 2011; Prah et al., 2015; Koks and Haer, 2018). There are many theoretical learnings from these studies, but an implementation in a comprehensive open source and easy access risk assessment model is still missing. Detailed exposure data are generally not publicly available and many societal actors have their own detailed view on exposure and do not need to rely on a publicly available dataset. There are open, spatially explicit datasets available based on the

distribution of nightlight and population (Eberenz et al. 2019), based on the Gross Domestic Product (GDP; Geiger et al. 2018), or on building data from OpenStreetMap (Koks and Haer, 2018). The sparse availability is why in some research studies loss ratios were used instead of information on exposure (Donat et al., 2011).

Using the modelling approach for Switzerland, Welker et al. (2016) applied the methods presented first by Stucki et al. (2015) to a sample of more than 80 high-impact winter windstorms that affected Switzerland in 1871-2011. The approach involves the dynamical downscaling of the Twentieth Century Reanalysis (20CR) using the Weather Research and Forecasting (WRF) model. The calculated windstorm footprints served as input for the modelling of economic damages using a precursor of the open source impact model CLIMADA (CLIMate ADAPtation; Aznar-Siguan and Bresch, 2019a). CLIMADA was successfully applied in several other studies for the purpose of risk assessment and quantification of socio-economic impacts (e.g., Della-Marta et al., 2010; Schwierz et al., 2010; Raible et al., 2012; Reguero et al., 2014; Gettelman et al., 2018; Walz and Leckebusch, 2019).

To increase the sample of windstorm footprints available for risk assessment, insurance and reinsurance companies often combine observed windstorm footprints as far as available with synthetic footprints generated by stochastic or dynamic atmospheric models. In this way, they obtain a more comprehensive view on risk.

The Windstorm Information Service (WISC) of the Copernicus Climate Change Service aims to provide a consistent and open database of hazard data to assess the risk of windstorms in Europe for all kinds of players in the insurance sector and beyond. The centrepiece of the WISC dataset are wind gust footprints at high spatial resolution of approximately 4.4 km for, on the one hand, a historic hazard event set of around 140 European winter windstorms in 1940-2014 and, on the other hand, a synthetic hazard event set of around 23'000 events. Similar to the predecessor project Extreme Windstorms Catalogue (XWS; Roberts et al., 2014), the WISC historic hazard event set contains windstorms that hit Europe, but provides the corresponding wind gust footprints at improved spatial resolution and covers more windstorms over a period longer than the [data basis/claims database](#) available to most insurance companies. [This makes it possible to reduce the sampling uncertainty of the risk assessment.](#) The windstorm hazard event sets as provided by WISC form an independent database to validate and further develop existing European winter windstorm models. The dataset can be used for both pan-European analyses and local analyses, as shown in this study.

Using the WISC historic hazard event set allows GVZ in a way to “re-check” historic events. By means of the synthetic hazard event set, the tail of the hazard and damage distributions should be investigated. However, Rösli et al. (2018) found that the synthetic hazard event set is not suitable for this purpose. Therefore, we propose instead a probabilistic windstorm hazard event set based on a method described in Schwierz et al. (2010) to overcome the shortcomings of the WISC synthetic hazard event set. This new probabilistic hazard event set of around 4'300 events contains windstorms from the WISC historic hazard event set altered by various perturbations. [As discussed in this study, such a statistical perturbation is based on the same observational period as the WISC historic hazard event set and therefore cannot reduce the sampling uncertainty.](#)

This study shows how GVZ uses both the WISC dataset and the new probabilistic hazard event set for assessing the potential building damage and risk due to extreme windstorm events, including an evaluation of the

uncertainties of such assessments³. A relationship between wind gust speed in the ~~entire area~~^aaffected region of the canton of Zurich and associated building damages is found, which allows for a rapid, straightforward estimation of damage directly after the occurrence of extreme, unprecedented windstorms. This study further shows how GVZ was able to improve its windstorm risk assessment on the basis of the WISC dataset and the new probabilistic hazard event set, and could serve as an example for other players in the insurance sector or other societal actors in Switzerland and in the rest of Europe. At the same time, this study also illustrates selected limitations of the WISC dataset.

2 Data and methods

After a description of the insurance claims data (Sect. 2.1) and the windstorm hazard event sets used (Sect. 2.2), we introduce the GVZ and the CLIMADA risk assessment models applied for damage modelling (Sect. 2.3) and conclude this section with a brief recapitulation of the risk assessment metrics employed in this study (Sect. 2.4).

2.1 Insurance claims data

The windstorm damages of past events are recorded in a proprietary database of GVZ. It consists of almost 40 years of insurance claims data, in total more than 84'000 single wind damage records. From this database all the events relevant for this study were selected by following the event definition of the windstorm event set “WISC historic” (Sect. 2.2.1). In total, 18 events are associated with WISC windstorms based on that definition (see also Table 1). Due to the nature of the database, only the damage reports actually insured by GVZ were considered. The insurance claims data allow GVZ to assess the risk for its own portfolio by analysing frequency and severity of past damages, i.e. to assess its risk due to winter windstorm events with a return period smaller than 40 years. Additional information can help GVZ to put their recorded damages into reference and to get a better estimate of the risk of events with a return period larger than the 40 years of experience.

For the sake of comparability, the insured damages had to be normalised to present-day exposure levels. In this study, the applied normalisation considers the general inflation on the basis of the Zurich construction price index (2020). Hereinafter, both insured and modelled windstorm damages are including occasional deductibles – so-called “gross damages”, to ease comparison.

2.2 Windstorm hazard event sets

Atmospheric models provide information about winter windstorm events that can be used as hazard component in a risk assessment model. WISC published several hazard datasets each containing a set of windstorm events and providing the maximum wind gust per geographic location per event. We used the historic windstorm footprints (Sect. 2.2.1) and constructed a probabilistic extension based on it (Sect. 2.2.3). In addition, we derived wind gust footprints from measurements for a selection of present windstorm events (Sect. 2.2.4). The additional windstorm hazard event sets published by WISC, that are however not considered in this study, are briefly summarised in Sect. 2.2.2.

2.2.1 Historic windstorm hazard event set

The historic windstorm hazard event set – denoted “WISC historic” – contains wind gust footprints for around 140 winter windstorm events in Europe in 1940-2014 (i.e., 75 modelled years in total). The events were selected, on the one hand, based on the high damage they caused and, on the other hand, because of their high intensity in meteorological terms (i.e., high vorticity). Because of this pan-European perspective, the dataset is not necessarily specific to windstorms in the canton of Zurich. Nevertheless, the high-impact windstorms Lothar/Martin (26–28 December 1999) and other intense windstorms such as Vivian/Wiebke (26 February–1 March 1990) are included.

The windstorm footprints were computed by running the UK Met Office Unified Model (MetUM; Davies et al., 2005) at approximately 4.4 km resolution with ERA-20C reanalysis (Poli et al., 2016) and ERA-Interim reanalysis (Dee et al., 2011) as boundary conditions, covering Europe and parts of the North Atlantic. ERA-20C was used for all windstorm events in 1940-1979 and ERA-Interim for all events in 1979-2014.

Each of the footprints is composed of gridded maximum 3-second gusts, with maxima determined for a 72-hour time window. This relatively long time window was chosen, because it is widely used in the insurance sector (WISC products, 2019). However, it also implies that the footprints of directly successive events (i.e., with a time difference of less than 72 hours) such as Lothar (26 December 1999) and Martin (27-28 December 1999) are combinations of the footprints of both successive events. In this study, the WISC windstorm footprints for events that have overlapping time windows are combined to represent one event – as insurance claims data does often not represent the exact time/date of damage either (for various reasons, a key one being reporting uncertainties). This combination is necessary to make sure that a maximum that occurred only once (e.g., the wind gusts reached during Lothar) is only represented once in the hazard event set (as event Lothar/Martin) and is not represented twice (once as Lothar and once as Martin). There are five pairs of windstorms with overlapping time windows in the original dataset that were combined by taking the maximum wind gust of both footprints at each location, giving in total 142 windstorm events (Table 1). The problem of overlapping windstorm footprints and the resulting combination of events could have been prevented by incorporating the geographical information into the event definition. For example, Roberts et al. (2014) aggregated only the wind gusts within a certain radius around the windstorm centre into a footprint to avoid this problem.

The wind gust speeds from “WISC historic” are considered to be realistic compared to observations for areas at sea level (WISC products, 2019). However, with regard to the hilly topography of the canton of Zurich the question arises as to how realistic the underlying model topography is in comparison to the real topography and, as a result, how good the height-dependent wind gust speeds are compared to observational data. Even though this could not be finally clarified in this study since available wind measurements are generally too sparse for historic windstorms in the canton of Zurich, a correction of all the WISC wind gusts in the form of simple correction factors does not seem reasonable and was therefore not applied.

2.2.2 Other WISC hazard event sets

There are two additional windstorm hazard event sets published by WISC, that are however not analysed in detail in this study:

1. The operational windstorm hazard event set – denoted “WISC operational” – contains around 110 windstorm events in 1979-2017 and thus more recent events than the windstorm hazard event set “WISC historic” used in this study, which contains windstorm events until 2014 only. “WISC operational” is based on a new generation of atmospheric reanalysis, the ERA5 reanalysis (Hersbach and Dee, 2016). As it does not cover the time range 1940-1979 (compared to “WISC historic”) it does not complement the recorded damages by providing information about historic events not covered by GVZ’s claims database.

2. The synthetic windstorm hazard event set – denoted “WISC synthetic” – was created within the UPSCALE (UK on PRACE - weather-resolving Simulations of Climate for global Environmental risk; UPSCALE, 2020) modelling framework and is a physically realistic set of plausible winter windstorm events in the period 1985-2011 based on the climatic conditions of that period. The modelling framework developed five ensembles. The dataset contains wind gust footprints for around 23’000 synthetic windstorms: i.e., three sets of 7’660 events each. Each of the three sets covers 135 modelled years. The original idea of the hazard event set “WISC synthetic” was to use wind information from climate models to provide wind gust footprints for winter windstorms in Europe with a return period of 250 years or even higher. However, this hazard event set was not considered because the findings of Röögli et al. (2018) could be replicated in this study, showing that the dataset does not contain the maximum wind gust speeds we would expect from the distribution of the historic windstorm hazard events (Fig. A1) nor the high intensities we would expect from very rare, high-impact windstorm events (Fig. 1).

For a detailed description of all unused windstorm hazard events sets provided by WISC, we refer to the documentations available online at WISC products (2019) and WISC hazard event set description (2019).

2.2.3 Probabilistic windstorm hazard extension

Based on “WISC historic”, we generated an additional probabilistic windstorm hazard event set – denoted “WISC probabilistic extension”. By applying a method described in Schwierz et al. (2010), the individual windstorm events in “WISC historic” (parent events) were altered to create 29 altered offspring events by various perturbations: e.g., spatial displacement and by weakening / intensifying the wind speeds (non-altered wind speeds are spatially displaced only). The spatial displacement was undertaken by shifting the respective windstorm footprint by about 20 km to the north, south, west, or east. The wind gust speeds were intensified and weakened by no more than 3 m/s (normally much less) according to the probabilistic alteration of wind speeds in Eq. (1), with a scale parameter $\alpha = 0.0225$ and a power parameter $\beta = 1.15$: [\(choice explained further below\)](#):

$$\begin{aligned}
 windspeed_{scenario\ 1} &= windspeed_{original} + \alpha * windspeed_{original}^{\beta} \\
 windspeed_{scenario\ 2} &= windspeed_{original} - \alpha * windspeed_{original}^{\beta} \\
 windspeed_{scenario\ 3} &= windspeed_{original} + \alpha * \sqrt{\beta} \sqrt{windspeed_{original}^{\beta}} \\
 windspeed_{scenario\ 4} &= windspeed_{original} - \alpha * \sqrt{\beta} \sqrt{windspeed_{original}^{\beta}}
 \end{aligned} \tag{1}$$

$$\begin{aligned}
 windspeed_{scenario\ 5} = & windspeed_{original} + \frac{\alpha}{2} * windspeed_{original}^{\beta} \\
 & + \frac{\alpha}{2} - \frac{\alpha}{2} * windspeed_{original}^{\beta} - \frac{\alpha}{2} \\
 & * \sqrt[\beta]{windspeed_{original}}
 \end{aligned}$$

These newly created “probabilistic” footprints can be viewed as scenarios of plausible windstorms as they only differ slightly from historic events, retaining both the spatial extent and general structure. [In countries close to the sea or with a pronounced and high topography, the methodology for creating the probabilistic events might need adaptation to better incorporate the difference in surface roughness and altitude.](#)

For using the scenarios in a qualitative risk assessment framework, the probabilistic windstorm footprints can be used as they are, but for a quantitative risk assessment the frequencies of the windstorm footprints need to be estimated. In an effort to assign reasonable frequency estimates to the probabilistic windstorm footprints, we considered the distribution of the historic, pan-European Storm Severity Index (SSI; [e.g., formula used by Dawkins et al., 2016; further information in](#) Lamb and Frydendahl, 1991; Leckebusch et al., 2008; [Dawkins et al., 2016](#)). Similar as in Schwierz et al. (2010), the algorithm of creating the probabilistic windstorm footprints was configured to recreate the cumulative distribution function of a generalized extreme value (GEV) distribution fitted to the historic SSI values. We defined the frequency of all probabilistic windstorm footprints to be equal and to sum up to the frequency of the parent windstorm. We then selected a set of parameters for weakening and intensifying the wind speeds (parameters α and β in Eq. (1)) that resulted in a similar probabilistic distribution of SSI as the extrapolated distribution from the historic SSI values. For the probabilistic hazard event set to best represent the tail of the historic distribution, we determined a combination of α and β , that minimises the difference in the cumulative distribution functions for events that [are rarer than have a return period of > 75 years.](#)

“WISC probabilistic extension” includes footprints for 4’118 probabilistic windstorm events, along with the 142 original windstorm events in “WISC historic” (Table 1), and provides a basis of an event-based risk assessment for winter windstorms with return periods of around 250 years, a scenario relevant for regulatory requirements in the insurance sector. It is important to note that this method incorporates a lot of uncertainty, including but not limited to the sampling uncertainty of rare events in a relatively short time range (i.e., 75 years in case of “WISC historic”).

Encouragingly, the hazard event set “WISC probabilistic extension” shows considerably higher wind gust speeds in the canton of Zurich as compared with “WISC synthetic” (Fig. 1). Nonetheless, the maximum wind gust speeds of the most extreme event in “WISC probabilistic extension” are not considerably higher than those of Lothar/Martin, the most extreme event in both “WISC historic” and the insurance claims data.

2.2.4 Observed footprints for current windstorms

Real-time wind gust observations can serve as the hazard part of the damage model for a rapid damage estimation directly after the occurrence of an extreme windstorm event. Such “observed” windstorm footprints can also be used for further validation of GVZ’s damage modelling approach (Sect. 2.3). To create such

footprints, we used interpolated wind gust measurements in the canton of Zurich based on the Common Information Platform for Natural Hazards (GIN; GIN platform, 2019) for a selection of seven winter windstorms in the years 2017 and 2018. With the exception of winter windstorm Burglind hitting Switzerland on 3 January 2018, the windstorms considered caused only minor damages in the canton of Zurich. The individual windstorm footprints are based on a total of around 110 measurement stations in the canton of Zurich and in the immediate vicinity (i.e., buffer zone with a distance of 20 km around the polyline of the canton). For spatial interpolation, we applied an Inverse Distance Weighting (IDW) interpolation with the Shepard method used for weight calculation. In this study, the gridded wind gust footprints derived from measurements have a horizontal resolution of 2 km. The topography of the canton of Zurich is not considered in the applied interpolation method and unquestionably the quality of the derived windstorm footprints could be improved by using a more elaborate interpolation method, which takes account of the topography.

2.3 Damage modelling approaches

The windstorm footprints of the different hazard event sets described in the previous section were used as input for damage modelling and GVZ's proprietary windstorm damage model was applied for this (Sect. 2.3.1). In addition, the CLIMADA impact model was used to be able to publish the method used in this study with open data and open source code (Sect. 2.3.2).

In both damage models, the extent of damage results from the intensity of the windstorm event (i.e., hazard), the value of the asset (i.e., exposure), and the susceptibility of the asset to damage (i.e., vulnerability). This concept is broadly used and is explained in more detail in Aznar-Siguan and Bresch (2019a). In this study, the windstorm hazard assessment is based on the winter windstorm footprints described in Sect. 2.2. The exposure is the value of the buildings in the canton of Zurich and the vulnerability is described by a functional relationship that defines how much the buildings are damaged at a certain wind gust speed. In both damage models, we use the vulnerability curve of Schwierz et al. (2010). This vulnerability curve combines the damage degree and the percentage of assets affected. Only damage to buildings is estimated. The estimate does not include damage to movable property, damage to infrastructure, nor business interruption.

2.3.1 GVZ damage model

The damage estimates in this model are computed using a rather conventional modelling framework and the reduced complexity of the approach allows a well interpretable assessment of the model skill. Normally, GVZ uses its damage model directly after the occurrence of a windstorm event to estimate the expected building damage. Furthermore, GVZ applies the damage model to estimate the damage potential and the risk associated with windstorms with regard to solvency considerations and prevention options. The main points of the modelling approach are described in the following.

The initial step is a simple spatial overlay of the gridded maximum wind gust speeds during the respective windstorm event with GVZ's current building stock (from 2018; without sublevel garages, as they are usually not affected by windstorms), where GVZ's proprietary building database with information about e.g. the sum insured of each building and the publicly available building footprints (GIS browser Zurich, 2019) were used. GVZ's insurance penetration in the canton of Zurich is almost 100 %. In the damage model, damage is possible

from a wind gust speed of more than 90 km/h, and only buildings affected by such gusts were considered in the following modelling steps.

Figure A2 shows the spatial distribution of all insured buildings in the canton of Zurich as well as of the total sum insured at municipal level. The aggregated sum insured for all buildings in the two main cities, Zurich and Winterthur (municipal boundaries indicated by blue polygons), accounts for almost 40 % of the total insured value for the entire canton.

To estimate the damage in monetary terms, the value of each individual building (i.e., its insured value) was multiplied by the factor “Mean Damage Degree” (MDD) ~~according to, a number between 0 and 1) calculated from the vulnerability curve of~~ Schwierz et al. (2010), where the gust speeds at building level computed in the first step were converted into the corresponding MDD factors. The MDD factors are a non-linear function of the maximum wind gust speed during a windstorm event ~~and are diagrammed in Welker et al. (2016).~~ The same vulnerability curve of Schwierz et al. (2010) is also implemented in the open source impact model CLIMADA (Aznar-Siguan and Bresch, 2019a). ~~The vulnerability curve is diagrammed in Welker et al. (2016).~~

In the next step of the damage model, the probability of buildings affected is calculated with a stochastic approach. The respective windstorm event was automatically categorised according to its severity (here, according to the 95th percentile of all gust speeds at building level in the [affected region of the](#) canton of Zurich), from which the assumed degree of impact is derived. The degree of impact for the different windstorm categories ([i.e., a percentage of total affected buildings for the canton of Zurich, \$m\$](#)) was derived from proprietary event damage data from GVZ’s database. Then, a random sample of m buildings was selected, with the number m depending on the windstorm’s severity. Only buildings with $MDD > 0$ were considered, i.e. only those buildings with potential damage > 0 . For the selected buildings, the amount of damage at building level was summed to obtain the total damage for the entire canton. This procedure of random sampling was repeated 1’000 times giving a total damage range for each windstorm event. Unless otherwise stated, for each windstorm the median of the damage distribution is given hereinafter.

2.3.2 CLIMADA impact model

The windstorm damage model in the open source risk assessment platform CLIMADA is relying on open data only and that is why it is deviating in some aspects from GVZ’s approach described above. As the windstorm hazard component is open, it is identical to the hazard input used in case of the GVZ damage model. The exposure is based on public data instead of GVZ’s proprietary portfolio information. CLIMADA uses produced capital for Switzerland published by the World Bank (2018) as the total value of physical assets for Switzerland and further uses a combination of nightlight intensity and population density to create a reliable geographical distribution of the assets (Eberenz et al., 2019). The resulting values are then distributed to building footprints from OpenStreetMap (OpenStreetMap contributors, 2017). Analogous to the GVZ damage model, CLIMADA uses the MDD curve of Schwierz et al. (2010). Instead of a random resampling of affected buildings, the MDD factor is combined with the deterministic factor “Percentage of Assets Affected” (PAA).

As the total value of the exposure is different between the GVZ exposure, the CLIMADA exposure, and the exposure used in Schwierz et al. (2010), the MDD and PAA factors might be wrongly scaled for this study. In

the CLIMADA model setup used, we adjusted for this by linearly scaling the MDD and PAA factors to reduce the difference of the modelled damages and the insured damages for matching events (i.e., by minimising the root-mean-square deviation, RMSD). This adjustment conserved the shape of the original vulnerability curve.

The CLIMADA impact model and the GVZ damage model have a different sensitivity to the hazard intensity: in CLIMADA, damage is possible for a wind gust speed of 72 km/h (20 m/s) and above, in the GVZ damage model for 90 km/h (25 m/s) and above.

2.4 Assessment of potential windstorm damage and risk

Risk is defined here as the product of the extent of damage and the probability of damage. The probability of damage is driven, on the one hand, by the probability that the building is within the area of high wind gust speeds and, on the other hand, by the return period of the windstorm event. The probability, that the building is within the area of high wind gust speeds is incorporated in the modelled damage amount by the spatially explicit modelling approach and the vulnerability, which includes the percentage of assets affected (in case of CLIMADA). The return period or frequency of windstorm events is derived from the hazard event sets. Return periods express the probability of occurrence of windstorm events (e.g., an event with a return period of 250 years is expected on average every 250 years).

There are several risk assessment metrics that can be calculated with a set of event damages, which are the main result from the damage modelling described above.

2.4.1 Average annual damage

The average annual damage (AAD) is an important risk measure in the insurance industry. It describes the risk from all events reported on an annual basis:

$$AAD = \frac{\text{sum of all event damages}}{\text{time range covered by event set}} = \sum_{\text{event } i} \text{event damage}_i * \text{annual frequency}_i \quad (2)$$

2.4.2 Exceedance frequency curve

Using the annual frequencies of the events in a hazard event set, it is possible to determine at what frequency a certain damage amount is exceeded. The largest damage amount is exceeded once in the time range covered by the damage event set, the second largest damage amount is exceeded twice, the third one thrice and so on. The exceedance frequency curve shows the damage amount as a function of exceedance frequency. For large damage amounts, this matching typically relies on only a few damage events, which increases the statistical uncertainty.

2.4.3 Pareto pricing

In the insurance industry, the concept of “Pareto pricing” is a simple approach to represent and extrapolate the distribution of a damage event set to define the price of insurance contracts (Mitchell-Wallace et al., 2017). We imitated this pricing method by fitting a Generalized Pareto Distribution (GPD) to damage event sets using a Maximum Likelihood Estimate (MLE). We do this even though some assumptions in statistical theory are not valid for these datasets (e.g., windstorm damage event sets are clustered which breaks the independence

assumption), as we use the GPD only to show the underlying sampling uncertainty. To fit a GPD to a damage event set, only the threshold has to be chosen. We chose a threshold for each damage event set, which results in a parameterised GPD with similar exceedance frequencies for the largest damage amount in the event set. For the insured damages we chose a threshold of CHF 0.4 million and for the modelled damage event set based on “WISC historic” we chose a threshold of CHF 0.1 million. By using the percent point function (the inverse of a cumulative distribution function) on the fitted distributions, an exceedance frequency curve for the fitted distribution was calculated.

To illustrate the statistical uncertainty of the exceedance frequency curve, we undertook a resampling- [and thereby show the sampling uncertainty for each damage event set](#). In the resampling, we generated 200 random samples from the fitted distribution and used the MLE to fit a GPD to each random sample. The exceedance frequency curves of these resampled distributions illustrate the uncertainty especially for rare events with a high return period. We show the 90-% confidence interval of damage amounts for each exceedance frequency, which spans from the 5th percentile to the 95th percentile of the 200 samples.

[In case of the damage event set computed on the basis of “WISC probabilistic extension”, the uncertainty is best illustrated by the sampling uncertainty of the damage event set based on “WISC historic” for the following reasons. The procedure of computing the hazard event set “WISC probabilistic extension” by statistical perturbation \(as described in Sect. 2.2.3\) transforms part of the sampling uncertainty of the hazard event set “WISC historic” into an uncertainty of the parameters \$\alpha\$ and \$\beta\$ in Eq. \(1\). However, this parameter uncertainty is difficult to illustrate, since no combination of \$\alpha\$ and \$\beta\$ could be found which adequately represents the upper and lower boundaries of the sampling uncertainty of the pan-European SSI distribution. Additionally, the sampling uncertainty of “WISC probabilistic extension” no longer represents the same uncertainty as in case of the other damage event sets. Thus, for comparison of the uncertainties of the different damage event sets, we suggest to use the sampling uncertainty of “WISC historic” as best illustration of the uncertainty of “WISC probabilistic extension”.](#)

3 Results

3.1 Single events

The damage due to Lothar/Martin is by far the largest windstorm event damage in GVZ’s insurance claims database (Fig. A3a): Lothar/Martin caused insured damages of CHF 62.4 million. Lothar/Martin is the most damaging windstorm event in the canton of Zurich in both the 34-years period of insurance claims data as well as in the 75-years period of “WISC historic”. The damages modelled with the GVZ damage model range between CHF 58.0 million and CHF 69.0 million, and the median of all modelled damages amounts to CHF 62.7 million (Fig. A3b). For Burglind, the most damaging event of the “observed footprints”, the modelled damages range between CHF 10.4 million and CHF 14.5 million, with a median of CHF 12.0 million. For comparison, the insured damages amount to CHF 14.2 million. Thus, damages associated with intense windstorm events like Lothar/Martin or Burglind are very well modelled with GVZ’s damage modelling approach, providing confidence in the methodology. For all recorded windstorm events since 1981 (including the additional seven windstorms in 2017 and 2018), the RMSD between the insured damage and the median

modelled damage amounts to CHF 2.4 million. Furthermore, the example of Burglind shows that our methodology of creating windstorm footprints on the basis of interpolated wind gust observations (Sect. 2.2.4) is suitable for present and probably also for future windstorm events.

3.2 Average annual damage

The average annual damage (AAD) calculated based on the insured damages (i.e., the mean damage over the observational period of 34 years) is almost twice as high as the AAD computed on the basis of “WISC historic” (Table 2). Several factors contribute to the fact that the AAD is higher for the insured damages than for the modelled damages based on “WISC historic”: (i) the occurrence of the very intense event Lothar/Martin, along with other intense events, in the relatively short available period of insurance claims data (Fig. A3a), (ii) the higher damages of events in the 5-year return period range (Table 2), and (iii) the different number of events per year considered. The hazard event set “WISC probabilistic extension” was created to best represent the low-frequency tail of the pan-European SSI and not the full distribution of (high frequency) damages in the canton of Zurich. Nevertheless, the modelled AAD based on the GVZ damage model and “WISC probabilistic extension” is close to the AAD of “WISC historic”.

3.3 Assessment of risks due to extreme windstorm events

Figure 2 shows GVZ’s windstorm risk assessment of building damage, including uncertainty, on the basis of all available data sources. Based on the insurance claims data only, the return period for the extreme windstorm event Lothar/Martin is estimated to be 34 years (blue squares). Based on “WISC historic”, the return period for Lothar/Martin is estimated to be 75 years (yellow dots). Based on the hazard event set “WISC probabilistic extension” and using GVZ’s approach for damage modelling, the return period for a damage amount due to Lothar/Martin would be around 125 years (red diamonds). These estimates represent the best guess for each damage event set. It is important to note that the quantified uncertainty of the estimate for the return period of Lothar/Martin based on “WISC historic” (yellow ribbon, 25 years to > 500 years) incorporates both the estimate for the insurance claims data (blue ribbon) as well as the estimate based on “WISC probabilistic extension”.

The extrapolated event damage with a return period of 250 years amounts to about CHF 500 million for “WISC historic” and using the same method for the insured damages the extrapolated 250-year event damage would be even higher, around CHF 2.4 billion (yellow and blue lines in Fig. 2). Contrary to this, the 250-year event damage amounts to only about CHF 75 million in case of the hazard event set “WISC probabilistic extension” (red diamonds). The 90-% confidence interval, which represents the sampling uncertainty of the extrapolation of the damage exceedance frequency, based on “WISC historic” provides a range for the 250-year return period damage of CHF 19 million to CHF 33 billion (yellow ribbon). As “WISC probabilistic extension” is based on the same historic information this uncertainty also applies to its results. At a return period of 250 years, the quantified uncertainty of the estimate based on “WISC historic” incorporates both the estimate for the insurance claims data as well as the estimate based on “WISC probabilistic extension”.

~~Interesting to see~~An interesting feature illustrated in Fig.- 2 is that ~~the tail of at higher return periods the~~ modelled damages on the basis of “WISC probabilistic extension” ~~is reaching far smaller damages per return period than increase less strongly compared to~~ the two extrapolations based on the fitted distributions. Evident

“jumps” in the modelled damage (e.g., at return periods of approximately 30 years, 70 years, and 90 years) result from the discrete categorisation of the individual windstorm events and the assumed degrees of impact, respectively, as applied in GVZ’s damage modelling approach (Sect. 2.3.1).

3.4 Reproducibility of the results using CLIMADA

In general, GVZ’s proprietary windstorm damage model is suitable for correctly simulating building damage in the canton of Zurich (see Fig. 3, Fig. A3, and Sect. 3.1). Using the calibrated CLIMADA impact model for windstorm damage modelling is also suitable and the corresponding RMSD amounts to CHF 1.5 million for all recorded windstorm events since 1981 for which WISC wind gust footprints are available (excluding the additional windstorms in 2017 and 2018). The statistics in Table 2 calculated using the GVZ damage model were also calculated using the CLIMADA impact model and the results can be found in Table A1. In summary, it can be stated that the setup of the two damage models applied works well and e.g. replicates the order of the events, provides a reasonable modelled damage for historic events (compared to insurance claims data), and both RMSD are sufficiently good.

The exceedance frequency curve of the modelled damages based on “WISC probabilistic extension” and the CLIMADA impact model (green triangles in Fig. 2) show in general lower values compared to the damage modelling using the GVZ approach (red diamonds), in particular for return periods between 30 and 70 years. This difference is also reflected in the scatter plots in Fig. 3, where in Fig. 3a the GVZ damage model shows an overestimation of the damage amount due to the windstorm event Vivian/Wiebke (with insured damage of approximately CHF 11 million), whereas the CLIMADA impact model shows an underestimation for the same event. The reason for this over- and underestimation of the damage in case of events such as Vivian/Wiebke could be due to the hazard or exposure part of the respective model, but is more likely due to the applied vulnerability curve itself. Apparently, the two damage models perform differently for windstorm events in a medium intensity category. This difference between the two models also becomes evident regarding the AAD risk metric: the AAD of the CLIMADA impact model with “WISC historic” amounts to CHF 1.1 million (Table A1) and is thus almost a third smaller than the AAD associated with the GVZ damage model (CHF 1.4 million). In addition, the curve of the modelled damages is much smoother in case of CLIMADA (Fig. 2), which can be explained by the fact that in CLIMADA the smooth curve of the PAA factors is used. This shows the importance of the applied vulnerability curve in the presented damage modelling approach.

3.5 Rapid damage estimation

Rapid damage estimation directly after a windstorm event is very useful for insurance companies to get a first rapid assessment of the damage to be expected and to e.g. assign their staff accordingly. For current windstorm events, the GVZ does this using its damage model and the wind gust footprints based on “observed footprints” (Sect. 2.2.4). The 95th percentile of the wind gust speeds at building level in the [entire area affected region](#) of the canton of Zurich, which is also used in GVZ’s damage model to categorise windstorm events (Sect. 2.3.1), is used as a rapid indicator of the range of possible damages. This process is illustrated in Fig. 4. With the help of the dataset “WISC probabilistic extension”, assessments can also be made about potential damages from unprecedented, extreme windstorm events. The uncertainty of the damage assessment for such extreme events can be visualised by the large number of available (extreme) events. In total, “WISC probabilistic extension”

contains 17 events which are potentially more damaging than Lothar/Martin. A (modelled) total damage amount of more than CHF 96 million is associated with the most extreme windstorm event in “WISC probabilistic extension” (Fig. 1). Thus, this windstorm is potentially about 1.5 times as damaging as Lothar/Martin.

Figure 4 further shows, by the length of the red bars, the stochastic component in GVZ’s damage modelling approach, which tries to approximate the random selection as not every building is equally affected during a windstorm event (Sect. 2.3.1). The range of modelled damages (length of red bars) increases with increasing wind gust speed. On the other hand, the quotient of the range of modelled damages and the median of the damage distribution (red points) generally decreases with increasing wind gust speed. “Jumps” in the modelled damage (e.g., for wind gust speeds lower than 126 km/h) again result from the discrete categorisation of the individual windstorm events in the GVZ damage model.

The absolute difference between the modelled damage amount and the corresponding value of the regressed relationship (red points and solid red line in Fig. 4) generally increases with increasing wind gust speed. Accordingly, the number of available wind gust footprints decreases with increasing wind gust speed.

4 Discussion

Any information about the historic risk of winter windstorms in the canton of Zurich contains the record of the event Lothar/Martin. As this is the most damaging event in the record by far, the general risk assessment is connected to the assessment of the return period of such an event damage, which will always be uncertain. We argue that the return period based on the historic windstorm footprints (75 years) is much more reliable than the return period based on the insured damage record (34 years). Well knowing that the two estimates each have overlapping uncertainties, the estimates do not contradict each other. Rather the estimates, as best guesses, can inform varying deterministic risk views. Other information, like the return period of Lothar/Martin’s damage amount based on “WISC probabilistic extension” and an independent catalogue of historic windstorms in Switzerland by Stucki et al. (2014) suggest that the return period of such a damage amount could be even rarer than 75 years. This clearly shows the added value that GVZ achieves in its risk assessment through applying the WISC wind data compared to using insurance claims data only – and, above all, through the additional dataset “WISC probabilistic extension”. The return period of extreme windstorm events such as Lothar/Martin can now be assessed more reliably.

The windstorms Lothar and Martin affected, in addition to Switzerland, in particular France, Belgium, Luxembourg, and Germany. The original industry damage associated with Lothar and Martin amount to approximately EUR 5.8 billion and EUR 2.5 billion, respectively (PERILS, 2020). The return period for exceeding the damage amount due to Lothar alone in all of Europe was estimated to be 15 years by Munich Re (2002) and the return period for the cluster of the three windstorms in December 1999 Anatol (3 December 1999), Lothar, and Martin was estimated to be between 22 and 45 years (Renggli and Zimmerli, 2016). This study shows that it is important to make a distinction between the return period of an event like Lothar/Martin in all of Europe and the return period of this event locally, in a relatively small region. The damage modelling shown in this study, using the event set “WISC historic” and the local

exposure information, enables a much more reliable derivation of the return period specific to GVZ than the existing scientific work is able to provide.

Based on “WISC historic” and the GVZ damage model, the average annual damage for building damages in the canton of Zurich amounts to CHF 1.4 million according to our calculation and we argue that this is the best available estimate for the AAD. However, this estimation is still uncertain due to the high sampling uncertainty, the uncertainty associated with the assessment of the event Lothar/Martin, and the uncertainty with regard to the damage modelling itself. For comparison, in the last 10 years GVZ has experienced yearly damage from all natural hazards of CHF 16 million and additionally yearly damage by fire of CHF 42 million (all numbers from 2018; GVZ annual report, 2018). Compared to the risk from these hazards, the estimated AAD from winter windstorms of CHF 1.4 million is relatively small. However, the occurrence of windstorm events such as Vivian/Wiebke, Lothar/Martin, and Burglind has shown that single windstorms are able to cause huge damage amounts and they are consequently an important causal element when assessing capital requirements.

Insurance companies undertake their business under a strict regulatory environment, and having enough capital to cover rare events is one of the regulatory requirements. The damage amount reached on average every 250 years is an often-mentioned indicator for such a rare event. However, the insured damages and also the modelled damages based on “WISC historic” do not span a long enough period by far to make an empirical prediction of a damage amount with a return period of 250 years. All methods of extrapolation from these datasets suffer from the sampling uncertainty (shown as confidence intervals in Fig. 2). The hazard event set “WISC probabilistic extension” uses the distribution of pan-European SSI values to create a set of probable events with higher return periods than “WISC historic”. The uncertainty of the return periods of such events however cannot considerably be reduced compared to “WISC historic”, because it relies on the same historic information. [In future studies, the information from dynamical models, which are run for many model years, would help to further reduce this uncertainty.](#) Despite the uncertainty, it can nevertheless be important to study the sensitivity of the 250-year return period damage to changes in the portfolio (like growth or changed building codes), changes in the deductible or other changes. “WISC probabilistic extension” provides windstorm footprints of events with a return period of 250 years (and more), that allow the modelling of damages with changes in the exposure or the vulnerability.

It comes as no surprise that the choice of the vulnerability curve in the damage modelling approach applied strongly influences the results of the damage estimation (e.g., Koks and Haer, 2018), and unsurprisingly no optimal “one-size-fits-all” vulnerability curve exists. Every damage model behaves differently, not least because different vulnerability curves are used and each of the damage models has been calibrated differently. The vulnerability curve of Schwierz et al. (2010) is based on movable property and building damages associated with European winter windstorms. The rather general function does not make a distinction between building types, in contrast to other available functions (e.g., Feuerstein et al., 2011). For a modelling setup with focus on the hazard, the vulnerability curve of Schwierz et al. (2010) is however suitable and was successfully applied in earlier studies (e.g., Stucki et al., 2015; Welker et al., 2016). The function does not require detailed information regarding the values at risk, which is certainly an advantage for such insurance and reinsurance companies that do not have detailed exposure data for their damage modelling. [A disadvantage of the used vulnerability curve is that it does not implicitly provide a quantification of the uncertainty as a probabilistic vulnerability curve would](#)

(e.g., Heneka et al., 2006; Prah et al., 2012). The quantification of the uncertainty of exposure and vulnerability information was generally omitted in this study to focus on the comparison of the claims and hazard datasets. But of course, for comparison of the presented risk numbers with other studies the uncertainty of the vulnerability and exposure information play a bigger role. The vulnerability assumed in this study and the

corresponding hazard intensity only considers the maximum gust speeds during an event and not the duration of high wind gusts within a windstorm event, which can however have a major impact on the damage to be expected. Taking the windstorm duration into account (e.g., Etienne and Beniston, 2012) could improve our damage modelling, and it is planned to implement this in a future version of GVZ's damage model. Furthermore, it is not considered that buildings are partially adapted to local wind conditions (e.g., multi-storey buildings or exposed buildings located on mountain tops).

Not every building is equally affected during a windstorm event. To take that into account, in the GVZ damage model a random resampling of affected buildings was applied according to an assumed degree of impact (red bars in Fig. 4). The assumed degree of impact was derived according to the respective severity category of the windstorm. This severity categorisation and the assumed degrees of impact are inevitably relatively rough in GVZ's current model setup, because the assumptions are based on insurance claims data from only a few past windstorm events in the canton of Zurich. With every further windstorm, these assumptions will however become more reliable in the future. In contrast, the deterministic PAA values (Schwierz et al. 2010), as used in the CLIMADA impact model, are much smoother and thus allow a smooth damage modelling (Fig. 2). However, these values are not specific for windstorms in the canton of Zurich and they do not allow a stochastic sampling as in GVZ's damage modelling approach.

The rapid estimate of the damage potential in the event of extreme, unprecedented windstorm events shown in Fig. 4 is just one example of how the WISC data and in particular the additional damage event set "WISC probabilistic extension" can be used for insurance applications. The idea was to be able to make a statement about the damage to be expected simply based on available wind observations in the area of the canton of Zurich. It is always important for insurance companies to be able to give a damage assessment as rapidly as possible after an event, not least when it comes to media inquiries. However, one should keep in mind that the uncertainty shown does not incorporate the full uncertainty of the damage estimate, but rather the uncertainty that results from the random selection as not all buildings are affected equally during a windstorm event. In a future study, it would be interesting to quantify the full uncertainty of the rapid damage estimate.

Not least, the WISC wind data enable insurance companies to evaluate the variability and long-term changes of winter windstorms and their associated damage since 1940. Besides a marked interannual and decadal-scale variability of windstorms in the canton of Zurich, we find a tendency for more intense windstorms since approximately mid of the 1980s (Fig. A3d). One possible reason for this positive trend is that "WISC historic" consists of two "parts" with different databases: until 1979, the ERA-20C reanalysis (Poli et al., 2016) was used for downscaling, followed by the ERA-Interim reanalysis (Dee et al., 2011). Furthermore, a change in the large-scale, atmospheric dynamics has been observed in recent decades, which was conducive to increased winter windstorm activity and intensity in Switzerland (Welker and Martius, 2015). This change was accompanied by an atmospheric circulation pattern resembling a southeastwardly displaced winter North Atlantic Oscillation (NAO) pattern. Which of the two reasons is dominant for the found positive tendency in winter windstorm

intensity and associated damages in the canton of Zurich could not be finally clarified in the present study. Furthermore, how winter windstorm activity and intensity in mid-latitude Europe will change in a future warmer climate is still uncertain (Catto et al., 2019).

5 Conclusion

This study is an example of how a regional building insurance company in Switzerland uses the open database of European windstorm event sets provided by WISC in combination with a probabilistic extension for their assessment of potential building damages and risks as a result of extreme winter windstorm events, including an evaluation of the uncertainties. The windstorm event Lothar/Martin in December 1999 is the most damaging event in both the insurance claims data and “WISC historic” (damage of more than CHF 60 million). The average annual damage for building damages in the canton of Zurich is CHF 1.4 million, computed based on “WISC historic” and the GVZ damage model.

Both the insurance claims data and the modelled building damages based on “WISC historic” are rather unsuitable for evaluating rare windstorm damage events with return periods considerably exceeding the observational period. The new hazard event set “WISC probabilistic extension” projects a damage amount of approximately CHF 75 million for a return period of 250 years, while the uncertainty for an extrapolation to such return periods is still very large. However, the probabilistic hazard event set allows for testing the sensitivity of the risk to e.g. changes in the insurance portfolio or in the insurance condition (e.g., the deductible) for events of a higher intensity than the observed historic events.

Our analysis is implemented in GVZ’s proprietary windstorm damage model as well as in the open source risk assessment platform CLIMADA (Bresch and Aznar-Siguan, 2019a). This guarantees scientific reproducibility and offers insurance companies and other societal actors in Switzerland and the rest of Europe the opportunity to apply the shown methodology to their own portfolio with a low entry threshold. This study illustrates how open climatological data and open source damage models can be used to assess windstorm risks in Europe and how this approach complements risk assessments based on proprietary insurance claims data only.

There is a growing societal need for physical risk disclosure, not least in the context of the Task Force for Climate-related Financial Disclosure (TCFD; Surminski et al., 2020). The presented methodology, in particular the combination of the WISC hazard data with the open source CLIMADA platform, can be used for such a disclosure report.

Code availability and data availability

The scripts reproducing the main results of the paper and the figures [isare](https://github.com/CLIMADA-project/climada_papers) available under https://github.com/CLIMADA-project/climada_papers. The probabilistic hazard event set “WISC probabilistic extension” for each European country is made available for download under <https://doi.org/10.3929/ethz-b-000406567> (Rösli and Bresch, 2020).

CLIMADA is openly available at GitHub (https://github.com/CLIMADA-project/climada_python; Bresch and Aznar-Siguan, 2019a) under the GNU GPL license (GNU operating system, 2007). The documentation is hosted

on Read the Docs (<https://climada-python.readthedocs.io/en/stable/>; Aznar-Siguan and Bresch, 2019b) and includes a link to the interactive tutorial of CLIMADA. CLIMADA v1.4.1 was used for this publication, which is permanently available at the ETH Data Archive: <http://doi.org/10.5905/ethz-1007-252> (Bresch et al., 2020).

Author contribution

CW and TR share first co-authorship and contributed equally to defining the case study, performing the analyses, writing the article, and participating in the review process. CW developed the GVZ damage model and TR generated the hazard event set “WISC probabilistic extension”. DNB contributed to writing the article, conceptualised CLIMADA, and over-saw its implementation in Python, based on the previous MATLAB implementation by himself.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

We are very thankful to the WISC consortium and project team for making all the data and documentation available and fully open access. Map data copyrighted OpenStreetMap contributors and available from <https://www.openstreetmap.org>. We want to thank Jan Hartman for his help implementing the Storm Europe hazard module in the Python version of CLIMADA, Evelyn Mühlhofer for implementing the OpenStreetMap exposure module in CLIMADA, as well as Samuel Eberenz and Maurice Skelton for providing valuable input on the manuscript.

References

- Aznar-Siguan, G. and Bresch, D. N.: CLIMADA v1: a global weather and climate risk assessment platform, *Geosci. Model Dev.*, 12, 3085-3097, <https://doi.org/10.5194/gmd-12-3085-2019>, 2019a.
- Aznar-Siguan, G. and Bresch, D. N.: CLIMADA_python documentation, <https://climada-python.readthedocs.io/en/stable/>, last access: 17 July 2019, 2019b.
- Bresch, D. N.: Shaping Climate Resilient Development – Economics of Climate Adaptation, in: *Climate Change Adaptation Strategies – An Upstream-downstream Perspective*, edited by: Salzmänn, N., Huggel, C., Nussbaumer, S., and Ziervogel, G., Springer, Cham, 241-254, https://doi.org/10.1007/978-3-319-40773-9_13, 2016.
- Bresch, D. N. and Aznar-Siguan, G.: CLIMADA-python, https://github.com/CLIMADA-project/climada_python, last access: 17 July 2019, 2019a.

643 Bresch, D. N., Aznar Siguan, G., Bozzini, V., Bungener, R., Eberenz, S., Hartman, J., Mühlhofer, E., Pérus, M.,
644 Rösli, T., Sauer, I., Schmid, E., Stalhandske, Z., Steinmann C., Stocker, D.: CLIMADA_python v1.4.1
645 <http://doi.org/10.5905/ethz-1007-252>, 2020.

646 Catto, J. L., Ackerley, D., Booth, J. F., Champion, A. J., Colle, B. A., Pfahl, S., Pinto, J. G., Quinting, J. F., and
647 Seiler, C.: The future of midlatitude cyclones, *Curr. Clim. Change Rep.*, 5, 407-420,
648 <https://doi.org/10.1007/s40641-019-00149-4>, 2019.

649 Davies, T., Cullen, M. J. P., Malcolm, A. J., Mawson, M. H., Staniforth, A., White, A. A., and Wood, N.: A new
650 dynamical core for the Met Office's global and regional modelling of the atmosphere, *Q. J. Roy. Meteor.*
651 *Soc.*, 131, 1759-1782, <https://doi.org/10.1256/qj.04.101>, 2005.

652 Dawkins, L. C., Stephenson, D. B., Lockwood, J. F., and Maisey, P. E.: The 21st century decline in damaging
653 European windstorms, *Nat. Hazards Earth Syst. Sci.*, 16, 1999-2007, [https://doi.org/10.5194/nhess-16-](https://doi.org/10.5194/nhess-16-1999-2016)
654 [1999-2016](https://doi.org/10.5194/nhess-16-1999-2016), 2016.

655 Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.
656 A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N.,
657 Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V.,
658 Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J.-J.
659 Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N., and Vitart, F.: The ERA-Interim
660 reanalysis: configuration and performance of the data assimilation system, *Q. J. Roy. Meteor. Soc.*, 137,
661 553-597, <https://doi.org/10.1002/qj.828>, 2011.

662 Della-Marta, P. M., Liniger, M. A., Appenzeller, C., Bresch, D. N., Koellner-Heck, P., and Muccione, V.:
663 Improved estimates of the European winter windstorm climate and the risk of reinsurance loss using
664 climate model data, *J. Appl. Meteor. Climatol.*, 49, 2092-2120, <https://doi.org/10.1175/2010JAMC2133.1>,
665 2010.

666 Donat, M. G., Pardowitz, T., Leckebusch, G. C., Ulbrich, U., and Burghoff, O.: High-resolution refinement of a
667 storm loss model and estimation of return periods of loss-intensive storms over Germany, *Nat. Hazards*
668 *Earth Syst. Sci.*, 11, 2821-2833, <https://doi.org/10.5194/nhess-11-2821-2011>, 2011.

669 Eberenz, S., Stocker, D., Rösli, T., and Bresch, D. N.: Exposure data for global physical risk assessment, *Earth*
670 *Syst. Sci. Data Discuss.*, <https://doi.org/10.5194/essd-2019-189>, in review, 2019.

671 Etienne, C. and Beniston, M.: Wind storm loss estimations in the Canton of Vaud (Western Switzerland), *Nat.*
672 *Hazards Earth Syst. Sci.*, 12, 3789-3798, <https://doi.org/10.5194/nhess-12-3789-2012>, 2012.

673 Feuerstein, B., Groenemeijer, P., Dirksen, E., Hubrig, M., Holzer, A. M., and Dotzek, N.: Towards an improved
674 wind speed scale and damage description adapted for Central Europe, *Atmospheric Research*, 100, 547-
675 564, <https://doi.org/10.1016/j.atmosres.2010.12.026>, 2011.

676 Geiger, T., Frieler, K., and Bresch, D. N.: A global historical data set of tropical cyclone exposure (TCE-DAT),
677 *Earth Syst. Sci. Data*, 10, 185–194, <https://doi.org/10.5194/essd-10-185-2018>, 2018.

678 Gettelman, A., Bresch, D. N., Chen, C. C., Truesdale, J. E., and Bacmeister, J. T.: Projections of future tropical
679 cyclone damage with a high-resolution global climate model, *Clim. Change*, 146, 575-585,
680 <https://doi.org/10.1007/s10584-017-1902-7>, 2018.

681 GIN platform: https://www.info.gin.admin.ch/bafu_gin/en/home/gin/overview.html, last access: 19 November
682 2019.

683 GIS browser Zurich: <http://web.maps.zh.ch/>, last access: 18 September 2019.

684 GNU operating system: GNU General Public License, version 3, <https://www.gnu.org/licenses/gpl.html>, last
685 access: 17 July 2019, 2007.

686 GVZ annual report: https://www.gvz.ch/_file/1228/01111018003-web-gvz-gb2018-210x297-es-anhang.pdf, last
687 access: 21 February 2020, 2018.

688 GVZ homepage: <https://www.gvz.ch/>, last access: 14 January 2020.

689 Haas, R. and Pinto, J. G.: A combined statistical and dynamical approach for downscaling large-scale footprints
690 of European windstorms, *Geophys. Res. Lett.*, 39, L23804, <https://doi.org/10.1029/2012GL054014>, 2012.

691 [Heneka, P., Hofherr, T., Ruck, B., and Kottmeier, C.: Winter storm risk of residential structures – model
692 development and application to the German state of Baden-Württemberg. *Nat. Hazards Earth Syst. Sci.*, 6,
693 721–733, <https://doi.org/10.5194/nhess-6-721-2006>, 2006.](#)

694 Hersbach, H. and Dee, D.: ERA-5 reanalysis is in production, ECMWF Newsletter, Reading, UK, 2016.

695 Imhof, M.: Analyse langfristiger Gebäudeschadendaten, Interkantonaler Rückversicherungsverband IRV, Bern,
696 Switzerland, 2011.

697 IPCC: Climate Change 2014: Impacts, Adaptation and Vulnerability. Part A: Global and Sectoral Aspects.
698 Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on
699 Climate Change, edited by: Field, C. B., Barros, V. R., Dokken, D. J., Mach, K. J., Mastrandrea, M. D.,
700 Bilir, T. E., Chatterjee, M., Ebi, K. L., Estrada, Y. O., Genova, R. C., Girma, B., Kissel, E. S., Levy, A. N.,
701 MacCracken, S., Mastrandrea, P.R., and White, L. L., Cambridge University Press, Cambridge, UK, and
702 New York, USA, 2014.

703 Klawa, M. and Ulbrich, U.: A model for the estimation of storm losses and the identification of severe winter
704 storms in Germany, *Nat. Hazard Earth Syst. Sci.*, 3, 725-732, 2003.

705 Koks, E. and Haer, T.: A high-resolution wind damage model using OpenStreetMap.
706 <https://doi.org/10.13140/RG.2.2.23053.59360/2>, 2018.

707 Lamb, H. H. and Frydendahl, K.: Historic storms of the North Sea, British Isles, and Northwest Europe,
708 Cambridge University Press, Cambridge, UK, 1991.

709 Leckebusch, G. C., Renggli, D., and Ulbrich, U.: Development and application of an objective storm severity
710 measure for the Northeast Atlantic region, *Meteorol. Z.*, 17, 575-587, 2008.

711 Mitchell-Wallace, K., Jones, M., Hilier, J., and Foote, M.: Natural Catastrophe Risk Management and
 712 Modelling: A Practitioners Guide, John Wiley and Sons Ltd, Chichester, UK, 2017.

713 Munich Re: Winter storms in Europe (II): Analysis of 1999 losses and loss potentials, Munich Re, Munich,
 714 Germany, 2002.

715 OpenStreetMap contributors: Planet dump retrieved from <https://planet.openstreetmap.org>,
 716 <https://www.openstreetmap.org>, last access: 25 February 2020, 2017.

717 PERILS: <https://www.perils.org/losses?year=1999&classification=&status=#event-losses>, last access:
 718 31 January 2020.

719 Poli, P., Hersbach, H., Dee, D. P., Berrisford, P., Simmons, A. J., Vitart, F., Laloyaux, P., Tan, D. G. H.,
 720 Peubey, C., Thépaut, J.-N., Trémolet, Y., Hólm, E. V., Bonavita, M., Isaksen, L., and Fisher, M.: ERA-
 721 20C: An atmospheric reanalysis of the Twentieth Century, *J. Climate*, 29, 4083–4097,
 722 <https://doi.org/10.1175/JCLI-D-15-0556.1>, 2016.

723 Prah, B. F., Rybski, D., [Kropp, J. P., Burghoff, O., and Held, H.: Applying stochastic small-scale damage](#)
 724 [functions to German winter storms, *Geophys. Res. Lett.*, 39, L06806, <https://doi.org/10.1029/2012GL050961>,](#)
 725 [2012.](#)

726 [Prah, B. F., Rybski, D.,](#) Burghoff, O., and Kropp, J. P.: Comparison of storm damage functions and their
 727 performance, *Nat. Hazards Earth Syst. Sci.*, 15, 769–788, <https://doi.org/10.5194/nhess-15-769-2015>, 2015.

728 Raible, C. C., Kleppek, S., Wüest, M., Bresch, D. N., Kitoh, A., Murakami, H., and Stocker, T. F.: Atlantic
 729 hurricanes and associated insurance loss potentials in future climate scenarios: limitations of high-
 730 resolution AGCM simulations, *Tellus, Ser. A Dyn. Meteorol. Oceanogr.*, 64, 15672,
 731 <https://dx.doi.org/10.3402/tellusa.v64i0.15672>, 2012.

732 Reguero, B. G., Bresch, D. N., Beck, M. W., Calil, J., and Meliane, I.: Coastal risks, nature-based defenses and
 733 the economics of adaptation: an application in the Gulf of Mexico, USA; *Coast. Eng. Pro.* 1, 25,
 734 <https://dx.doi.org/10.9753/icce.v34.management.25>, 2014.

735 Renggli, D. and Zimmerli, P.: Winter storms in Europe: messages from forgotten catastrophes, Swiss Re
 736 publication 1507205_16_EN, https://media.swissre.com/documents/Swiss_Re_Winter_storms.pdf, last
 737 access: 06 February 2020, 2016.

738 Roberts, J. F., Champion, A. J., Dawkins, L. C., Hodges, K. I., Shaffrey, L. C., Stephenson, D. B., Stringer, M.
 739 A., Thornton, H. E., and Youngman, B. D.: The XWS open access catalogue of extreme European
 740 windstorms from 1979 to 2012, *Nat. Hazards Earth Syst. Sci.*, 14, 2487–2501,
 741 <https://doi.org/10.5194/nhess-14-2487-2014>, 2014.

742 Rösli, T., Bresch, D.N.: Probabilistic Windstorm Hazard Event Set for Europe, ETH Zurich Research
 743 Collection, <https://doi.org/10.3929/ethz-b-000406567>, 2020.

744 Rösli, T., Bresch, D. N., and Wüest, M.: A comparison of the WISC events sets with both industry and
 745 research data, WISC Summary Report of Task 5.3 – ETH / Swiss Re Case Study,
 746 <https://doi.org/10.3929/ethz-b-000269483>, 2018.

747 Schadenstatistik VKG: <http://www.vkg.ch/de/versicherung/rueckversicherung>, last access: 25 February 2020.

748 Scherrer, S., Salamin, C., Weusthoff, T., Kaufmann, P., Bader, S., Rösli, T., Aemisegger, N., and Gut, M.: Der
 749 Wintersturm Burglind/Eleanor in der Schweiz, Fachbericht MeteoSchweiz, 268, 2018.

750 Schwierz, C., Köllner-Heck, P., Zenklusen Mutter, E., Bresch, D. N., Vidale, P.-L., Wild, M., Schär, C.:
 751 Modelling European winter wind storm losses in current and future climate, *Clim. Change*, 101, 485-514,
 752 <https://doi.org/10.1007/s10584-009-9712-1>, 2010.

753 Stucki, P., Brönnimann, S., Martius, O., Welker, C., Imhof, M., von Wattenwyl, N., and Philipp, N.: A catalog
 754 of high-impact windstorms in Switzerland since 1859, *Nat. Hazards Earth Syst. Sci.*, 14, 2867-2882,
 755 <https://doi.org/10.5194/nhess-14-2867-2014>, 2014.

756 Stucki, P., Brönnimann, S., Martius, O., Welker, C., Rickli, R., Dierer, S., Bresch, D. N., Compo, G. P., and
 757 Sardeshmukh, P. D.: Dynamical downscaling and loss modeling for the reconstruction of historical
 758 weather extremes and their impacts: A severe foehn storm in 1925, *Bull. Am. Meteorol. Soc.*, 96, 1233-
 759 1241, <https://doi.org/10.1175/BAMS-D-14-00041.1>, 2015.

760 Surminski, S., Westcott, M., Ward, J., Sayers, P., Bresch, D. N., and Bronwyn, C., 2020: Be prepared –
 761 exploring future climate-related risk for residential and commercial real-estate portfolios, accepted for
 762 publication in 2020 by the Journal of Alternative Investments, 2020.

763 Swisstopo DEM: https://shop.swisstopo.admin.ch/en/products/height_models/dhm25200, last access:
 764 8 August 2019.

765 The Economics of Climate Adaptation Working Group: Shaping climate resilient development. A framework
 766 for decision-making, joint report by ClimateWorks Foundation, Global Environmental Facility, European
 767 Commission, McKinsey & Co., The Rockefeller Foundation, Standard Chartered Banks and SwissRe,
 768 [https://ethz.ch/content/dam/ethz/special-interest/usys/ied/wcr-](https://ethz.ch/content/dam/ethz/special-interest/usys/ied/wcr-dam/documents/Economics_of_Climate_Adaptation_ECA.pdf#page=100)
 769 [dam/documents/Economics_of_Climate_Adaptation_ECA.pdf#page=100](https://ethz.ch/content/dam/ethz/special-interest/usys/ied/wcr-dam/documents/Economics_of_Climate_Adaptation_ECA.pdf#page=100), 2009.

770 UPSCALE: <http://proj.badc.rl.ac.uk/upscale>, last access: 21 February 2020.

771 Walz, M. A. and Leckebusch, G. C.: Loss potentials based on an ensemble forecast: How likely are winter
 772 windstorm losses similar to 1990?, *Atmos. Sci. Lett.*, 20, e891, <https://doi.org/10.1002/asl.891>, 2019.

773 Welker, C. and Martius, O.: Large-scale atmospheric flow conditions and sea surface temperatures associated
 774 with hazardous winds in Switzerland, *Clim. Dyn.*, 44, 1857-1869, [https://doi.org/10.1007/s00382-014-](https://doi.org/10.1007/s00382-014-2404-1)
 775 [2404-1](https://doi.org/10.1007/s00382-014-2404-1), 2015.

776 Welker, C., Martius, O., Stucki, P., Bresch, D. N., Dierer, S., and Brönnimann, S.: Modelling economic losses
 777 of historic and present-day high-impact winter windstorms in Switzerland, *Tellus, Ser. A Dyn. Meteorol.*
 778 *Oceanogr.*, 68, 29546, doi:10.3402/tellusa.v68.29546, 2016.

779 WISC products: <https://wisc.climate.copernicus.eu/wisc/#/help/products>, last access: 26 July 2019.

780 WISC hazard event set description:

781 https://wisc.climate.copernicus.eu/wisc/documents/shared/C3S_WISC_Event%20Set_Description_v1.0.pdf

782 f, last access: 26 July 2019.

783 World Bank: Building the World Bank's Wealth Accounts: Methods and Data, Environment and Natural

784 Resources Global Practice, World Bank, [https://development-data-hub-s3-](https://development-data-hub-s3-public.s3.amazonaws.com/ddhfiles/94641/wealth-methodology-january-30-2018_4_0.pdf)

785 [public.s3.amazonaws.com/ddhfiles/94641/wealth-methodology-january-30-2018_4_0.pdf](https://development-data-hub-s3-public.s3.amazonaws.com/ddhfiles/94641/wealth-methodology-january-30-2018_4_0.pdf), last access:

786 14 January 2019, 2018.

787 Zurich construction price index: [https://www.stadt-zuerich.ch/prd/de/index/statistik/themen/bauen-](https://www.stadt-zuerich.ch/prd/de/index/statistik/themen/bauen-wohnen/wohnbaupreise/zuercher-index-der-wohnbaupreise.html)

788 [wohnen/wohnbaupreise/zuercher-index-der-wohnbaupreise.html](https://www.stadt-zuerich.ch/prd/de/index/statistik/themen/bauen-wohnen/wohnbaupreise/zuercher-index-der-wohnbaupreise.html), last access: 14 January 2020.

789 **Table 1:** Summary statistics for the windstorm hazard event sets and insurance claims data used in this study.

Dataset	Available years (period)	Total number of available windstorm hazard events	Number of damage events in the canton of Zurich
“WISC historic”	75 (1940-2014)	142	27
“WISC probabilistic extension”	2’250 (30*75)	142 (parent events) and 4’118 (altered offspring events)	754
“WISC synthetic”	405 (3*135)	22’980	42
“WISC operational”	39 (1979-2017)	106	untested
“Observed footprints”	2 (2017-2018)	7	7
Insurance claims data	36 (1981-2014 and 2017-2018)	-	18 (“WISC historic”) and 7 (“observed footprints”)

790 **Table 2:** Annual average damage (AAD) and event damage for different return periods (RP) and the windstorm
791 event Lothar/Martin on the basis of insurance claims data and modelled damages using the GVZ damage model
792 and the hazard event sets “WISC historic” and “WISC probabilistic extension”, respectively.

	Available years (period)	AAD [CHF m.]	Event damage with 5- year RP [CHF m.]	Event damage with 10- year RP [CHF m.]	Event damage with 50- year RP [CHF m.]	Event damage with 250- year RP [CHF m.]	Event damage due to Lothar/ Martin [CHF m.]
Insurance claims data	34 (1981- 2014)	2.3	0.6	1.1	-	-	62.4
“WISC historic”	75 (1940- 2014)	1.4	0.2	1.3	31.4	-	62.7
“WISC probabilistic extension”	2’250 (30*75)	1.4	0.2	1.3	17.0	74.6	-

793

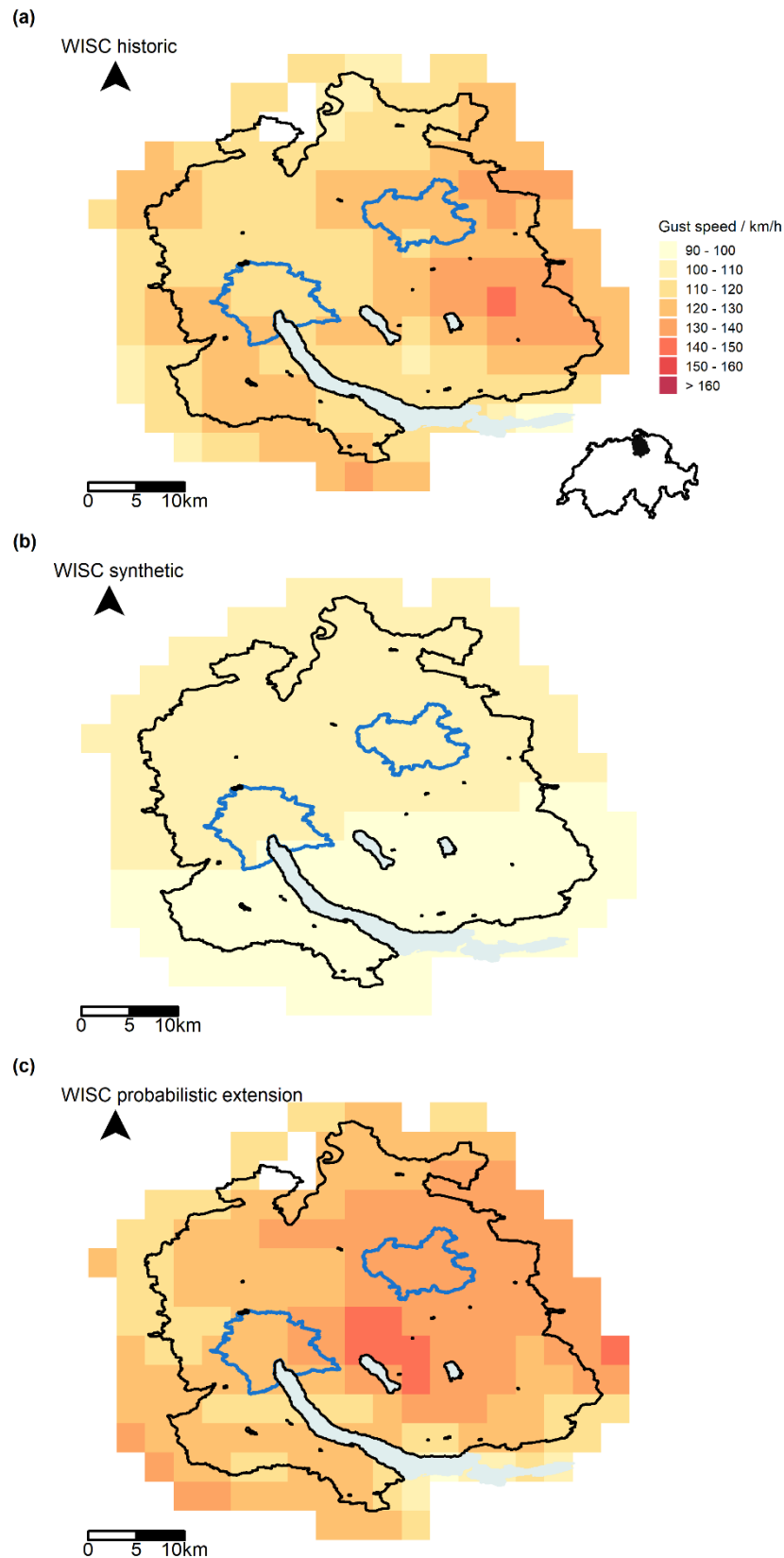


Figure 1: Maximum wind gusts for every grid cell in the canton of Zurich (i.e., windstorm footprints) for the most damaging events in (a) “WISC historic”, (b) “WISC synthetic”, and (c) “WISC probabilistic extension”. The urban areas of the two main cities Zurich (left) and Winterthur (right) are marked in blue.

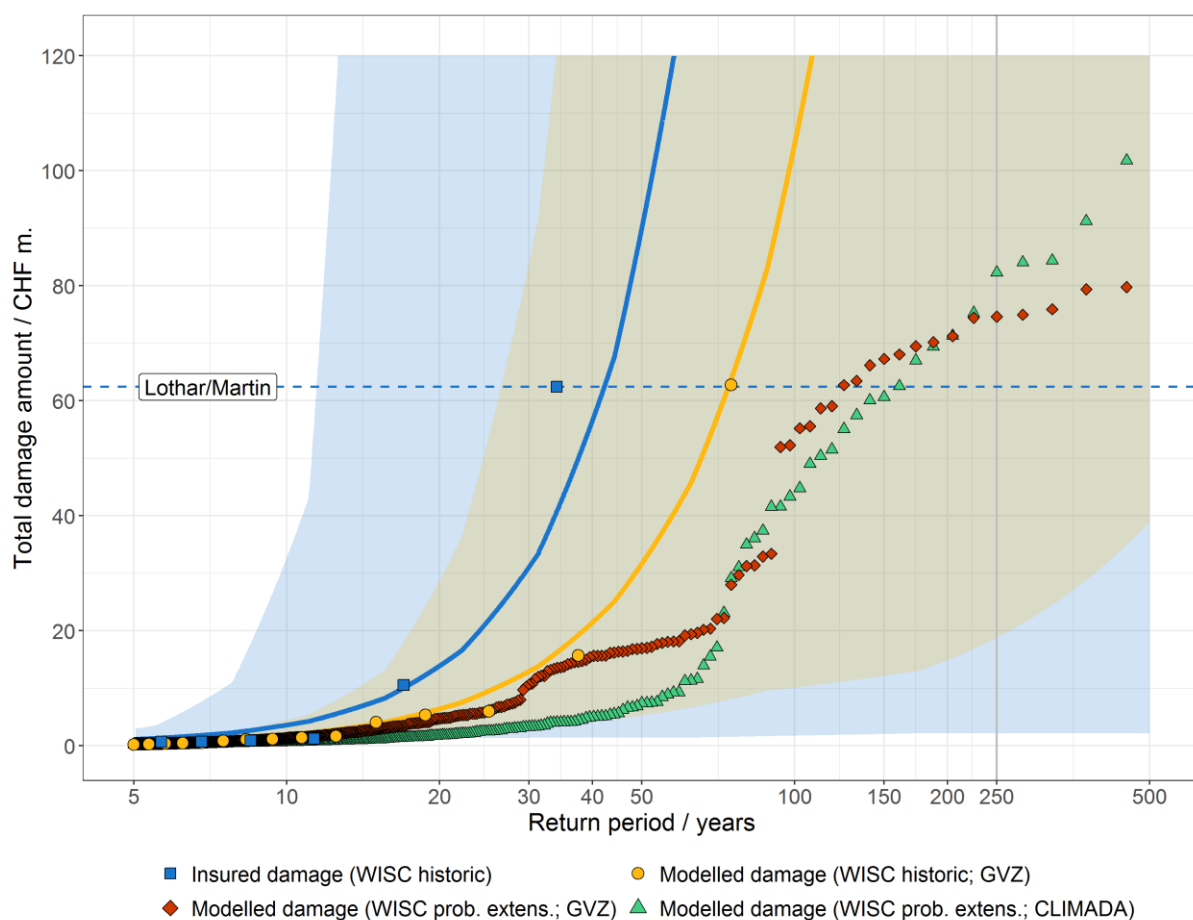


Figure 2: Exceedance frequency curves for building damages in the canton of Zurich based on different data sources. The blue squares indicate the insured damages according to GVZ's database (excluding the additional windstorms in 2017 and 2018), the blue solid line represents a GPD fitted to the insured damages, and the blue ribbon is the 90-% confidence interval produced by resampling. The yellow dots, solid line, and ribbon are analogous to the blue, but for the modelled damages based on "WISC historic" and the GVZ damage model. The red diamonds (green triangles) show the exceedance frequency curve of the modelled damages based on the hazard event set "WISC probabilistic extension" and the GVZ damage model (CLIMADA). The insured total damage for Lothar/Martin is shown by a blue dashed horizontal line, and the 250-year return period is indicated by a grey solid vertical line.

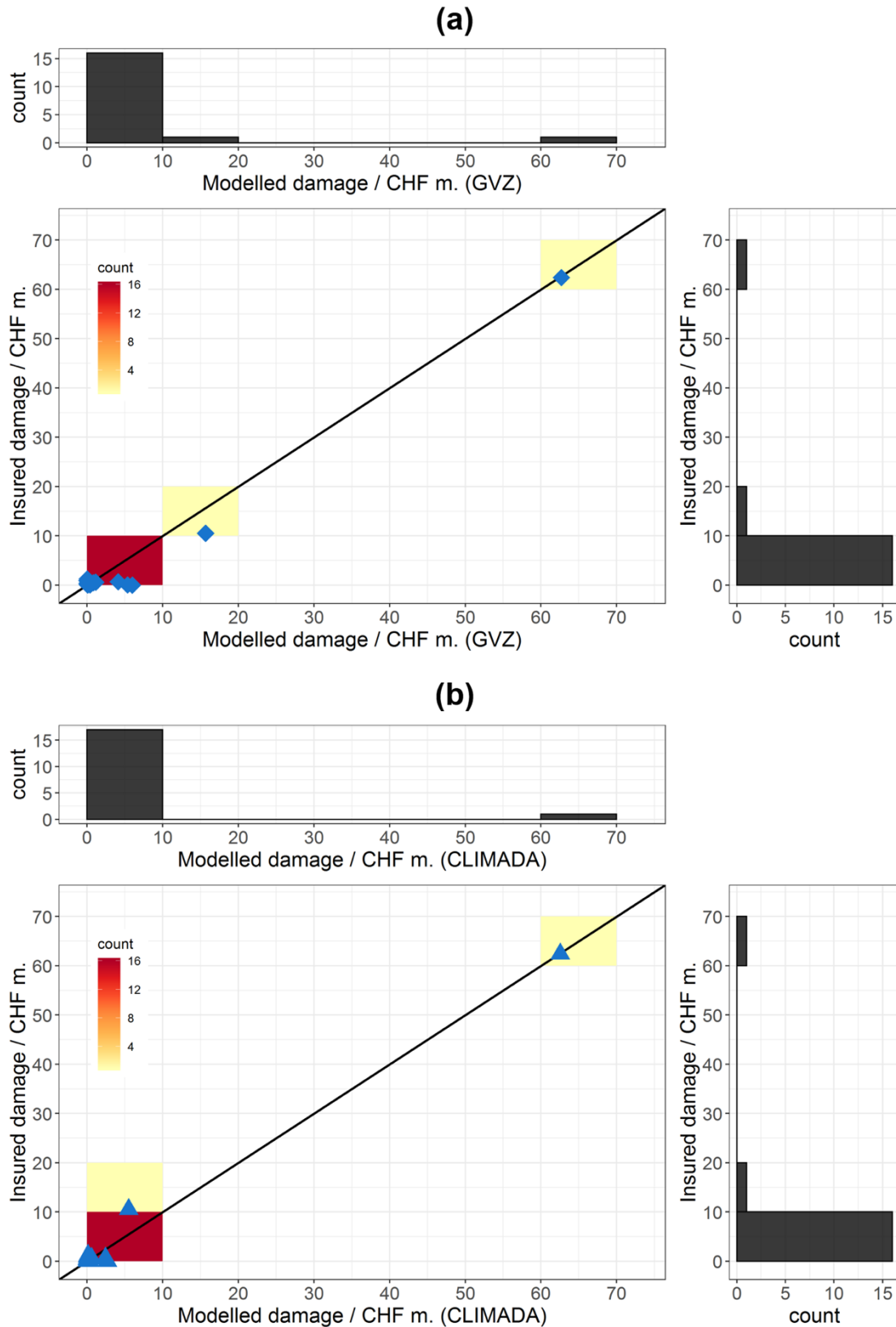
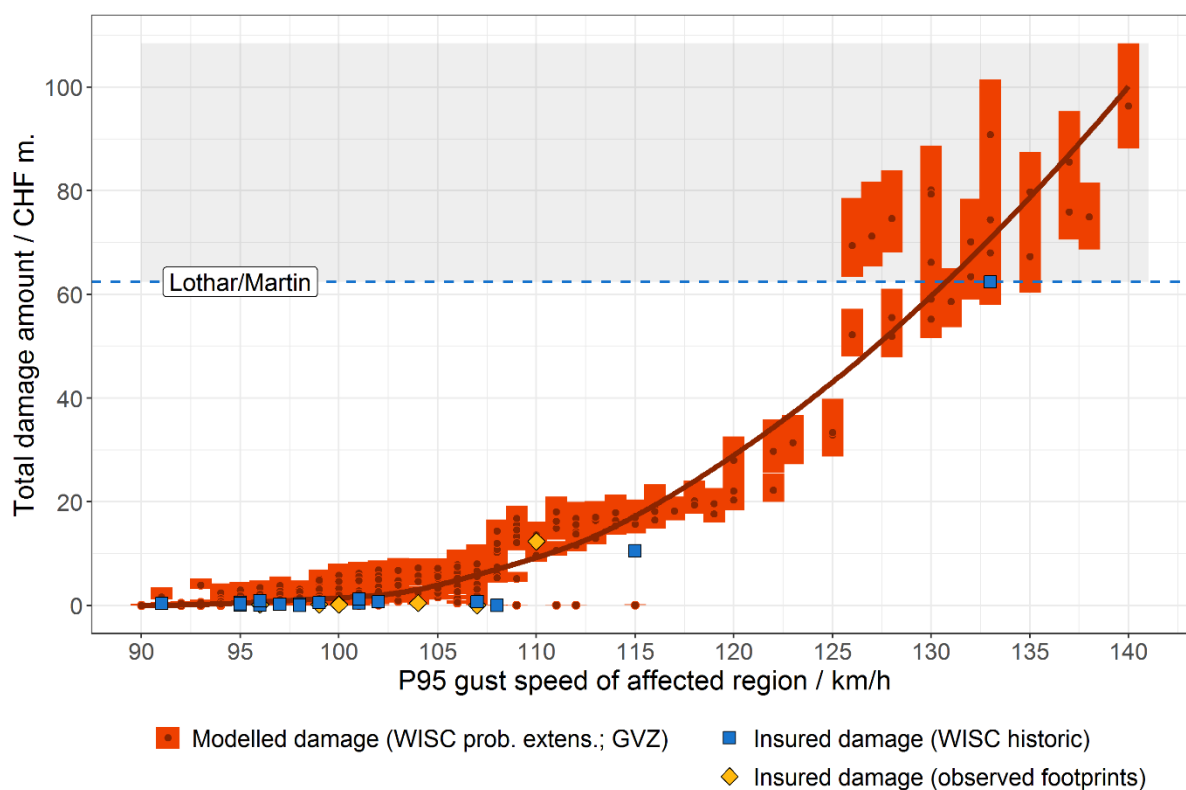
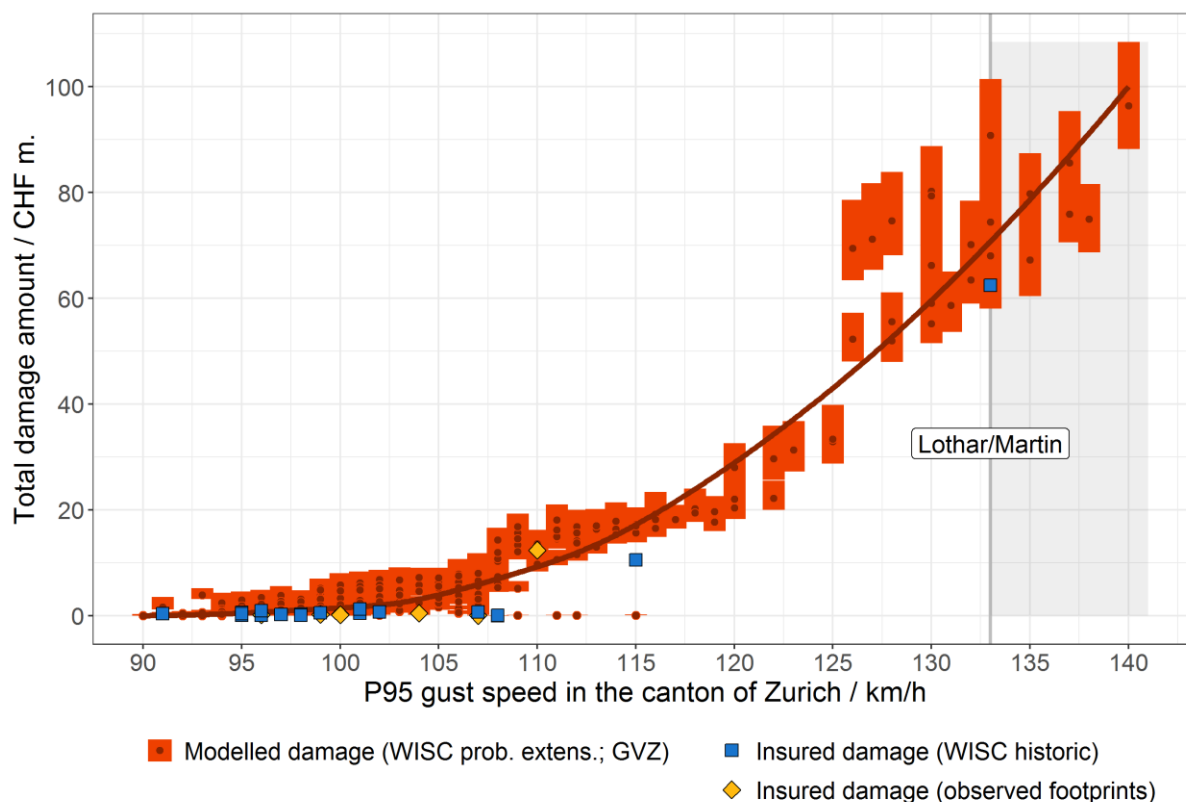


Figure 3: 2d-histograms for the normalised insured total damages in the canton of Zurich versus the modelled total damages based on **(a)** the GVZ damage model (diamonds) and **(b)** the CLIMADA impact model (triangles), respectively, for all windstorms with damage > 0 in the hazard event set “WISC historic”. Marginal histograms are shown in the top and right panels.



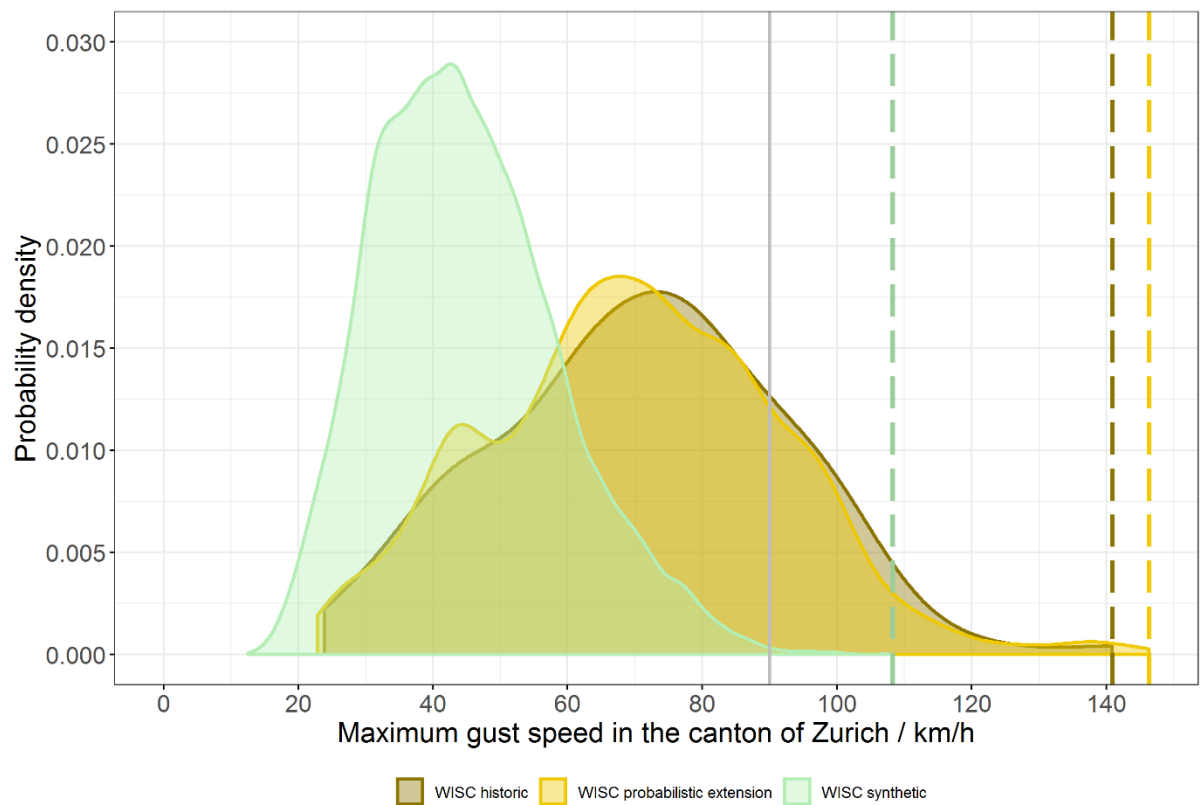
816 **Figure 4:** Total damage modelled using the GVZ damage model and the hazard event set “WISC probabilistic
817 extension” versus the 95th percentile of the corresponding gust speeds in the [affected region of the](#) canton of
818 Zurich (median of 1’000 random damage modelling as red points; range of modelled damages indicated as red
819 bars). The 95th percentile of the gust speeds is shown, because the 95th percentile is used in GVZ’s damage

820 model to categorise windstorm events (Sect. 2.3.1). The relationship between wind gust speed and modelled
821 total damage is further approximated by a locally estimated scatterplot smoothing (LOESS) and a bootstrap
822 method (i.e., random resampling with replacement, number of samples = 1'000; median of confidence interval
823 given as solid red line). Furthermore, the relationship between gust speeds and normalised insured total damages
824 based on “WISC historic” and independent, interpolated wind gust observations (selection of windstorms in
825 2017 and 2018, including winter windstorm Burglind) are given as blue squares and yellow diamonds,
826 respectively. The domain for unprecedented ~~windstorms~~windstorm damages – i.e. beyond Lothar/Martin – is
827 shaded grey.

Appendix

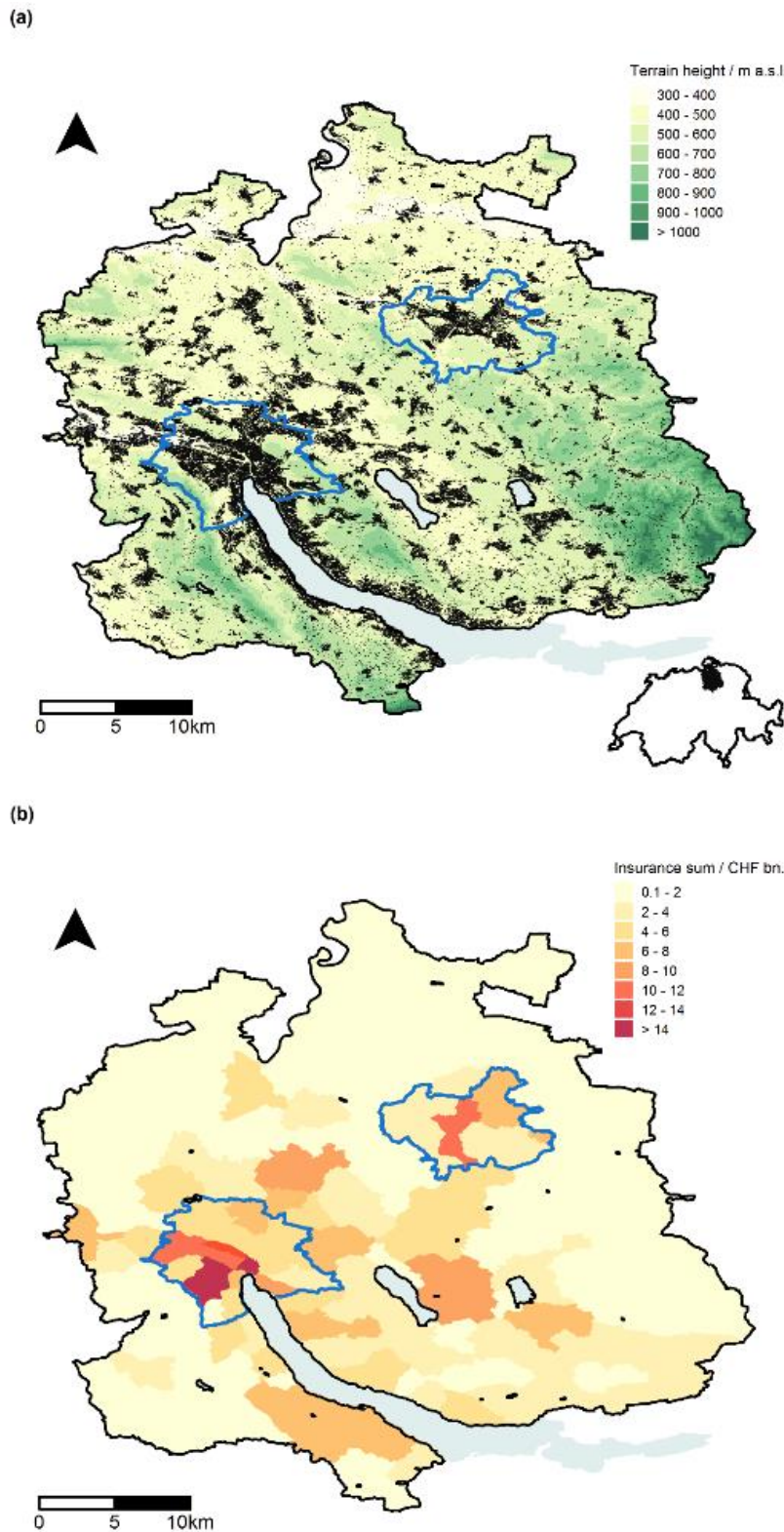
Table A1: AAD and event damage for different return periods (RP) and the windstorm event Lothar/Martin on the basis of insurance claims data and modelled damages using the CLIMADA impact model and the hazard event sets “WISC historic” and “WISC probabilistic extension”, respectively.

	Available years (period)	AAD [CHF m.]	Event damage with 5- year RP [CHF m.]	Event damage with 10- year RP [CHF m.]	Event damage with 50- year RP [CHF m.]	Event damage with 250- year RP [CHF m.]	Event damage due to Lothar/ Martin [CHF m.]
Insurance claims data	34 (1981- 2014)	2.3	0.6	1.1	-	-	62.4
“WISC historic”	75 (1940- 2014)	1.1	0.2	0.6	24.5	-	62.6
“WISC probabilistic extension”	2'250 (30*75)	1.2	0.2	0.6	7.4	82.3	-



833

834 **Figure A1:** Probability density functions of the maximum gust speeds at building level in the canton of Zurich
835 for the three hazard event sets “WISC historic” (brown), “WISC probabilistic extension” excluding the parent
836 windstorms (yellow), and “WISC synthetic” (green). The maxima of the individual distributions are shown as
837 dashed vertical lines. In the GVZ damage model, damage is possible from a wind gust speed of more than
838 90 km/h, which is here indicated by a grey solid vertical line.



839

840

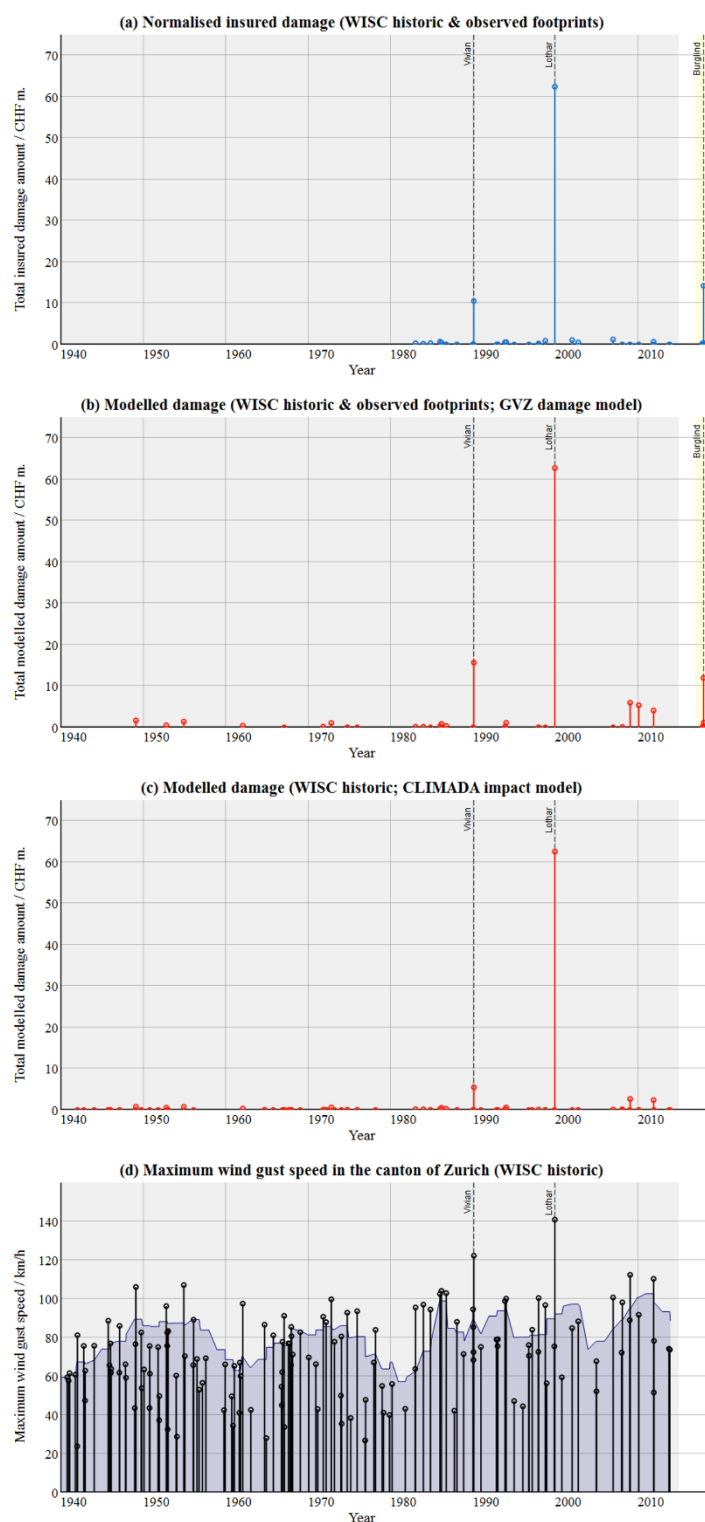
841

842

843

844

Figure A2: (a) Terrain height for the canton of Zurich (colour scheme) according to a digital elevation model with a horizontal grid size of 200 m ([Source](#): Swiss Federal Office of Topography; Swisstopo DEM, 2019). In addition, the spatial distribution of all buildings insured by GVZ is indicated and the urban areas of the two main cities, Zurich (left) and Winterthur (right), are marked in blue. (b) Total building sum insured for each municipality (colour scheme).



845

846 **Figure A3:** Variability of windstorms and associated damages in the canton of Zurich: (a) normalised insured
847 damage, (b) modelled windstorm damage based on the GVZ damage model and the hazard event sets “WISC
848 historic” and “observed footprints”, (c) modelled windstorm damage based on the CLIMADA impact model and
849 “WISC historic”, and (d) maximum gust speeds at building level in the canton of Zurich according to “WISC
850 historic” (black stem plot). The filled time series in (d) additionally shows the 5-year moving average of the
851 yearly maximum gust speeds in the canton of Zurich. The period for which “WISC historic” hazard data
852 (“observed footprints”) is available is shaded grey (yellow) in (a) and (b). The windstorm events
853 Vivian/Wiebke, Lothar/Martin, and Burglind are marked.