DISS. ETH NO. 27670

The impact of winter storms in Switzerland – prototyping decision-support tools

A thesis submitted to attain the degree of

DOCTOR OF SCIENCES of ETH ZURICH
(Dr. sc. ETH Zurich)

presented by

THOMAS RÖÖSLI

MSc ETH Environmental Sciences, ETH Zurich

born on January 15, 1988

citizen of Wolhusen LU and Werthenstein LU

accepted on the recommendation of

Prof. Dr. David N. Bresch (doctoral thesis supervisor)

Prof. Dr. Christof Appenzeller

Dr. Elco Koks

2021

Summary

Winter windstorms are among the most destructive and costliest natural hazard events in Europe. Insured losses from the events Daria 1990, Lothar 1999, and Kyrill 2007 amount to 8.6 billion, 8.4 billion, and 7.1 billion USD respectively. In Switzerland, the most recent severe event Burglind/Eleanor caused 165 million CHF in building damages additional to other socio-economic impacts like forest damage and disruption in traffic and power supply. Societal decisions for the management of winter windstorm risk require information about those impacts to be able to reduce them or handle them sustainably and efficiently. This thesis documents the development and prototyping of decision-support tools for different questions of risk management. The tools are implemented in the CLIMADA framework, an open-source risk-modelling platform in the programming language python. It models risk as a combination of hazard, exposure and vulnerability. Meteorological and climatological research has culminated in hazard datasets describing the intensity, spatial distribution, and likelihood of storm events. This thesis implements, calibrates and evaluates risk information derived from the combination of these hazard datasets with exposure and vulnerability. The exposure describes the assets or value at risk: a spatial description of infrastructure, natural resources, population, or vulnerable groups. The vulnerability defines how the proportional impact to exposure, such as a damage degree, is linked to the hazard intensity. One tool describes the risk assessment of building damages from winter windstorms and is applied to the building insurance industry. The second tool forecasts building damages based on weather forecasts. It firstly supports decision-making for preventive actions in the building insurance industry, and secondly can be used in the context of incorporating impacts into weather warnings by national meteorological services. In chapter 1, the scientific context of the tools is introduced regarding winter windstorms, impact data, risk modelling, risk assessment and decision-making.

In chapter 2, the socio-economic impacts of winter windstorms are illustrated by the example of a recent event. The impacts of the winter windstorm Burglind/Eleanor (3 January 2018) in Switzerland are collected from different government agencies and other organizations. The event is responsible for the largest infrastructure and forest damage from a winter storm in Switzerland since Lothar 1999.

Burglind/Eleanor caused building damages of around 165 million CHF. There were also disruptions to road- and rail-traffic and in power supply. In Swiss forests, around 1.3 million cubic metres of wood were felled.

Chapter 3 reviews two newly published hazard datasets of winter storms, one containing high-resolution gust speed intensities of more than 140 historical storms, and the other a synthetic event set with more than 7’660 events generated in climate model runs. A comparison with previously used datasets in industry and academia reveals that the historical dataset represents similar storm severity characteristics to the other datasets. Its high spatial resolution, the long historical time period covered, and its open-access and free availability recommend this dataset for use in risk assessments in industry and research. The synthetic event set shows different storm severity characteristics from industry and academic datasets as well as from the historical dataset, as especially the spatial extends of the events were smaller. The use of this particular synthetic event set in risk assessments is cautioned.

In chapter 4, the first decision-support tool, i.e., risk-assessments for building damages, is presented in an applied context. The open-access historical event set from chapter 3 and a purpose-built probabilistic event set are used in a risk assessment for the insurance industry in a collaboration with the cantonal building insurance of the canton of Zurich GVZ. Insurance companies, with access to their claims data, have been in a good position to assess their risk from winter windstorms. The risk assessments based on claims data are compared with risk assessments from modelled building damages from the GVZ proprietary impact model and the open-source impact model within the CLIMADA platform. Insurance companies can benefit from complementing their claims-based risk assessments using the newly available events sets, especially concerning rare events. In a special focus, the uncertainties of the different approaches are discussed and illustrated.

Chapter 5 presents the second decision-support tool, a newly developed impact forecasting system for building damages from winter windstorms in Switzerland. Since societal decisions on preventive actions are best supported with estimations of expected impacts of the weather events, national meteorological services aim to incorporate impacts into their warnings. This system’s forecasted impacts support decision-making for specific users, e.g. the building insurance sector who need to pre-allocate additional resources for claims adjustments and claims handling. In a comparison with claims, the impact forecasts of building damages from winter windstorms are promising, but for other wind phenomena like thunderstorms and foehn storms they do not work as reliably.

This is followed by a synthesis of the thesis and the four main chapters. The uncertainties in impact modelling for risk assessment and impact forecasts are discussed. In future endeavors, the uncertainties in exposure and vulnerability could be explicitly represented in an ensemble of opportunity of different model implementations. This would allow a comparison of the uncertainty of the hazard, exposure and vulnerability components, and a discussion of second order uncertainty. The role of exposure in impact warnings is highlighted: it provides the metric and spatial pattern of impact forecasts which are straightforward and relatable information. Suggestions for future topics and implications in research and applications are provided in an outlook. This thesis demonstrates how the decision-support tools within the CLIMADA framework in combination with climatological datasets, as well as open-access weather forecasts, can provide actionable risk assessments and impact warnings. The free, open-source methods lend their support for the suggested future developments.

Zusammenfassung

Winterstürme gehören zu den schädlichsten und teuersten Naturgefahrenereignissen in Europa. Versicherte Schäden von den Ereignissen Daria 1990, Lothar 1999 und Kyrill 2007 beliefen sich jeweils auf 8.6 Milliarden, 8.4 Milliarden und 7.1 Milliarden USD. In der Schweiz führte der letzte grössere Sturm Burglind/Eleanor zu 165 Millionen CHF an Gebäudeschäden und zusätzlich zu anderen gesellschaftlichen Auswirkungen wie Waldschäden und Unterbrüchen im Verkehr und in der Stromversorgung. Entscheidungen in der Gesellschaft für den Umgang mit dem Sturmrisiko bedürfen Informationen zu den Auswirkungen um diese zu vermeiden oder möglichst nachhaltig und effizient zu bewältigen. Diese Doktorarbeit dokumentiert die Entwicklung und beispielhafte Anwendung von Softwaretools zur Entscheidungshilfe für verschieden Fragen im Umgang mit Risiken. Diese Entscheidungshilfen wurden als Teil der open-source Risikomodellierungsplattform CLIMADA in der Programmiersprache python implementiert. CLIMADA modelliert Risiko als eine Kombination aus Gefährdung (hazard), Exposition (exposure) und Verletzlichkeit (vulnerability). Die meteorologische und klimatologische Forschung hat Gefährdungsdatensätze hervorgebracht, die die Intensität, die geographische Verteilung und die Wahrscheinlichkeit von Sturmereignissen beschreibt. Diese Doktorarbeit implementiert, kalibriert und bewertet die Risikoinformationen, die aus der Kombination dieser Gefährdungsdatensätzen mit Exposition und Verletzlichkeit entstehen. Die Exposition beschreibt gefährdete Vermögenswerte oder Elemente: es ist eine geographische Beschreibung von Infrastruktur, natürlichen Ressourcen, Bevölkerung oder besonders verletzliche Gruppen. Die Verletzlichkeit definiert zu welchen relativen Auswirkungen, zum Beispiel welchen Schadensgrad, eine gewissen Gefährdungsintensität bei der Exposition führt. Ein Tool beschreibt die Risikoabschätzung von Gebäudeschäden durch Stürme in der Versicherungsindustrie. Das zweite Tool macht Vorhersagen zu Gebäudeschäden basierend auf Wettervorhersagen. Dieses Tool kann erstens die Entscheidungsfindung zu Vorbereitungshandlungen in der Versicherungsindustrie unterstützen und zweitens kann es genutzt werden um Auswirkungen in den Warnprozess von nationalen Wetterdiensten zu integrieren. Im ersten Kapitel wird der

wissenschaftliche Hintergrund dieser beiden Tools eingeführt in den Bereichen Winterstürme, Datensätze zu Auswirkungen, Risikomodellierung, Risikoabschätzung und Entscheidungsfindung.

Im zweiten Kapitel werden die gesellschaftlichen Auswirkungen von Winterstürmen illustriert anhand dem Beispiel eines kürzlich erfolgten Ereignisses. Die Auswirkungen des Sturms Burglind/Eleanor (3. Januar 2018) in der Schweiz wurden bei verschiedenen Behörden und anderen Organisationen zusammengestellt. Das Ereignis hat in der Schweiz die grössten Infrastrukturschäden und Waldschäden im Zusammenhang mit Winterstürmen seit Lothar 1999 verursacht. Burglind/Eleanor beschädigte Gebäude für eine Schadenswert von ungefähr 165 Millionen CHF. Es kam auch zu Unterbrüchen im Strassen- und Schienenverkehr sowie zu Stromausfällen. In Schweizer Wäldern wurden ungefähr 1.3 Millionen Kubikmeter Holz umgeworfen.

Kapitel drei begutachtet zwei neu veröffentlichte Gefährdungsdatensätze zu Winterstürmen, einer beinhaltet hochaufgelöste Böengeschwindigkeiten von mehr als 140 historischen Stürmen, der andere Datensatz enthält mehr als 7’660 synthetische Ereignisse welche mit Klimamodellen erzeugt wurden. Ein Vergleich mit bewährten Datensätzen aus der Vesicherungsindustrie und aus der Forschung zeigte auf, dass der historische Datensatz ähnliche Charakteristiken bezüglich des Schweregrads von Sturmereignissen aufweist wie die bewährten Datensätze. Die hohe räumliche Auflösung, die lange abgedeckte historische Zeitspanne und die offene und freie Zugänglichkeit empfehlen diesen Datensatz für die Verwendung in Risikoabschätzungen in der Industrie und in der Forschung. Der synthetische Datensatz zeigt abweichende Charakteristiken bezüglich des Schweregrads von Sturmereignissen im Vergleich zu den bewährten Datensätzen, im speziellen war die räumliche Ausdehnung der Events kleiner. Für die Verwendung von diesem spezifischen synthetischen Datensatz wurde deshalb zur Vorsicht gemahnt.

Im vierten Kapitel wird das erste Tool zur Entscheidungshilfe, also die Risikoabschätzung von Gebäudeschäden, in einem angewandten Kontext vorgestellt. Der frei zugängliche historische Datensatz aus Kapitel drei und ein zweckorientiertes probabilistisches Ereignisdatenset werden für eine Risikoabschätzung in der

Versicherungsindustrie angewendet in einer Zusammenarbeit mit der Gebäudeversicherung Kanton Zürich GVZ. Versicherungsunternehmen waren schon immer in einer guten Ausgangslage um ihre Risiken abzuschätzen, da sie Zugang zu ihren eignen Schadensfalldatenbanken haben. Die Risikoabschätzung basierend auf Schadensfällen wird verglichen mit Risikoabschätzungen mit modellierten Schäden mithilfe des Schadensmodells der GVZ und des öffentlichen Schadensmodells in der CLIMADA Plattform. Versicherungsunternehmen können davon profitieren ihre Schadensfall-basierten Risikoabschätzungen mithilfe der neuen öffentlichen Gefährdungsdatensätzen zu erweitern, speziell gilt das für die Abschätzung von seltenen Ereignissen.

Kapitel fünf präsentiert ein zweites Tool zur Entscheidungshilfe, ein neu entwickeltes Auswirkungsvorhersagesystem für Gebäudeschäden durch Winterstürme in der Schweiz. Da gesellschaftliche Entscheidungen über vorbeugende Massnahmen am besten unterstütz werden durch Schätzungen zu erwarteten Auswirkungen, zielen nationale Wetterdienste darauf Auswirkungen in ihre Warnungen zu integrieren. Die vorhergesagten Auswirkungen unterstützt die Entscheidungsfindung von einzelnen Benutzern, zum Beispiel der Gebäudeversicherungsindustrie, welche zusätzliche Ressourcen für die Abschätzung und Behandlung der Schadensfälle einplanen müssen. In einem Vergleich mit tatsächlichen Schadensfällen sind die Auswirkungsvorhersagen für Gebäudeschäden von Winterstürmen vielsprechend. Für andere Windphänomene wie Gewitter und Föhnstürme funktionieren sie jedoch nicht gleich zuverlässig.

Es folgt eine Synthese der Doktorarbeit und der vier Hauptkapitel. Die Unsicherheit in der Modellierung der Auswirkungen für Risikoabschätzungen und Auswirkungsvorhersagen werden diskutiert. In zukünftigen Anstrengungen könnte die Unsicherheit in der Exposition und der Verletzlichkeit explizit durch ein gelegenheitsorientiertes Ensemble aus verschiedenen Modellimplementierungen abgebildet werden. Damit könnte man die Unsicherheit der verschiedenen Komponenten, Gefährdung, Exposition und Verletzlichkeit vergleichen und die Unsicherheit zweiter Ordnung diskutieren. Die spezifische Rolle der Exposition in den Auswirkungswarnungen wird hervorgehoben: Sie bestimmt die Metrik und das räumliche Muster der Auswirkungsvorhersagen welche

unkomplizierte und zuordenbare Information darstellen. In einem Outlook werden Vorschläge für zukünftige Themenbereiche und mögliche Konsequenzen gegeben. Diese Doktorarbeit demonstriert wie Tools zu Entscheidungshilfe in der CLIMADA Plattform in Kombination mit klimatologischen Datensätzen und Wettervorhersagen Risikoabschätzungen und Auswirkungswarnungen hervorbringen kann. Die frei zugängliche und quelloffenen Methoden können für diese zukünftigen Entwicklungsschritte wiederverwendet und ergänzt werden.

Acknowledgments

Many people helped in some form or another in the creation of this thesis. I am deeply grateful to everybody, who collaborated with me, provided support, or in some other form helped create an inspiring environment.

I would like to thank my supervisor David Bresch for providing me with the opportunity to work on this thesis, with the freedom to explore and with encouragement to follow my own instincts. He also helped me to see the bigger picture when I would lose myself in details. I am thankful to Christof Appenzeller, who provided feedback to my work regularly since the beginning of my doctoral studies, especially in the context of meteorological forecasts and national meteorological services and quickly became a second advisor. I am happy to have him as a co-author on my last paper and as member of my examination committee.

I am very thankful that Elco Koks has agreed to be part of my examination committee as external co-examiners. I also want to thank Daniela Domeisen for helping device my initial research plan.

I was in a lucky situation to collaborate with interesting partners for my research projects. I especially want to thank Christoph Welker for the interesting exchanges and the collaboration that culminated in a joint publication. This gratitude is extended to further colleagues at the cantonal building insurance of the canton of Zurich GVZ for their collaboration and the generous provision of claims data for my studies. I also want to thank Marc Wüest, Dominik Renggli and further colleagues at Swiss Re for the collaboration during the evaluation of the WISC event datasets.

I want to thank Urs Beyerle for his expertise and support with regard to the technical infrastructure used in deploying the semi-operational prototype of the impact forecasting system. I also want to thank Emanuel Schmid for his expertise and for the management of the CLIMADA git repository, Sandro Bösch and Hans Hirter for their support in IT matters, as well as Sarah Spitzauer for her help in administrative matters.

My workplace was partly at MeteoSwiss and I was able to enjoy a very inspiring atmosphere. I would like to thank: Christoph Frei for his

expertise in statistics, Marco Stoll and Patrick Stierli for showing me the responsibilities of a forecaster on duty, Simon Scherrer for the collaboration on the technical report, Daniel Maurer und Urs Graf for discussions regarding the warning system at MeteoSwiss, and Saskia Willemse, Irina Mahlstein and Daniele Nerini for discussions about incorporating impact into warning systems. Also I want to thank Heike Kunz for her support in administrative matters.

At MeteoSwiss I was welcomed by members of the division APN, and the group of Marco Arpagaus (APND) specifically, who provided me with a very comfortable working environment with many interesting and inspiring lunch and coffee breaks. I want to thank all its members, especially Guy DeMorsier, Claire Merker, Andreas Pauling, Pirmin Kaufmann, Stephanie Westerhuis, Andre Walser, Daniel Leuenberger and Petra Kaufmann, and many more including short-term employees, master students, and interns for the nice time and for their patience in filling in for shortcomings in my meteorological background.

I am extremely grateful for my other working environment at ETH where I always found a home during the past few years. The group Weather and Climate Risks and especially the first cohort of PhD-students Maurice Skelton, Benedikt Knüsel, Marius Zumwald, Samuel Eberenz and Luise Fischer provided a stimulating environment with a broad mix of disciplines including philosophy of science and social science, with which I otherwise would not have been in contact so intensively. These thanks extend to all PostDocs and newer or external PhD-students: Benoît Guillod, Gabriela Aznar, Jamie McCaughey, Chahan Kropf, Chris Fairless, Evelyn Mühlhofer, Mannie Kam, Simona Meiler, Samuel Lüthi, Inga Sauer, Gregor Ortner, Theresa Ertl, and Lisa Deutsch. I also want to thank the master students who I was able to supervise Ediz Herms, Kaspar Tobler, Thomas Rölli, Remo Sigg, and Jan Wütherich. I want to thank Jan Hartman who helped me translate the basis of the windstorm module from MATLAB to python as well as all other master students and research assistants of our group. Additionally, I want to thank the members of the neighbouring TD-Lab and the developers of the CLIMADA platform for the interesting exchanges. Special thanks go out to everybody who provided feedback on the core chapters and to Samuel Eberenz, Chris Fairless and Maurice Skelton who provided feedback on the thesis.

I especially want to thank Samuel Eberenz. We started working at the group Weather and Climate Risk on the same day and have exchanged ideas and provided each other with support since the beginning. In the last third of our doctoral studies, we started to meet once a week for a walk in person or via telephone and we shared our issues, ideas, challenges and triumphs. This coaching helped me structure my thoughts and guide me forward when I was stuck.

I am immensely grateful to my parents, brother, and sister: Andrea, Sepp, Franziska and Stefan for always supporting me. And to my friends and other important people in my life for being there, helping me reflect, and also distract me when needed: Adrian, Boris, Giorgio, Jonas, Julian, Julian, Lukas, Markus, Miro, Miro, Patricia, Roman, Sam, Sämi, Samuel, Sandra and Silvan.

Table of Contents

Figures

Tables

1 Introduction

1.1 Preamble

Experiencing the variability of weather is a wonderful and interesting part of being on this planet. As many parts of our society depend on the weather, the variability provides both opportunity and difficulty. In the worst case, extreme weather events constitute an “unpredictable” force, which can lead to substantial damage, disruptions and other impacts. “Unpredictable” in this context is a colloquial word, which means rare and/or random (Andrews & Quintana, 2015). The forces are strong winds, floods, heavy rain, hail and lightning among others that affect infrastructure and activities of society. To minimize such impacts, society aims to be more resistant (adapted from PLANAT, 2018). If possible, hazard prone areas are avoided. Otherwise, adequate protection is implemented by putting protection measures in place for people and natural resources and by reinforcing buildings and facilities. Additionally, redundancies are provided for critical infrastructures and activities, such parallel systems ensure that they are not entirely disrupted by one natural hazard event (PLANAT, 2018).

These resistance measures can be expensive and cannot cover all possible impacts of extreme weather events. The risk of such impacts is best managed in an integrated framework, that also includes recovery and adaptation to changes (PLANAT, 2018). Risk reduction should be an ongoing endeavour, influencing decisions not only prior to, during and after an event. In between events, risk should be monitored, new non-acceptable risks should be avoided and learnings from past events should be derived. A general framework is described in the Sendai framework for disaster risk reduction (UNISDR, 2015).

One priority is to build a better understanding of the risk in all its dimensions: vulnerability, capacity, exposure, hazard characteristics and environment (UNISDR, 2015). This includes the understanding of extreme weather events and societal impacts such as the location, the intensity of the weather event, the severity of the impacts, and the probability that such an event occurs. This information is provided by science-based methodologies and tools e.g. disaster risk models or impact models and early warning systems (UNISDR, 2015). This thesis presents and provides methods and tools to support decision-making in the context of risk reduction about one such weather extreme: the impacts of winter windstorms in the alpine region.

A series of models predict certain aspects of extreme weather events: reanalysis and climate models describe the frequency and intensity of rare extremes and long-term trends, this hazard information needs to be combined with the other risk dimensions e.g., vulnerability and exposure. Weather forecast models predict the intensity of upcoming weather events. To help decision around preventive actions, potential impact need to be incorporated into the communication of weather warnings (WMO, 2015a). In recent years, such datasets have become more openly available which provides new opportunities for their usage. With this thesis, such hazard information and weather forecasts is coupled with an event-based impact model to arrive at an understanding of the risk used for decisions in risk reduction of “unpredictable” weather extremes.

The structure of the thesis is as follows: Section 1.2 will present the aim and focus of this thesis and introduce the four publications (chapters 2, 3, 4 and 5) that form the core of this thesis. The following sections of the introduction provide the necessary scientific background regarding winter windstorms (section 1.3), socio-economic impact data (section 1.4), risk assessment and impact modelling (section 1.5) as well as pertinent to decision-making support for managing risks (section 1.6). Next follow the already mentioned core chapters 2-5. The synthesis (chapter 6) puts the achievements of the core chapters in context and provides a broader view on uncertainties and other overarching topics. The synthesis chapter ends with an outlook and is followed by the main conclusions (chapter 7).

1.2 Aim and focus of this thesis

The general aim of this thesis is to understand the socio-economic impacts of winter windstorms and to support decision-makers with straightforward information about these impacts to answer questions about risk reduction management.

To this end, the thesis covers winter windstorms and their impacts at three different points in time in relation to an actual event. Directly after an event, new information regarding socio-economic impacts usually becomes available, which allows to deduce learnings for the future handling of such events. Between events, research might generate new and deepened knowledge and it should be used to create new or update previous risk assessments. Prior to an event, there is a preparation window, when a storm event is forecasted to happen. In this window, estimation of the location and severity of the expected impacts are needed to support preventive decisions.

The results of the thesis are of interest to a wide range of stakeholders such as meteorological experts and risk assessment experts, but towards decision-makers of varying backgrounds. It sets technical standards for decision-support tools and provides scientific and applied learnings in this interdisciplinary field.

More specifically, four aims guide this thesis:

1. Contribute to a better understanding of the socio-economic impacts of winter windstorms and the severity of individual events.
2. Evaluate intensity estimates of historical and synthetic winter windstorm events in publicly available datasets.
3. Evaluate the risk assessment of building damages from winter windstorms based on a claims-based perspective and a probabilistic risk modelling approach and form an understanding of the associated uncertainty.
4. Build an impact forecasting system for building damages in Switzerland deployed as a semi-operational prototype and assess the skill with insurance claims data.

The core of this thesis consists of four publications that deal with different aspects of socio-economic impacts of winter windstorms in the alpine region.

1.2.1 The impact of the winter windstorm Burglind/Eleanor (chapter 2)

Scherrer S., Salamin C., Weusthoff T., Kaufmann P., Bader S., Röösli T., Aemisegger N., Gut M., 2018: Der Wintersturm Burglind/Eleanor in der Schweiz, Fachbericht MeteoSchweiz, 268, 35 pp.

The first aim of this thesis, namely to contribute to a better understanding of the socio-economic impacts of winter windstorms, was addressed by a technical report of MeteoSwiss about the winter windstorm Burglind/Eleanor (3 January 2018), for which the author of this thesis provided a chapter about the socio-economic impacts (Scherrer *et al.*, 2018). The chapter followed the general structure and format of a report about the impacts of winter windstorm Lothar in 1999 (WSL & BUWAL, 2001). The work consisted of a collection of impact data from several Swiss-wide organisations and federal offices, which gather impact data in Switzerland as part of their operations. The severity of the socio-economic impact of Burglind/Eleanor was quantitatively and qualitatively assessed and compared to previous severe winter windstorm events Lothar (26 December 1999) and Vivian (25 February 1990).

Next to the assessment of the socio-economic impacts, the report informs about the synoptical weather situation, the prognosis and warnings of the event, the verification of the prognosis and models, the climatological classification and the communication of MeteoSwiss. Based on this report MeteoSwiss and other affected organisations can deduce learnings for the handling of future events.

1.2.2 Comparison of existing event sets (chapter 3)

Röösli T., Bresch DN., Wüest M. 2018.A comparison of the WISC events sets with both industry and research data. WISC Summary Report of Task 5.3 – ETH / Swiss Re Case Study. Available at https://wisc.climate.copernicus.eu/wisc/#/help/products#casestudies_section (accessed May 3, 2021).

The second aim, to evaluate intensity estimates of historical and synthetic winter windstorm events in publicly available datasets, was addressed with a technical report about the open-access winter windstorm datasets was devised together with the reinsurer Swiss Re (Röösli *et al.*, 2018). The **W**indstorm **I**nformation **S**ervi**C**e (a C3S Sectoral Information Service project, WISC, 2018) produced two new datasets for the intensity of wind storm events in a historical event set and probabilistic event set. To compare the datasets, the storm severity index (Hamish Steptoe, 2017) was used, that is a simple metric for the severity of a storm using only its intensity and affected area. A comparison with industry and research data showed that the historical dataset provided by WISC is an important contribution of a high-resolution dataset spanning a long period of 75 years. Future users of the open-access dataset can use this analysis to build trust that the historical event set represents the necessary characteristics of severe winter windstorms. The probabilistic dataset published by WISC on the other hand contained storms with smaller affected areas than in any other dataset and the use of it for risk assessment was cautioned. This finding directly motivated the development of the probabilistic dataset presented in chapter 4.

1.2.3 Risk assessment of winter windstorms (chapter 4)

Welker C., Röösli T., Bresch DN. 2021. Comparing an insurer's perspective on building damages with modelled damages from pan-European winter windstorm event sets: a case study from Zurich, Switzerland. *Natural Hazards and Earth System Sciences* 21:279–299.

The third aim, to evaluate the risk assessment of building damages from winter windstorms based on a claims-based perspective and a probabilistic risk modelling approach and form an understanding of the associated uncertainty, was addressed in a collaborative scientific publication together with GVZ, the public building insurer of the canton of Zurich, Switzerland (Welker *et al.*, 2021). The author of this thesis and Christoph Welker equally contributed as first authors to this study. They present a proprietary and an open-source implementation of an impact model for winter windstorms in Europe. The impact model simulates severity of the impacts and the resulting risk as a function of hazard, exposure, and vulnerability (see section 1.5.1). The modelled average annual impact and impact of a 250-year event based on historic and probabilistic event sets are compared with estimates based on building damage records of an insurance claims database. The source and range of uncertainty were assessed for the different datasets and it was shown that impact modelling provides a more robust and less uncertain perspective on remote risks like the 250-year event damage compared to statistical analysis of claims data.

This work also resulted in an open-source code of the methodology (Röösli *et al.*, 2021b) and an open-access dataset of probabilistic winter windstorm events (Röösli & Bresch, 2020), and the StormEurope module in CLIMADA (Aznar-Siguan *et al.*, 2021):

Röösli, T., Welker, C., Bresch, D.N., 2021. ThomasRoosli/climada_papers_winter_windstorms_model: Winter windstorm model. Zenodo. https://doi.org/10.5281/zenodo.4442602

Röösli, T., Bresch, D.N., 2020. Probabilistic Windstorm Hazard Event Set for Europe. https://doi.org/10.3929/ethz-b-000406567

1.2.4 Impact forecasting system (chapter 5)

Röösli T., Appenzeller C., Bresch DN. 2021. Revised version published as: Towards operational impact forecasting of building damage from winter windstorms in Switzerland. *Meteorological Applications* 28:e2035.

The fourth aim of this thesis, to build and evaluate an impact forecasting system for building damages in Switzerland, was addressed with a paper about the development of an impact forecasting system (Röösli *et al.*, 2021a). The impact forecast uses the weather forecast of MeteoSwiss as hazard data within the impact model presented in chapter 4. The forecasting system forecasts building damages with a lead time of two days on a regular spatial grid at a resolution of 500 meters for the whole of Switzerland. The study showed that the forecasted building damages for severe winter windstorm events compare reasonably well with insurance claims data, but less so for thunderstorms and foehn storms. The methodology is directly applicable to support decisions making processes around aggregated impacts, but might be misunderstood when used as a warning to individuals of the public. The results allow a discussion about the role of impact forecasting for the aim of national meteorological services to incorporate possible impacts in their warnings.

This work also resulted in an open-source code of the methodology (Röösli, 2021) and the Forecast module in CLIMADA (Aznar-Siguan *et al.*, 2021):

Röösli T. 2021. ThomasRoosli/climada_papers_building_damage_forecast. Zenodo. https://doi.org/10.5281/zenodo.4659030

1.2.5 Other publications

One more publication originated from the work on this thesis, but it is not included in the text. The publication documents a globally consistent asset exposure dataset named LitPop. It uses gridded population data and nightlight intensity to arrive at an estimation of asset values on a global high-resolution 500-meter grid (Eberenz *et al.*, 2020). The author of this thesis contributed to code development, the evaluation and visualisation of results and helped the main author with the preparation of the manuscript. The asset exposure data was used in chapters 4 and 5. A precursor of this dataset was also used in chapter 3.

Before the four presented studies are reprinted in chapters 2-5, more background is presented about the meteorological phenomenon winter windstorms (section 1.3), data about socio-economic impacts of extreme weather events (section 1.4) and the risk assessment and impact modelling framework used in this thesis (section 1.5) before providing select background on decision support for risk assessments, forecasts and warnings (section 1.6).

1.3 Winter windstorms

This thesis investigates winter windstorms as one example of several weather phenomena that cause socio-economic impacts. This choice is not by coincidence: Winter windstorms cause the highest economic impact per event of any weather-related hazard in Europe as well as in Switzerland. Other weather-related hazards with high socio-economic impacts are thunderstorms, hail, heavy rain and floods, frost, snowfall and avalanches, heatwaves and drought. Many findings of this thesis are directly transferable to other hazards as discussed in chapter 6.5.

As meteorological phenomena, winter windstorms are extratropical cyclones. Their development and evolution is well described in the literature as for example summarised in the Erik Palmén Memorial Volume on extratropical cyclones (see Shapiro and Keyser, 1990). Hewson and Neu (2015) sketch a conceptual model to describe high wind speed zones associated with these severe winter windstorms. They start from a wave feature at the boundary of polar colder air masses and warmer air masses at the mid-latitudes (Hewson & Titley, 2010). This is illustrated in panel (b) of Figure 1. An interaction of this wave feature with pronounced upper level trough or jet can result in the development of a cyclone. If such cyclones produce high surface gusts as they move over land, high measured wind gusts occur in elongated zones along their track and leave behind high damages, called gust footprints and damage footprints respectively (Hewson & Neu, 2015). Schematically, three different windstorm zones can be identified in such winter windstorms: the warm jet (width: 200-500km, length: 1000 km, duration 24-48 hours), the sting jet (width: 20-200km, length: 800

km, duration 1-12 hours) and the cold jet (width: 100-800km, length: 2500 km, duration 12-36 hours)(Hewson & Neu, 2015). The zones are illustrated in panel (a) of Figure 1. In the real world, the winter windstorms can have a huge variety in their structure and can exhibit one, two or all of these windstorm zones. For most winter windstorms, the damages can be largely attributed to one of these three zones (Hewson & Neu, 2015). This variety leads to different spatial extents of the footprints for different events and leads to differences how well events can be represented in weather models (more on weather models in section 1.3.2).

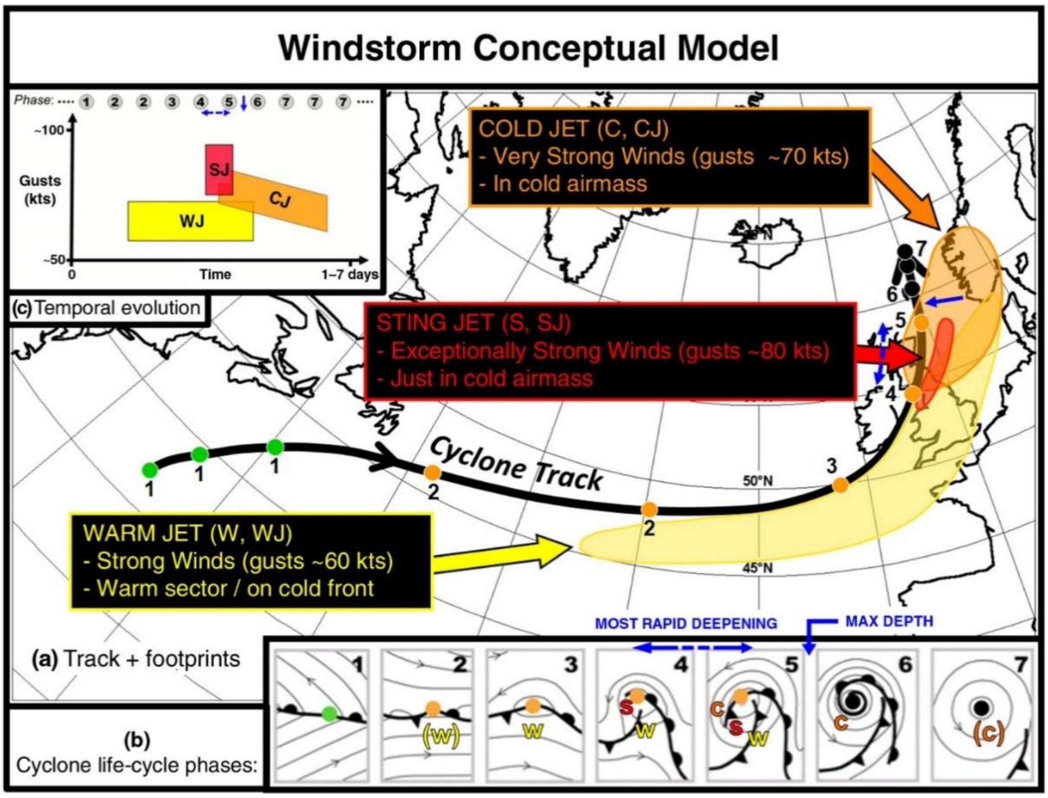


Figure 1 Conceptual model of extreme winter windstorms. Figure and caption are reproduced from Hewson and Neu (2015): "Panel (a) shows the cyclone track (black), with spots denoting positions equally separated in time, and numbered according to the cyclone life-cycle phases in panel (b). Spot colour relates to the identification method and objective typing used in Hewson and Titley (2010), green being a diminutive frontal wave, orange a frontal wave cyclone, and black a barotropic low. Shading denotes the footprints, or nominal damage swathes, attributable to the warm jet/warm conveyor (yellow), the cold jet/cold conveyor (orange) and the sting jet (red). Panel (b) shows the synoptic-scale evolution of fronts and isobars around the cyclone, after Hewson and Titley (2010) and Shapiro and Keyser (1990), with added letters denoting relative locations of the strong wind features, and brackets indicating marginal existence. Panel (c) denotes the temporal evolution of gust strength for each jet zone, with numbers cross-referencing phases on panel (b). On each panel, a dashed blue line denotes the period of most rapid deepening, whilst the solid blue

arrow shows the time of maximum depth. This conceptual model should be considered to be very malleable; for example most intense cyclones will have only one or two of the three strong wind footprints associated." Figure reproduced under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/).

Other weather phenomena can cause high wind speeds. In Switzerland, these are namely thunderstorms and foehn storms. The "Bise", a cold easterly wind, is not as gusty and thus is not as damaging (Wanner & Furger, 1990). There are also localized weather phenomena with strong winds as for example "Joran" along the Jura mountain chain (Etienne & Beniston, 2012) and "Laseyer" in the canton Appenzell (Sprenger *et al.*, 2018), which were not investigated for this thesis.

In section 1.3.1, the most important winter windstorm events, based on their socio-economic impact are listed. The meteorological data used in this thesis are introduced in section 1.3.2 and a small excursus on winter windstorms under climate change can be found in section 1.3.3.

1.3.1 Damaging storms in Switzerland and Europe

Winter windstorms occur several times each winter. At the same time, extreme winter windstorms with widespread socio-economic impacts are more rare and a single location in central Europe is only affected a few times per decade. Winter windstorms don't occur independently of each other and can form clusters with several events taking place shortly after one another (Karremann *et al.*, 2014; Priestley *et al.*, 2018). Winter windstorms are the costliest natural hazard in Europe, in the past 50 years the three events with the highest insured damages in Europe were the winter windstorm events Daria 1990, Lothar 1999 and Kyrill 2007, with insured damages between 7.1 and 8.6 billion USD each (Swiss Re, 2017).

Storm Lothar was the strongest storm hitting Switzerland in the past several decades. The impacts in Switzerland included 14 people killed directly and 15 people killed during recovery activities, over 600 Million CHF in building damages, forest damage of more than 4 times an annual harvest and many widespread disruptions in traffic and electricity (WSL & BUWAL, 2001). Lothar was most certainly the most damaging storm in the last century (chapter 4 and Stucki *et al.*, 2014). More details about the socio-economic impacts of the severest winter windstorm since, Burglind/Eleanor 2018, can be found in chapter 2.

Measured by building damage, storms are responsible for a third of all damages caused by natural hazards in Switzerland, closely followed by flood and hail. Snow, avalanches and mass movements each contribute below 5% to the total building damages caused by natural hazards (numbers from 2010-2019, VKG, 2021).

1.3.2 Representation in various meteorological datasets

There is a multitude of meteorological data that describe the state of the atmosphere and of course the footprints of winter windstorms are also represented in these data. Here follows an overview how winter windstorms and especially the damage-causing gust speeds are represented in different types of meteorological datasets, such as in measurements and weather models. By design, this thesis uses the meteorological data as input to its impact model and did not aim at further developing or calibrating meteorological datasets. It is important to understand the properties of this data to discuss the attributed uncertainties in the context of the resulting risk assessment. The following paragraphs were written with a user of risk assessment results and decision support tools in mind who by no means needs to be an expert in the field of meteorology.

Measurements

Weather stations measure several meteorological parameters, preferably based on guidelines of the World Meteorological Organisation (WMO; World Meteorological Organization, 2018). One of them is the wind speed. These measurements are normally aggregated over a specific time period. The wind speed or “mean wind” is a 10 minute average of all measurements within that time period (WMO, 2018). A second important metric is the gust speed. The gust corresponds to the highest three second average of the measured wind speeds within a time period, for example ten minutes, one hour or a day (WMO, 2018). The gust speed is important for socio-economic impacts of the winter windstorm, as it best reflects the occasionally strong force exerted. As mentioned above, the representation of the maximum gust speed at each measurement station for the duration of one winter windstorm event is referred to as its footprint (Hewson & Neu, 2015).

Such measured footprints are used in the rapid damage estimation featured in chapter 4.

Weather and climate models

Numerical weather and climate models contain a modelled version of the state of the atmosphere structured on a horizontal grid at several vertical layers. For each grid point and each level there is a representation of the relevant meteorological parameters: temperature, pressure, humidity and wind speed and direction – among many others. Based on the physical understanding of atmospheric processes the models simulate the next state of the atmosphere based on the previous state. By doing this repeatedly, the physical state of the atmosphere over a specified time period is modelled (Steppeler *et al.*, 2003). The mean wind at the surface level is a direct output from these models, as it corresponds to the transport vectors used in the model simulations. The gust on the other hand is a derived quantity, which needs to be specifically generated (more details below in Gust parameterisation). There are several possible modes of running a weather model, three of which will be summarized in the following paragraphs. They are differentiated by their purpose and consequently by how they make use of observational weather data. Traditionally, the geographical and temporal scales to which such models were applied were closely linked to the desired purpose of these modes. With increasing computational power, the geographical and temporal scales as well as the resolution started to overlap between the modes and now only provide a rough differentiation.

Climate general circulation models are initiated and guided by a few environmental factors including sea surface temperature or the concentration of greenhouse gases (Gettelman & Rood, 2016). Climate model runs do not consider observational weather data and only the atmospheric processes define the next state of the atmosphere As a result the model simulates artificial weather events that are typical for the climate defined by the given environmental factors. This methodology is most commonly used to study future climate states of the whole climate system on global geographical and up to century-long time scales based on e.g. prescribed pathways of greenhouse gas concentrations. Running such models repeatedly for today’s climate can create datasets of many model years and allows us to study rare events (Mizielinski *et al.*, 2014). The probabilistic dataset studied in chapter 3 is generated from climate model output.

For the best possible representation of past events, weather models are run in what is called the reanalysis mode (Compo *et al.*, 2011). During such a reanalysis model run, the modelled states of the atmosphere are routinely adjusted towards all available corresponding observations for that particular time. The resulting representations of the atmosphere are called reanalysis data sets and normally span decadal timescales. A key advantage is that the numerical model itself is not changing for the entire period. The gust footprints of these reanalysis products have the advantage to be structured on a regular grid, compared to footprints based on meteorological ground measurements with varying and potentially low spatial resolution. There is often higher uncertainty in the gust footprints of weather models than in measured data, because it includes additional model uncertainty (Donat *et al.*, 2010; Stucki *et al.*, 2016). Of course, there are also uncertainties in measurements, especially if individual measurements are aggregated and processed into a gridded dataset (Zumwald *et al.*, 2020). One example of the uncertainty in reanalysis models are resolution-related limitations to resolve the most damaging phase in the lifecycle of a winter windstorm (Hewson & Neu, 2015). In the context of this thesis, the reanalysis data of the products ERA Interim (Dee *et al.*, 2011) and ERA 20C (Poli *et al.*, 2016) were the foundation of the footprints of the historical events in chapter 3 and 4.

For the forecast of events in the near future, weather models are run in forecast mode. As a start, observations are used to create an initial modelled state of the atmosphere that is representing the current state of the atmosphere as well as possible (Schraff *et al.*, 2016). Afterwards the model makes use of the governing equations of the atmospheric processes as mentioned above to model future states of the atmosphere. This process is also called numerical weather prediction (NWP) and is normally applied for global or regional scales and over time scales of days to weeks. These forecasts are uncertain because of insufficient knowledge of the initial state (Lorenz, 1963) and insufficient understanding of the physical processes, as well as insufficient representation of these processes in the numerical model (Palmer, 2000). To represent these uncertainties, forecast models are regularly run in ensemble mode with many ensemble members representing varying but possible states of the atmosphere at any future time point. This is achieved by firstly perturbing the initial state of the individual members to represent measurement errors and other uncertainties. Secondly, the processes of the model are perturbed to represent the uncertainty in the knowledge and in the representation of these processes (Palmer *et al.*, 1990; Palmer, 2000). A better representation of these uncertainties could always be achieved with more ensemble members or higher numerical, spatial or temporal resolution, but providers of weather model data have to economize their limited resources. The ensemble forecast model used at MeteoSwiss as the foundation of the weather forecasts in Switzerland is the IFS-ENS (Integrated Forecasting System–ENSemble) model of the European Centre for Medium-Range Weather Forecasts (ECMWF, 2021), run at 18 km grid resolution. To provide a forecast at higher resolution, MeteoSwiss uses an additional weather model to downscale mentioned lower-resolution weather forecast model. The **Co**nsortium for **S**mall-scale **Mo**deling (COSMO) model is a limited-area atmospheric model, meaning it does not cover the globe, but only a much smaller area in higher resolution (COSMO, 2020). COSMO uses the forecasts of the IFS-ENS model as boundary conditions for all processes concerning the edges of the covered area. Currently MeteoSwiss runs the COSMO model in ensemble mode with 2.2 km (COSMO-2E) and 1.1 km grid resolution (MeteoSwiss, 2020). The COSMO model also uses perturbations in initial conditions and physical processes to represent the uncertainty of the weather forecast. Chapter 5 is based on wind gust footprints derived from the MeteoSwiss COSMO-2E model forecast (MeteoSwiss, 2020).

Starting from reanalysis or climate model output, higher resolution is achieved by downscaling. In dynamical downscaling, a higher resolution weather model is nested inside a lower resolution model (as described above). The historical gust footprints in chapter 3 are produced with the UK Met Office Unified Model (Davies *et al.*, 2005) nested into the ERA-Interim and ERA-20C reanalysis data. Another method to downscale reanalysis data is statistical downscaling. It uses statistical relationships inferred between the grid points of the lower resolution model and any other set of points, e.g. the grid points of a grid with higher resolution or observations. It was used to create the synthetic event set of the WISC project analysed in chapter 3. The statistical downscaling can only partially reduce the problem of resolution-related limitations of weather models mentioned by Hewson and Neu (2015).

Gust parameterisation

Most analyses in this thesis are in principle based on gust footprints from weather models. As all these datasets are dependent on the gust parameterisation to derive the gust speed, it is worth to quickly summarize that step. Statistical gust parameterisation infers gust speed from other model parameters by means of a formula. This formula is then fitted to observational data. The simplest from of such a formula is provided by (1), where the gust speed is only dependent on the mean wind and a constant scaling factor α (Ágústsson & Ólafsson, 2004). Such statistical gust parametrisation formulas can also be dependent on other model parameters describing the turbulence or surface roughness (Born *et al.*, 2012; Stucki *et al.*, 2016).

$$gust = \propto * \, mean \; wind \qquad (1)$$

There is also the possibility of a physical parameterisation of gust speed as suggested by Brasseur (2001). This method is based on the physical consideration that gusts "originate from air parcels flowing at higher levels in the boundary layer that are deflected downward to the surface" (Brasseur, 2001). The algorithm considers the turbulent kinetic energy and the buoyancy forces to decide which wind speed from higher levels can reach the surface. One interesting assumption is that surface roughness, the influence of surface disturbances and the impact of buildings does not influence the gust speed, even though they are known to influence the mean wind (Brasseur, 2001).

In a comparison between different gust parameterizations over Switzerland, Stucki et al., (2016) found little difference between different gust parameterizations and they argue that the biases in mean wind dominate the model skill of representing gusts.

Regarding chapter 5, the current COSMO model setup at MeteoSwiss uses a mixture between the physical model suggested by Brasseur (2001) and a statistical model for gust parameterisation. For mean winds larger than 25 m/s only a statistical parameterisation is used (Heim, 2018). The historic gust footprints provided by WISC uses the

UK MetOffice Unified model (Davies *et al.*, 2005) with no further specification on the gust parameterisation on public record. So it is not clear what gust parameterisation was used to create the footprints in chapter 3.

Storm Severity Index

In addition to the detailed geographical representation of a winter storm, for applications auch as to classify events, more aggregate measures are appropriate. A storm severity index (SSI) or storminess index is an indication for the severity of a storm event. It only relies on meteorological data like the gust footprint of an event. This only provides a proxy for the severity of socio-economic impacts assessed with impact models (section 1.5.1). Mostly such indices use the gust speed or the affected area as a metric (Lamb & Frydendahl, 1991; Klawa & Ulbrich, 2003; Dawkins *et al.*, 2016).

In chapter 3 of this thesis, the SSI of the WISC project is used (Hamish Steptoe, 2017; WISC, 2018). It is very similar to the SSI proposed by Lamb and Frydendahl (1991). The SSI is based on two elements derived from the gust footprint: the affected area $A\left(vmax > 25\frac{m}{s}\right)$ referring to the land area where the maximum gust speed exceeds a 25 m/s threshold (Equation (2)), and the cube of the average of all maximum gust speed in the affected area (Equation (3)). The SSI is the product of those two numbers and is defined for each storm event (Equation (4)).

$$affected\ area = A\left(v_{max} > 25\frac{m}{s}\right) \tag{2}$$

$$gust\ speed^3 = \left(mean\left(v_{max}\ in\ A\left(v_{max} > 25\frac{m}{s}\right)\right)\right)^3 \tag{3}$$

$$SSI = affected\ area * gust\ speed^3 \tag{4}$$

1.3.3 Climate change

Anthropogenic climate change is happening and a changing climate will generally lead to changes in the characteristics of extreme weather events (IPCC, 2012). Many studies were conducted so far regarding European winter windstorms and climate change with overall inconclusive results (Vautard *et al.*, 2019). Vautard et al. (2019) summarized the contrast between observed trends and changes in climate projections: There is a decreasing trend of storminess indices in observations or reanalysis (Smits *et al.*, 2005; Wever, 2012; Dawkins *et al.*, 2016). On the other hand, some model studies project a slight increase in extreme wind speeds for the future under climate change (Ulbrich *et al.*, 2009; Vautard *et al.*, 2014; Mölter *et al.*, 2016). But overall there is lacking model consensus for direction of change due to climate change, as summarized in Catto et al. (2019). Despite the uncertainty, Donat et al. (2011) showed that using a simple impact model to calculate the annual loss ratio driven by several global and region climate model projections, an increase of 25% in winter storm losses in Germany could result by the end of the 21st century. Burglind/Eleanor, the most recent severe winter windstorm event to affect Switzerland, cannot be attributed to climate change (Vautard *et al.*, 2019).

Climate change is an important topic to have in mind when thinking about impacts of weather events (Schwierz *et al.*, 2010). Nevertheless, the main chapters do not further take climate change into account. For chapters 2 and 5, the questions about climate change were out of scope as the focus of the studies were recent events. For chapter 3 and 4, an open-access dataset for winter windstorm events under climate change was missing at the time of publication.

1.4 Impact data

Winter windstorms are not only represented in meteorological data as introduced above, also socio-economic impacts are gathered and recorded in datasets. In some cases, socio-economic impact data are gathered specifically for the purpose to document the winter windstorm event. Often the data are gathered as part of operational data of an organisation, and documentation of socio-economic impacts can profit from data that is collected routinely for other purposes. This section provides an overview of the different involved parties and the possible datasets.

Regarding physical damage to property, one of the most extensive and systematic effort in collecting impact data takes place in the insurance industry. The operational process of an (re)insurance company involves damage assessments in order to properly pay claims and keeping a record of past damages to determine a sustainable price for the insurance product. These claims datasets are normally not shared publicly to restrict access of competitors (Hauge *et al.*, 2018). There are some insurance industry platforms that share aggregated impact data publicly: NatCatService of the reinsurance company Munich Re (Munich Re, 2011), Sigma studies and CatNet service of the reinsurance company Swiss Re (Swiss Re, 2017, 2021a) and the public excerpts of the Industry Exposure and Loss Database by the company PERILS (PERILS AG, 2021). These claims datasets, especially in non-aggregated form, are prone to uncertainties and inaccuracies (Guha-Sapir & Below, 2002; Imhof, 2011). According to Imhof (2011) claims can e.g. be assigned to an incorrect date, due to errors in the data entry or lack of knowledge. The causing hazard can be hard to determine if several hazard types are involved – or in case the place of damage is far from any measurement site. Finally, the sum of the damage is hard to exactly assess and can include removal and cleaning cost, next to the replacement value or present value or the damage (Imhof, 2011).

Some governmental offices or non-governmental organizations gather impact data relevant to winter windstorms. Regarding physical damage in forests, the Federal Office for the Environment (FOEN) publishes a yearly report about forest use including information about felled wood after large storm events (BAFU, 2021a). After the destructive event Lothar in 1999, FOEN published a report containing an extensive collection of the socio-economic impacts of the winter windstorm split up to several sectors, but such a concise and multidimensional is very rare (WSL & BUWAL, 2001). The structure of the report on Lothar inspired the collection of the impacts of storm Burglind/Eleanor in chapter 2.

During the experience of gathering socio-economic impact data for chapter 2, the author of this thesis experienced that service providers, railroad providers, electricity providers, etc., often possess information about interruption of their services. This information is normally not shared publicly and may or may not be available upon request. Additionally, a lot of impact data is shared as press releases of individual organizations or researched and then gathered by journalists. This renders newspapers a very important source of impact data.

It is worth mentioning the free database EM-DAT (Guha-Sapir Debarati, 2021), that gathers impact data on disasters globally. It is the most cited impact database (De Groeve *et al.*, 2013). It gathers the information on most global disasters based from newspaper articles, and governmental and non-governmental reports and provides the most complete global perspective (Shen & Hwang, 2019). EM-DAT also gathers data on number of affected or injured people or the death toll. This information exposes another source of uncertainty of impact data, they are politically sensitive as high death tolls can point to e.g., inefficient state infrastructure or social inequalities (Guha-Sapir & Checchi, 2018). EM-DAT was not used in this thesis as more granular datasets were available in the specific case of Switzerland.

All in all impact data remain scarce and the uncertainty through non-standardized definitions and the issues of incomplete records and coverage in general are considerably big (De Groeve *et al.*, 2013). The scarcity of data adds to the rareness of the events itself and has to be considered in risk assessments and resulting decision-making support. To reduce such shortcomings in the future, there are initiatives in Europe and globally to gather impact data more broadly and systematically (JRC EU expert working group on disaster damage and loss data, 2015). One example is the project CESARE in Austria that aims to combine different governmental impact datasets (CESARE, 2019).

1.5 Risk assessment and impact modelling

Risk is "the effect of uncertainty on objectives", a positive or negative deviation from what is expected (International Standards Organization, 2009). In the context of natural hazards, the "deviation from what is expected" are the socio-economic impacts of the hazard. It is important that the hazard itself is not enough to constitute a risk; the hazard needs to interact with the socio-economic dimension (the "objectives") in some way to create a risk. In natural hazard risks, the uncertainty often refers to the probability of the occurrence of the hazard and consequently, the probability of the resulting impacts.

Risk management all activities around prevention, mitigation, preparedness, response, recovery and rehabilitation with the goal to be resistant, able to recover and able to adapt (PLANAT, 2018). Understanding disaster risk is one priority in risk management (UNISDR, 2015). One important part of understanding is the quantification of the risk, often referred to as risk assessment (Mitchell-

Wallace, 2017). This risk assessment can be done based on past impacts and their experienced frequency, this is partly featured in chapter 4. Another way of assessing the risk is using impact modelling. It models the adverse outcomes based on the intensity of hazard events and uses the frequency of the hazard events for the risk assessment. The impact model features prominently in chapters 4 and 5 of the thesis.

In section 1.5.1 the basics of such impact models are summarized. In section 1.5.2 probabilistic hazard event sets that can be used instead of historic event sets are introduced. In section 1.5.3, the current use of impact modelling for building damages due to winter windstorms in the scientific literature is presented.

1.5.1 Impact modelling

The risk of natural hazards can be modelled as a combination of hazard, exposure, and vulnerability (IPCC, 2012; Mitchell-Wallace, 2017; Aznar-Siguan & Bresch, 2019). This concept is widely used, in the following, the particular formulation by Aznar-Siguan and Bresch (2019) will be used. Hazard refers to a spatial representation of a natural hazard, e.g., as the gust footprints introduced in section 1.3.2 including an indication of the associated probability. The socio-economic elements at risk from that hazard, like property, people or service infrastructure are represented in the exposure. The relationship between the hazard intensity, e.g. the gust speed, and a degree of impact is specified in the vulnerability information. In impact models used for this thesis, the vulnerability component is represented by impact functions.

In Aznar-Siguan and Bresch (2019), risk is defined as a convolution of probability and severity as specified in Equation (5). Severity is referring to some measure of the socio-economic impact.

$$risk = \ probability\, x\, severity \qquad (5)$$

The probability is a property of the hazard and can for example be inferred from the observed frequency or the probability outputted from the hazard model. The severity can be formulated as a function of hazard intensity, exposure and vulnerability (Equation (6), Aznar-Siguan and Bresch, 2019).

$$severity = F(hazard\ intensity, exposure, vulnerability) \tag{6}$$

In the risk assessment platform CLIMADA, a python implementation of such an impact model, the severity at each point of exposure can be formulated more explicitly (Equation (7) with the vulnerability expressed as an impact function (Aznar-Siguan & Bresch, 2019).

$$severity = exposure * f_{imp}(hazard\ intensity) \tag{7}$$

CLIMADA's risk and severity are spatially explicit and event-based (Aznar-Siguan & Bresch, 2019). The exposure is defined as a set of point exposures, each point with an associated value or other metric of the exposure. The exposure can thus represent a regular grid with an associated value per grid point or an irregularly located set of points. Equation (7) is applied to each exposure point and each event resulting in a matrix of severities. Using the probability of the events this matrix can be summarized in different risk metrics (Aznar-Siguan & Bresch, 2019).

The *expected annual impact* per exposure point is a metric for the risk at every analysed location. It highlights the difference in the risk between different exposure points (Aznar-Siguan & Bresch, 2019). These differences can originate from different hazard intensities, different values at risk from the exposure, different vulnerability or a mixture thereof.

The *average annual impact* aggregates the expected annual impact over all single events and exposure points and is a metric for the aggregated risk (Aznar-Siguan & Bresch, 2019). This metric is often used in risk assessments. By aggregating the severities per exposure point for one specific event the aggregated impact of each event can be analysed. Using the probability information of each event, the return period for exceeding a certain aggregated impact can be calculated (Aznar-Siguan & Bresch, 2019). This technic is used to define the *probable maximum impact* to inform risk management. The probable maximum impact is often defined as the impact of a certain return period, e.g., 250 years (Aznar-Siguan & Bresch, 2019).

In chapter 5, CLIMADA is used to forecast building damages due to winter windstorm. For this endeavour, the risk framework of

CLIMADA is adapted to the specifications of forecasts. Gust footprints of weather forecasts are used as hazard component (see section 1.3.2). The probability now no longer represents an annual frequency but the probability of occurrence. For ensemble forecasts, all ensemble members have the same probability and the sum of all probabilities are equal to one. Similarly to above, an expected impact per exposure point can be calculated for the risk of an upcoming event at every location. An average impact which aggregates the risk per exposure point to a total risk metric can be calculated contains a weighted average of all the different representations of one event in the near future. Of course, the basis of these calculations is still a matrix of severities at each location and for each ensemble member of this event. The severities of each ensemble member are ready for individual analysis to focus on the median or on a worst case scenario. It would also be possible to apply a more sophisticated method to fit a distribution to the ensemble members for further analysis.

1.5.2 Probabilistic approaches – excursus on statistical perturbation

Next to the quantifying the severity of the impact, the quantification of the probability is an important part of the risk assessment. The probability can be defined as the experienced frequency of historic events, either of recorded impacts or of modelled impacts (chapter 3). For defining the probable maximum impact, the experienced time period is often too short and the information has to be extrapolated to estimate the probable maximum impact (more in chapter 3). Probabilistic approaches help to achieve a more comprehensive view on the probable maximum impact.

To achieve a probabilistic and event-based view on the full spectrum of probability and severity, including the probable maximum impact, several methodologies can be used. Climate models can be run for many model years based on the current climate to produce probable weather events for risk assessment (Mizielinski *et al.*, 2014). This approach was used to create the synthetic event set of the WISC project analysed in chapter 3. Also, the events created from seasonal forecast models run in ensemble mode can be interpreted as independent and thus constitute a probabilistic set (Della-Marta *et al.*, 2010; Walz & Leckebusch, 2019). For details on forecast models run in ensemble mode, see section 1.3.2. The advantage of using model output for probabilistic events is the creation of truly independent and physically consistent unexperienced events (Walz & Leckebusch, 2019). On the other hand there are model uncertainties and problems with biases (Donat *et al.*, 2010). Additionally, the lack of events in the hazard set that were actually experienced by stakeholders and decision-makers can lead to a smaller identification with the impact model results and thus a reduced uptake of the resulting risk assessment for decision-making (Hayes *et al.*, 2018).

Another option to create a probabilistic and event-based view on the probable maximum impact is the use of statistical perturbation to create unexperienced events based on historical events (Schwierz *et al.*, 2010). This approach has the advantage that it can be applied on the existing historical event set in a straightforward fashion. This means that firstly, this approach does not rely on the development on another open-access probabilistic dataset and secondly the basis of the probabilistic storms are recognizable events that might increase the uptake of the resulting risk assessment by decision-makers. Statistical perturbation was used in chapter 4 to create a new probabilistic event set.

1.5.3 Modelling building damages

The process leading to damage to buildings from an engineering point of view was summarized in a report by the Präventionsstiftung kantonaler Gebäudeversicherungen in Switzerland (Weidmann, 2010). Especially the pressure and suction forces associated with wind gusts lead to damage at roofs etc. of buildings. These are very localized, small-scale processes. Storm phenomena in Switzerland creating strong enough to cause relevant damage are mainly winter windstorms and thunderstorms (Weidmann, 2010). Storm damages of winter windstorms are mostly minor per building (around 2000 CHF) and reach their large total damages by affecting many buildings over vast areas (Imhof, 2011). Differences between winter windstorm events mostly lie in the number of affected buildings, while the average damage per building does not vary as much (Imhof, 2011).

Impact models for building damage due to European winter windstorms are used in the insurance and reinsurance industry, but are scarce in the open domain. Examples of openly shared implementations of such impact models are very rare and include Koks and Haer (2020) and CLIMADA (Aznar-Siguan & Bresch, 2019) as further developed and used in this thesis. Another open-source impact model, the OASIS loss modelling platform, can readily make use of Copernicus WISC data on the hazard side, yet corresponding exposure and impact functions are not implemented (Hayes *et al.*, 2018). In other scientific studies, impact models of building damages have been used to assess the current risk of winter windstorms in Europe (Donat *et al.*, 2011b; Walz & Leckebusch, 2019) or the future risk (Schwierz *et al.*, 2010; Donat *et al.*, 2011a).

There are a few publications on adequate impact functions for building damages due to winter windstorms. Schwierz et al. (2010) used and published an impact function from an insurance industry model, that was used in several further studies (Della-Marta *et al.*, 2010; Stucki *et al.*, 2015; Welker *et al.*, 2016; Walz & Leckebusch, 2019), and also for this thesis. Prahl et al. (2015) compared the performance of four regularly used parameterizations of such impact functions, that need to be statistically fitted to observed loss ratios, instead to an absolute value of impact. Depending on the targeted risk metric (extreme events, moderate events, spatial variability) different impact function parameterizations performed best. There is dependence on the distribution of the gust speeds originating from the hazard model used, and transferability to other model setups remains a challenge. All studied parameterizations require substantial impact data for calibration (Prahl *et al.*, 2015).

Feuerstein et al. (2011) applied a bottom up approach and created impact functions by linking observed building damages to windspeeds, and the impact model of Koks and Haer (2020) is building on those functions additionally fitting them to aggregate impact data.

1.6 Decision-making support for managing risks

Many sectors are influenced by weather and climate and thus profit from integrating weather and climate data into their decision-making (Hewitt *et al.*, 2012). There is a growing body of literature about the provision of useful climate information to decision-makers assembled under the term “climate services”. Additionally, the provision of meteorological forecast data and warnings and their use in decision-making have been studied. In both bodies of literature, there has been a trend towards user specific solutions and integrating socio-economic impacts.

In the following subsections, the findings for climate services (section 1.6.1) and forecast and warnings (section 1.6.2) are summarized. In section 1.6.3, the importance of collaboration and transdisciplinarity for decision-making support is emphasized with applied examples.

1.6.1 Climate services

Climate services have become a more prominent topic due to climate change and increasing impacts from weather events (Hewitt *et al.*, 2012). Many countries provide country specific information not only about the current, but also about the future climate (Skelton *et al.*, 2017). In Switzerland, the National Centre for Climate Services (NCCS) located at MeteoSwiss coordinate these activates among the different governmental bodies. Additionally, there are several international providers of climate services, e.g. the Copernicus Climate Change Services initiative, that provides services about past, current and future climate and publishes vast amounts of observational and modelling data (Thépaut *et al.*, 2018).

An important criteria for the success of climate services is the fact that they require knowledge of the decision-maker's needs and frequent interactions with them in the process (Hewitt *et al.*, 2012; Taylor *et al.*, 2015). According to Skelton *et al.* (2019), users can often be divided into three groups with different need profiles: *Sailors*, who gather several summary information to incorporate qualitatively into their decision-making, *Divers*, who look at quantitative climate datasets and *Observers*, who only want to be generally aware of the information without actually incorporating it into their decisions. It is important to provide each of the user groups with their preferred type of material. Additionally, there is potential to encourage more Sailors to become Divers (Skelton *et al.*, 2019).

Transparency and trustworthiness are further criteria for the success of climate services, which can be improved by making not only the knowledge and data, but also decision support tools openly accessible (Hewitt *et al.*, 2012; Taylor *et al.*, 2015).

The decision-making support of climate services includes weather and climate science experts and non-experts. Experts are challenged by the need to not only communicate their knowledge but also the associated uncertainties (Taylor *et al.*, 2015). Withheld or unsuccessful communication of the uncertainties might lead to a false sense of certainty, a loss of trust, mal-adaptation or even failures to act (Taylor *et al.*, 2015).

Chapter 4 uses climatological information of winter windstorm intensities from the Copernicus Climate Change Services platform and provides an open and transparent decision support tool directed at Divers, such as e.g. local insurance providers, to combine their claims-based risk assessment for building damages due to winter windstorms with modelled impacts based on climatological data. The fully open implementation in CLIMADA might also serve as an encouragement for previous Sailors (small organisations who did rely on others for handling such kind of information) to become Divers themselves. Chapter 4 also compares the uncertainty between claims based and model-based risk assessments.

1.6.2 Forecast and warnings

In Switzerland a nationwide and comprehensive weather warning system is in place since the early 2000s, it was actually initiated after the winter windstorm event Lothar in 1999 (MeteoSwiss, 2019). Since then the warning system has been constantly expanded and improved (Kube *et al.*, 2016). MeteoSwiss now provides weather warnings for wind, snow, thunderstorms, frost, heat waves, rain, slippery roads. The warnings are presented on a multi-hazard platform together with avalanche, earthquake, flood and forest fire warnings. The multi-hazard platform fulfils an important user requirement (Dallo *et al.*, 2020) is coordinated by the Steering Committee on Intervention in Natural Hazards (LAINAT) and is complemented by an app widely used by the general public and beyond (MeteoSwiss, 2016).

In a warning situation, a forecaster of a National Hydrological and Meteorological Services (NHMS) needs to achieve and maintain situational awareness in order to be in a position to provide useful advice (WMO, 2015b). Situational awareness means disposing of a mental model of the weather situation through constantly incorporating observational and forecast data in a cycle of analysis, diagnosis and prognosis (WMO, 2015b). A forecaster consolidates the information in a mental model to take warning decisions and to provide advice in answer to specific requests.

On a global level, the World Meteorological Organization (WMO) issued guidelines to encourage NHMS to incorporate socio-economic impacts into their warnings (WMO, 2015a). The WMO suggests three paradigms (excerpt from chapter 5 of this thesis): “In the first paradigm, so-called hazard warnings (HbW), only the hazard information and no impact information are considered as described as weather warnings above. In the second paradigm, named impact-based warnings (IbW), the vulnerability information is used in addition to the hazard to formulate potential impacts. In the third paradigm, the risk of impact is assessed using both vulnerability and exposure information arriving at impact forecasts (IFc) and impact warnings (IW).” MeteoSwiss also plans to focus on the incorporation of impacts in the next version of their warning system (Kube *et al.*, 2016). Chapter 5 of this thesis presents the implementation of an impact forecasting system for the third paradigm.

There are developments towards quantitative impact forecasting for almost any hazard type, but they mostly are in their infancy and operational impact forecasting systems exist only for heatwaves and earthquakes (Merz *et al.*, 2020). Impact modelling has to become more advanced to be comparable with hazard modelling, this is especially the case for uncertainty, that is provided in a lesser degree for impact models (Merz *et al.*, 2020). Forecasting socio-economic impacts goes beyond the established role of an NHMS, but NHMSs may be best equipped to forecast such impacts or may play a supporting role in enabling their partners to forecast impacts (WMO, 2015a). Open-source impact models, as presented in Chapter 5, also offer the opportunity for them to be operated by users, constantly fed with (meteorological) input as provided by NHMS, e.g. via an application programming interface (API), as e.g. piloted by the German Weather Service (http://opendata.dwd.de).

This thesis contributes to the discussion about incorporations of impacts into weather warnings. The implementation of an impact forecast in chapter 5 sets a new technological minimal requirement for impact forecasting for weather warnings.

Psychological and social science aspects

To improve the decision-making support of warnings, it is much more meaningful to first work on the communication of warnings and their potential to incite behavioural change than to increase the accuracy of the meteorological forecast (Nurmi *et al.*, 2013). That is why there is a growing body of literature that looks at the communication and perception of weather warnings.

Fleischhut *et al.* (2020) found that users have some deficits in weather literacy. General users might struggle to connect wind speeds with verbal category labels (e.g., gale, storm, hurricane) and with expected impacts (e.g., outdoor furniture blown away, trees uprooted). Additionally users tend to overestimate the wind speeds at which a certain impact is expected to happen. As a result, users might misjudge the risk if the provided warning is based on forecasted wind speeds or categories alone. These deficits might be remedied by incorporating impacts into warnings (Fleischhut *et al.*, 2020). The combination of impact information and behavioural recommendations often better communicates the warning content compared to purely meteorological information and might also lead to a more comprehensive perception of the weather situation (Weyrich *et al.*, 2018).

Regarding the perception of warnings, there is still a lack of understanding and thus there is a need for further experimental and post-event studies (Taylor *et al.*, 2019). For example, the previously mentioned results by Weyrich *et al.* (2018) were put into question by another survey using real-time events instead of an experimental setup (Weyrich *et al.*, 2020). But the importance of impact information for warnings is a recurring theme, as a survey in the aftermath of storm Doris in the UK shows. The willingness to follow behavioural recommendations is strongly linked with concern about the event, and the concern is linked to the perceived severity of impact (Taylor *et al.*, 2019). During the study of Weyrich *et al.* (2020) no severe event was taking place which might trigger a concern linked to the severity of impact. This decreases the explanatory power of the results of this study. Another point of mixed results is that rendering the content of warnings easy to understand normally leads to them being perceived more trustworthy, though willingness to follow behavioural recommendations may not be sensitive to gradations of warning levels (Taylor *et al.*, 2019).

1.6.3 Collaboration – Transdisciplinarity

Managing risk is a transdisciplinary undertaking, of which quantitative risk assessment as presented in this thesis is only one part. Defining what is at risk, how to handle risks etc. is a collaborative undertaking that most times needs to include many stakeholders.

Almost any risk management should start with engaging the relevant stakeholders. For example the methodology of "Economics of Climate Adaptation" uses a quantitative risk assessment of climate related hazards in combination with a well-structured stakeholder dialog to allow option appraisal for climate adaptation measures (Bresch, 2016; Souvignet *et al.*, 2016). Some of the structure of this methodology can be used for the creation of other risk managements. Two examples that are transferable from ECA: Firstly, it is important to gather all relevant stakeholders and define "what risks should be considered and what assets are relevant (group of people, areas, type of houses, commercial activity, etc.)" (Phase 1 in Souvignet *et al.*, 2016), similar to the Hazard Impact Framework in Hemingway and Gunawan, 2018 and to Shaping Climate Resilient Development in Bresch, 2016). Secondly, the vulnerability can be co-developed in expert workshops relying on past impact data (Phase 6 in Souvignet *et al.*, 2016). The outcome of such stakeholder and expert dialog directly informs the setup of the quantitative impact modelling and helps indirectly with the perception of resulting quantitative risk assessment.

There have been studies about weather dependence of socio-economic impacts, without using the resulting relationship for an impact forecasting system. Nevertheless, they illustrate that weather data and socio-economic impacts can be quantitatively linked for very diverse examples of impacts, and that such impact forecasting system would be possible for a broad spectrum of socio-economic impacts.

A good example of such an transdisciplinary effort is the study "Starkniederschläge und Einsatzplanung von Schutz & Rettung Zürich" by the Federal Office for Civil Protection (2019). Which combined information from different fields (meteorological measurements and operational data of civil protection) and defined a threshold for heavy rain for which an increase in the number of civil protection operations was observed in the past. This threshold was used to better communicate the expected future change of the number of likely requested civil protection operations due to population growth and climate change. This threshold and the underlying collaborative work provides also a solid foundation for impact forecasts or impact based warnings (Federal Office for Civil Protection, 2019).

Another example is the dependence of traffic crashes in Finland due to bad weather (Perrels *et al.*, 2015). In a multidimensional model the influence of precipitation, temperatures, snow depth, wind speed, and humidity on car crashes have been studied and regional as well as temporal differences defined. Early in winter freezing and thawing is a bigger indicator for the car crash risk as later in winter. Also the same bad weather conditions lead to a higher risk of car crashes on Fridays compared to the weekend (Perrels *et al.*, 2015). This multidimensional model would be ready to be implemented as an impact forecast of car crash risk.

For the transdisciplinary projects to further develop impact forecasting systems, it is very important to follow guidelines to define the needs of all involved parties and to collaboratively form a plan who will be involved how and when in the project (Pohl *et al.*, 2017). It is important that the transdisciplinary projects are setup with support from and project ownership of people high enough in the hierarchy of the involved institutions that enough time during the project is reserved for interaction and iterations in tackling, reconciling and resolving issues (Fischer *et al.*, under review).

1.6.4 Collaborative partners of this thesis

There have been three collaborative partners involved in this thesis. They are introduced in the following paragraphs.

MeteoSwiss – involved party as well as collaborator

The affiliation of the author of this thesis was ETH Zurich, as well as the Federal Office for Meteorology and Climatology MeteoSwiss. In most ways, MeteoSwiss was directly involved in this thesis and the author had direct access to data, infrastructure, resources and knowledge about the numerical weather forecast. After the storm event Burglind/Eleanor, the author of this thesis contributed a chapter to a technical report about the event published by MeteoSwiss (chapter 2). Other parts of this work had more of a collaborative nature. The author of this thesis was able to gain an insights into the responsibilities of a forecaster, especially the dimension of warning decisions. MeteoSwiss is currently in the initialisation phase of a project to renew its warning system (Kube *et al.*, 2016). Next to the direct implications of this project on the thesis documented in chapter 5 and 6, there have been many general discussions that were only indirectly related to this thesis, which always inspired, and shaped its outcome.

Cantonal building insurance GVZ

GVZ introduced itself with the following words in chapter 3: "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 CHF 500 billion (Swiss Francs) (in 2018). GVZ is an independent institution of the canton of Zurich under public law (GVZ, 2021)."

The collaboration with GVZ started with an agreement to use their claims data for the studies of this thesis. Following discussions showed a shared interest in the newly published hazard event set WISC, and the decision was formed to jointly discuss the use of this dataset and publish the results as a case study (chapter 4).

Additionally, GVZ uses short-term weather data for rapid damage estimations, which are documented in chapter 4. The discussion around the benefit of having a damage estimate as early as possible for a building insurance company also served as a use-case of the impact forecasting system in chapter 5.

Swiss Re

The company Swiss Re is one of the two largest global providers of reinsurance and other risk transfer solutions (Swiss Re, 2021b). The technical report of assessing the WISC event sets was done in a collaboration with Swiss Re. Swiss Re provided the perspective of the reinsurance industry, in particular as a large company with their own extensive model capabilities for winter windstorms impact assessments (chapter 3).

2 Der Wintersturm Burglind/Eleanor in der Schweiz - Schäden und Auswirkungen

Thomas Röösli[1,2]

Published as chapter 6 in the technical report “MeteoSchweiz, 2018: Der Wintersturm Burglind/Eleanor in der Schweiz, *Fachbericht MeteoSchweiz*, **268**, 35 pp.» edited by Simon Scherrer.

Burglind/Eleanor führte zu direkten Schäden und indirekten Auswirkungen in der Schweiz. Die im Februar 2018 geschätzten Gebäudeschäden erreichen einen Gesamtwert von 165 Millionen CHF, was den höchsten Wintersturmschaden seit Lothar 1999 darstellt. Es gab Beeinträchtigungen im Strassen- und Schienenverkehr sowie lokale Unterbrüche im Stromnetz. Im Wald wurden rund 1.3 Millionen Kubikmeter Holz geworfen, ein Viertel einer Jahresnutzung.

Wintersturm Burglind/Eleanor zählt zu den vier stärksten Winterstürmen der Schweiz seit 1981. Winterstürme dieser Stärke führen zu Schäden an Gebäuden, Waldflächen und für die Gesellschaft wichtigen Infrastrukturen. Durch grobe Schätzungen der Personen- und Sachschäden sechs Wochen nach dem Ereignis kann die nationale Bedeutung des Wintersturms Burglind/Eleanor aus einer Schadensperspektive abgeschätzt werden. Die hier publizierten Zahlen sind Schätzungen und stammen teilweise aus nicht abgeschlossenen Erhebungen. Es ist zu erwarten, dass sich diese Schätzungen im Verlaufe der nächsten zwei Jahren noch ändern.

Bei Lothar 1999 sind in der Schweiz 14 Personen während des Ereignisses zu Tode gekommen. Bei Burglind/Eleanor sind glücklicherweise keine direkt durch den Sturm verursachte Todesopfer bekannt. Bei Forstarbeiten sind jedoch gemäss Beratungsstelle für Unfallverhütung in der Landwirtschaft (BUL) bis Februar 2018 drei Personen tödlich verunfallt, bei denen ein Zusammenhang zu Aufräumarbeiten von Sturmschäden wahrscheinlich ist. Drei weitere Personen wurden schwer verletzt. Die Angaben des BUL sind mangels einer Meldepflicht nicht abschliessend.

---

[1] Institute for Environmental Decisions, ETH Zurich, Zurich, Switzerland
[2] Federal Office of Meteorology and Climatology MeteoSwiss, Zurich, Switzerland

Die geschätzten versicherten Gebäudeschäden von 165 Millionen CHF (vgl. Table 1) erreichen nur ein Viertel der Schäden von Lothar und bewegen sich auf ähnlichem Niveau wie der Sturm Vivian von 1990, der besonders in hohen, kaum bewohnten Lagen der Alpen wütete. Die grössten Gebäudeschäden durch Burglind/Eleanor entstanden in den Kantonen Bern mit 20 Millionen CHF, Luzern mit 18 Millionen CHF sowie in Solothurn, Aargau und Zürich (vgl. Figure 2). Nicht berücksichtigt sind die sieben Kantone Genf, Uri, Schwyz, Tessin, Appenzell Innerrhoden, Wallis und Obwalden, in denen anstelle staatlicher Gebäudeversicherungen private Versicherer Windschäden abdecken. Diese Kantone werden vom Schweizerischen Versicherungsverband SVV auf ein Schadenstotal von 35-40 Millionen CHF geschätzt.

Der dem BAFU gemeldete Waldschaden von 1.3 Millionen Kubikmeter geworfenem Holz entspricht etwa einem Viertel einer Jahresnutzung der Schweiz. Das BAFU erwartet gemäss der Medienmitteilung vom 18. Januar 2018, dass der Markt das verwertbare geworfene Holz ohne Preiszerfall aufnehmen kann. Anders war die Situation bei Lothar als zehnmal mehr Holz geworfen wurde oder bei Vivian mit vier Mal so hohem Schaden. Am stärksten von Waldschäden betroffen wurden durch Burglind/Eleanor die Kantone Bern, Luzern, Solothurn, Zürich und Aargau. Besonders die Kantone Bern, Luzern und Solothurn verzeichneten einige grössere Flächenschäden und damit Schadensmengen in der Höhe von bis zu zwei Drittel ihrer durchschnittlichen Jahresnutzung. Grosse Auswirkungen haben ebenfalls Streuschäden von Nadelbäumen, deren Entfernung zur präventiven Eindämmung von Borkenkäferbefall viel Arbeit verursacht. Aufräumarbeiten im Wald sind sehr gefährlich. Bei den Aufräumarbeiten nach dem Sturm Lothar starben 15 Menschen (WSL & BUWAL, 2001). Es bleibt zu hoffen, dass die Aufräumarbeit nach Burglind/Eleanor zu keinen weiteren Todesfällen führt.

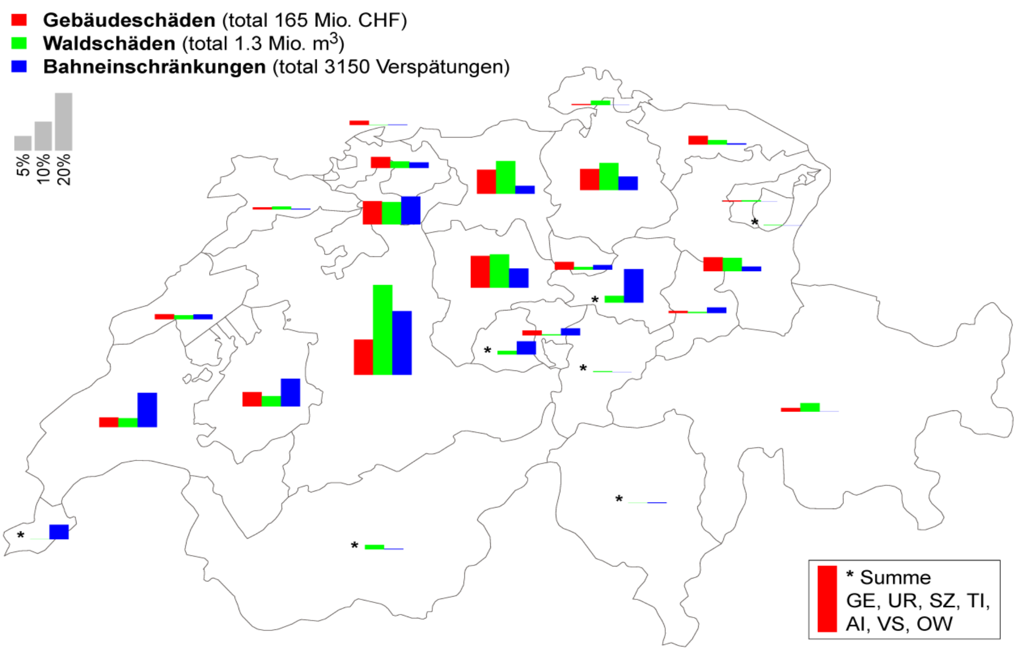


Figure 2 Verteilung der Gebäudeschäden (rot), Waldschäden (grün) und Einschränkungen im Bahnverkehr (blau) pro Kanton. Es wird der Anteil der kantonalen Schäden am gesamten Schaden der Schweiz gezeigt. Über die Gebäudeschäden der sieben Kantone Genf, Uri, Schwyz, Tessin, Appenzell Innerrhoden, Wallis und Obwalden ist nur ein Summenwert bekannt. Datenstand: Februar 2018.

Zusätzlich zu Schäden an Gebäuden und im Wald haben starke Winterstürme auch indirekte Auswirkungen durch Unterbrechung oder Ausfälle von Dienstleistungen oder kritischer Infrastruktur. Diese Unterbrechungen betreffen einen viel grösseren Anteil der Bevölkerung als direkte Schäden und können zu weiteren Folgekosten führen. Beim Sturm Lothar werden diese Kosten auf mindestens weitere 17 Millionen CHF geschätzt. Als Beispiele indirekter Auswirkungen von Burglind/Eleanor werden hier die Mobilität und die Stromversorgung betrachtet.

Erfreulicherweise meldet Swissgrid, dass das Übertragungsleitungsnetz der Schweiz trotz einzelner Schäden keine Versorgungslücke bei Verteilerstationen ausgelöst hat. Bei Lothar haben 70 beschädigte Übertragungsleitungsverbindungen zu grossflächigen Stromausfällen geführt. Bei Burglind/Eleanor haben Schäden im kleinräumigeren Verteilernetz, gemäss Recherchen des SRF, bei tausenden Haushalten in den Kantonen Bern, Luzern, Zürich und Graubünden zu einem Stromausfall geführt, die Beeinträchtigungen waren jedoch deutlich weniger massiv als bei Lothar.

Die SBB hat mit 168 Störungsereignissen (wie zum Beispiel Bäume auf Geleisen) ebenfalls Auswirkungen des Sturms im gesamten Bahnverkehr der Schweiz festgestellt, die bis zu 400'000 Passagiere betroffen haben. Von Verspätungen waren besonders stark die Romandie (920 Verspätungen) gefolgt vom Mittelland (680 Verspätungen) und dem Netz der BLS (430 Verspätungen) betroffen. Die direkt oder indirekt von Burglind/Eleanor ausgelösten Ereignisse müssen aber im Kontext der täglich im Durchschnitt 550 Ereignisse anderer Ursachen als nicht besonders schwerwiegend betrachtet werden.

Table 1 Zusammenstellung der Schäden verschiedener Winterstürme. Diese Tabelle vergleicht die Schäden an Wald und Gebäude der Stürme Burglind/Eleanor, Lothar und Vivian. Quellen Gebäudeschäden: Kantonale Gebäudeversicherungen / Kantonaler Rückversicherungsverband / Schweizerischer Versicherungsverband, Waldschäden: BAFU, Todesfälle: (WSL & BUWAL, 2001) und Beratungsstelle für Unfallverhütung in der Landwirtschaft. Datenstand: Februar 2018.

Sturm	**Todesfälle [Anzahl Personen]**	**Gebäudeschäden [Mio. CHF]**	**Waldschäden [Mio. m^3]**
Burglind/Eleanor 2018	mind. 3	165	1.3
Lothar 1999	29	630	12.7
Vivian 1990	24	255	4.9

Die nationale Verkehrsinformationszentrale der Schweiz (viasuisse) hat am 3. Januar 2018 über 1000 Meldungen zu unterschiedlichen Beeinträchtigungen, von Sperrung bis zu stockendem Verkehr im National- oder Kantonalstrassennetz, versendet. Das sind zehn Mal mehr als am ereignislosen 3. Januar 2017. 455 Meldungen standen im direkten Zusammenhang mit dem Sturm Burglind/Eleanor.

Die verschiedenen Kantone wurden unterschiedlich stark von Burglind/Eleanor betroffen. Die Schäden waren in den Kantonen Bern, Solothurn, Aargau, Luzern und Zürich besonders stark. Mit indirekten Auswirkungen ebenfalls in der Westschweiz, im restlichen Mittelland und in den Voralpen bis Graubünden. Die räumliche Aufteilung der Schäden (vgl. Figure 2) entspricht gut der klimatologischen Rangierung der Windspitzen in Abbildung 17 und der von der MeteoSchweiz veröffentlichten Gefahrenkarte in Abbildung 10 (Abbildungen 10 und 17 sind abgebildet in Scherrer *et al.*, 2018).

3 A comparison of the WISC events sets with both industry and research data

Thomas Röösli[1], David N. Bresch[1] and Marc Wüest[2]

This case study was published as part of the WISC project in the context of the Copernicus Climate Change Service (C3S). Available at: https://wisc.climate.copernicus.eu/wisc/#/help/products#casestudies_section.

3.1 Introduction

For the year 2016, the Swiss Re sigma study (Swiss Re, 2017) counted 191 natural catastrophe events globally, leading to an economic damage of 166 billion USD. Such catastrophes have a huge impact on the affected societies and need to be managed with foresight.

Risk management starts with proper identification of risks and their drivers, followed by quantification of frequency and severity. Catastrophe modeling has been brought to this task for many years by the (re)insurance sector.

Catastrophe models assess risk by combin[3]ation of hazard, exposure and vulnerability (CLIMADA, 2018). The hazard describes the intensity and the probability of a catastrophe event. The exposure describes the geographical distribution and kind of assets (e.g. private property within each postal code in France) and the vulnerability the effect of a particular hazard on each kind of assets for different hazard intensities (e.g. the damageability of private property due to wind).

Among the many natural hazards, wind is one of the most important natural catastrophe risks in Europe. It is not so much the risk of total destruction of a few assets in a small region, but rather the widespread (across multiple countries) minor damage that sums up to impressive amounts. Winter storms such as Daria in 1990 and Lothar in 1999 totaled economic damages of more than EUR 8 bn each1 and for Kyrill in 2007 economic damages amounted to EUR 7 bn (Swiss Re, 2017). Hence European winter storms deserve special attention, as illustrated

---

[1] ETH Zurich, Switzerland
[2] Swiss Re, Switzerland

again by Burglind in January 2018 (early estimates of economic damage in the range of at EUR 1.1-1.6 bn).

Copernicus' Wind Storm Information Service (WISC) aims to provide open source data for all players in the insurance sector (and beyond) to assess their European wind storm risk. The center piece of this open source data is the hazard intensity information - the wind gust footprints of storm events, provided at a high spatial resolution of approximately 4km. WISC provided two event sets: the historic event set containing the footprints of 147 severe storms of the last 70 years and the synthetic event set containing more than 7'500 footprints of roughly 130 modelled years.

We will undertake a comparison of the WISC event sets with the European wind storm catalog of both the open-source CLIMADA model as used at ETH Zurich and the operational Swiss Re loss model (part of Swiss Re's proprietary MultiSNAP platform) for selected storms and storm years with the aim to better understand extreme impacts and associated uncertainties.

3.2 Rationale

The CLIMADA impact modelling platform used at ETH is an open source and –access platform incorporating the same risk assessment principles and methodology as operated by the (re)insurance industry (CLIMADA (2018) has been used in peer-reviewed scientific studies, Stucki *et al.*, 2015; Bresch, 2016; Welker *et al.*, 2016; Gettelman *et al.*, 2017; in more than twenty Economics of Climate Adaptation (ECA) case studies worldwide, see ETH Zürich, 2021; as well as for bespoke studies with industry partners to look into weather and climate risks to sovereigns: S&P Global Ratings, 2015). CLIMADA can be used as a test environment for the WISC datasets, it even provides an automatic interface to the OASIS Loss Modelling Platform (LMF) ktools (https://oasislmf.org/ and the CLIMADA call ktools_model_from_climada). Given the modularity and high flexibility of the CLIMADA platform, we can emulate many combinations of hazard, exposure and vulnerability as used by other models, such as combining the WISC hazard sets with other exposure databases or different vulnerabilities.

Swiss Re is in a good position to calibrate and validate its in-house European winter storm model based on in-house damage data gathered across Europe at high resolution for many historic events. For rare events (return periods beyond 100 years), the hazard component of the damage model becomes the key driver of uncertainty and hence warrants further study.

Using the historic event set of winter storm footprints as generated in the WISC project provides Swiss Re with the opportunity to re-check historic events and double check its in-house validation. Using the synthetic event set of winter storm footprints as generated in the WISC project provides Swiss Re with the opportunity to investigate the tail of the hazard and damage distribution. Comparison along the chain of impacts (hazard, exposure, vulnerability, damage calculation) will allow for explicit quantification of uncertainty and hence further the understanding of drivers of expected damage and associated uncertainty, especially to compare the low- and high- frequency tails of the distribution.

Since we envisage publication of key insights and will run comparisons using the open-source CLIMADA and components of the OASIS loss modelling framework4, the present work undertaken will inform not only the modeling community, but also industry and society at large towards better understanding of European winter storm risk.

3.3 Data Use

The risk modelling framework of WISC provided dataset on the hazard, the exposure and the vulnerability. This study will focus on the hazard information.

3.3.1 Hazard

The case study will use both the historic as well as the synthetic set of storm footprints as provided by WISC (Hamish Steptoe, 2017). The historic event set containing the footprints of 147 severe storms in the period 1940-2013. The storm events were selected due to their high damage caused or due to a high meteorological intensity (high vorticity). The wind gust footprints were created from ERA-Interim (Dee *et al.*, 2011) and ERA-20c (Poli *et al.*, 2016) Reanalysis. The synthetic event set containing more than 7’500 footprints of roughly 130 modelled years. The storms were created in the UPSCALE modelling framework and form a “physically realistic set of plausible events, representative of the period from 1985 to 2011.”

CLIMADA uses the storm event set as published in Schwierz *et al.* (2010), a paper that investigated the change of the winter storm damages in Europe in the light of climate change. The event set was created out of four different climate models and a probabilistic extension of each original event (see paper for details) and consists of 8’060 storms representing a time span of 600 years. This final event set was calibrated using the winter storm model of Swiss Re as it was operational in 2004.

The case study will further use Swiss Re proprietary hazard information, namely the historic events within their European winter storm catalogue. Swiss Re uses the NOAA 20th Century Reanalysis as a basis of their wind gust footprints (20th Century Reanalysis V2 data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at https://www.esrl.noaa.gov/psd/). From the time period 1873 to 2010, 771 selected storms were downscaled using information from RCMs (Regional Climate Models) creating raw wind gust footprints on an irregular grid. This method created a consistent dataset of extreme storms of the last 130 years.

For important historic events Swiss Re produced scenario footprints: The raw model footprints were enhanced with observed wind gust measurements from a large set of station data in Europe. The losses modelled with scenario footprints show a higher alignment with observed losses than modelled losses based on raw footprints because of reducing unavoidable uncertainty in the methods of reanalysis and downscaling.

3.3.2 Exposure

The WISC exposure dataset contains every building in Europe from the OpenStreetMap database (OpenStreetMap, 2021) with the categorization of Corine Land Cover (EEA, 2016) and country specific rebuilding costs of the PAGER database (Porter *et al.*, 2008).

The CLIMADA exposure dataset is created starting from a fixed value for the total sum of assets per country based on its GDP and a scale-up depending on the income group as assigned by the World Bank (http://data.worldbank.org/indicator/NY.GDP.MKTP.CD/countries).

This total value for all assets is distributed over the country using satellite nightlight intensity (https://earthobservatory.nasa.gov/Features/NightLights/page3.php) at a resolution of up to 1x1km (here interpolated to the WISC resolution of about 4.4x4.4km).

The focus of this study is the comparison of the WISC hazards with both industry and research data. For this setup, the exposure is kept constant and calculations are only undertaken using the CLIMADA exposure.

3.3.3 Vulnerability

WISC uses the vulnerability curves of different building types published by Feuerstein *et al.* (2011). The Corine Land Cover categorisation and the PAGER information about building types per country allow for an individual vulnerability curve per building and consequently specific vulnerability curves per country.

CLIMADA uses the vulnerability information of Schwierz *et al.* (2010), i.e. one general vulnerability curve for all building categories and all countries in Europe. For a constant experimental setup with focus on the hazard only the Schwierz *et al.* (2010) vulnerability information is used for the calculations in this study.

3.3.4 Damage data

The Emergency Events Database (Guha-Sapir Debarati, 2021) provides independent disaster data including damages of winter storms in Europe. Swiss Re and other players in the reinsurance industry, such as PERILS (PERILS AG, 2021) also publish damage data for severe events. This damage data can be used as a counterfactual to provide context for the WISC hazard, exposure and vulnerability information.

3.4 Experimental Design

Both the existing Swiss Re European winter storm catalogue as well as the open-source CLIMADA platform and its European winter storm damage model will serve as a starting point/counterfactual.

WISC data (namely storm footprints) were be converted into the specific database format as used by MultiSNAP and CLIMADA. Swiss Re provided hazard frequency information for the study, to allow a

comparison. Swiss Re also used its event/hazard set with CLIMADA vulnerabilities to produce loss frequency curves. The interface from WISC to CLIMADA is openly available via GitHub as part of CLIMADA's storm Europe module (https://github.com/davidnbresch/climada_module_storm_europe).
We test with a focus on the differences in the low- and high-frequency tail of the damage distribution both across Europe (pan-European view) as well as for select regions and/or countries. Please note that, since the damage models operate at resolutions similar to the WISC storm footprints (few km), results could theoretically be obtained at a much more granular resolution than aggregated by country.

3.4.1 Exploration of WISC historic and synthetic event set with Schwierz et al. (2010)

The WISC event sets are explored by examining their climatological features. The storm severity index (SSI, Hamish Steptoe, 2017) and the modelled damage is driven by the gust speed and the size of the affected area. The distributions of these two variables are compared in the historic and synthetic WISC event set. The information of the Schwierz et al. (2010) event set is used as a reference.

3.4.2 Comparison WISC historic event sets with Swiss Re historic event set

The event set used by Swiss Re is used as a representation of the industry state of the art damage and risk modelling. Some frequency information of the hazard set of Swiss Re is used to provide context for the WISC event sets. This context allows for a judgement on the area and range of application of the WISC event sets in the industry.

The WISC historic event set is used as a counterfactual to verify the improvement of the creation of scenario footprints by Swiss Re as described in section 3.3.1.

3.4.3 Comparison WISC exposure data and with CLIMADA's default exposure database

WISC is also providing an exposure dataset based on Open Street Map (OpenStreetMap, 2021), rebuilding cost by PAGER and vulnerability curves for four different building types per country. The WISC methodology is compared with the methodology used by CLIMADA.

3.4.4 Comparison of Damages

Finally, we will show a comparison of return periods of per occurrence event damages as well as annual damages.

3.5 Results and Discussion

3.5.1 Exploration of WISC historic event set and WISC synthetic event set

The Storm Severity Index (SSI) of the storm footprints in the WISC synthetic event set are much lower than the SSIs of the WISC historic events set (Figure 3). The historic event set only contains select severe events that produced high insurance damage or have a high intensity on a meteorological scale. Hence a higher mean SSI is expected for the historic event set compared to the synthetic event set. The difference in SSI distribution is mainly due to missing events with high SSI in the synthetic set. Even though the timeframe of the synthetic event set of 130 years is longer than the 70 years of the historic event set, it does not contain any storm with an SSI of 1.5*109 or higher. The historic event set contains a quarter of its storms in this range of SSI. As for comparison the CLIMADA event set created in the study of Schwierz *et al.* (2010) is shown. It shows a smaller mean SSI compared to the WISC historic event set, but contains a tail of few, severe storms with high SSI, as expected for an event set covering roughly 600 years.

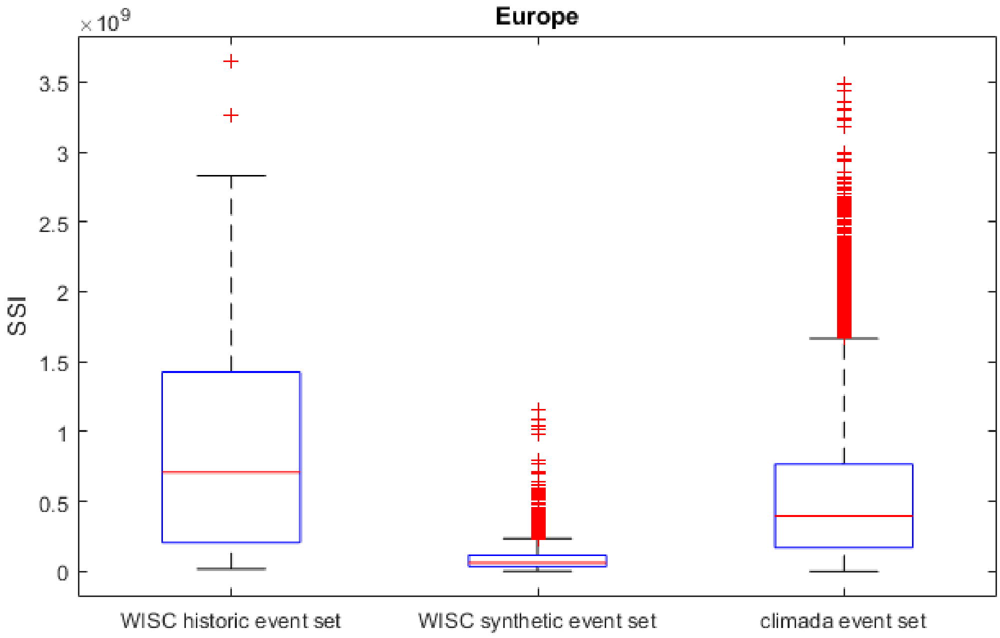


Figure 3 Distribution of Storm Severity Index (SSI) of the WISC historic (left) and synthetic (middle) event set as well as for the event set in Schwierz et al. (2010). See text for details.

The two factors controlling the SSI are the kinetic energy flux (the cube of the gust speed) and the affected area. In Figure 4 the distribution of these two factors are shown for the historic and synthetic WISC event set and for the reference CLIMADA event set. The difference in SSI can be attributed almost entirely on the difference in affected area. Compared to the historic event set and compared to the CLIMADA event set, the events of the WISC synthetic event set each affect a much smaller area.

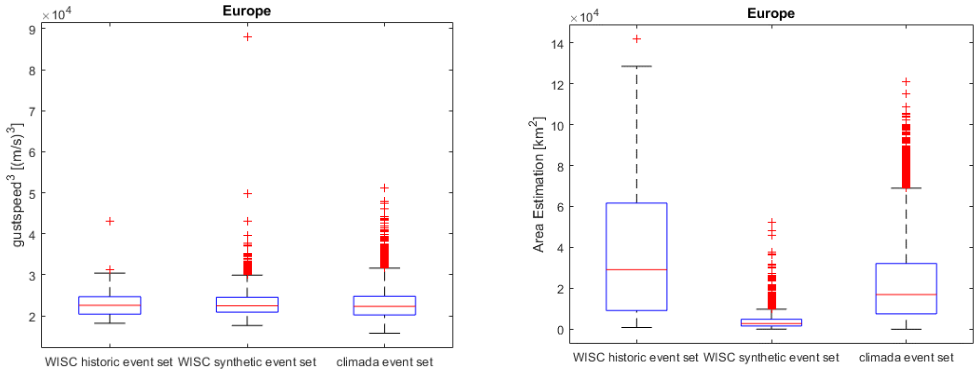


Figure 4 The cube of the gust speed and affected area estimation distributions for WISC historic and WISC synthetic event set and CLIMADA event set. The difference seen in the SSI between the different event sets is mirrored in the distributions of area affected, while the distributions of the cube of the gust speed are similar between all event sets.

3.5.2 Comparison WISC historic event set with Swiss Re historic event set

We compared the SSI of the WISC historic event set with the SSI of the Swiss Re historic event set. The different length of the covered time period (WISC: 70 years, Swiss Re: 130 years) and the different number of events (WISC: 147, Swiss Re: 771) make a comparison complicated. The median SSI of the Swiss Re historic event set is lower than the median SSI of the WISC historic event set. This is an expected result as the Swiss Re set contains more storms per year and thus also storms with lower severity (Figure 5). The most severe events of the WISC set have a higher SSI than the most severe events in the Swiss Re set. Looking at the components of the SSI in Figure 6, the WISC set can also have a bigger affected area compared to the biggest events in the Swiss Re set, while the cube of the mean gust speed seems to be higher for the Swiss Re events. There is further investigation needed to see if the vulnerability curves, fitted to the Swiss Re events severity, account for that difference in gust speed and if the difference in affected area also is reflected in the spread of modelled losses.

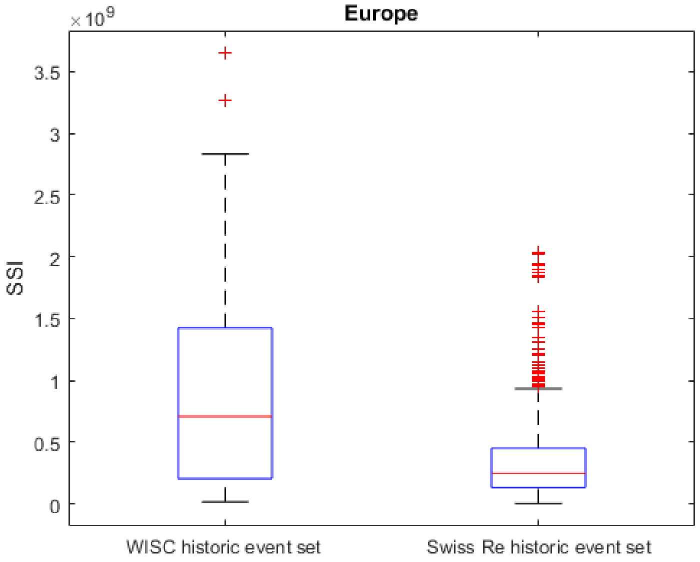


Figure 5 Storm Severity Index (SSI) of the WISC historic event set (147 events in 70 years, left) shows a similar distribution to the SSI of the Swiss Re historic event set (771 events in 130 years, right).

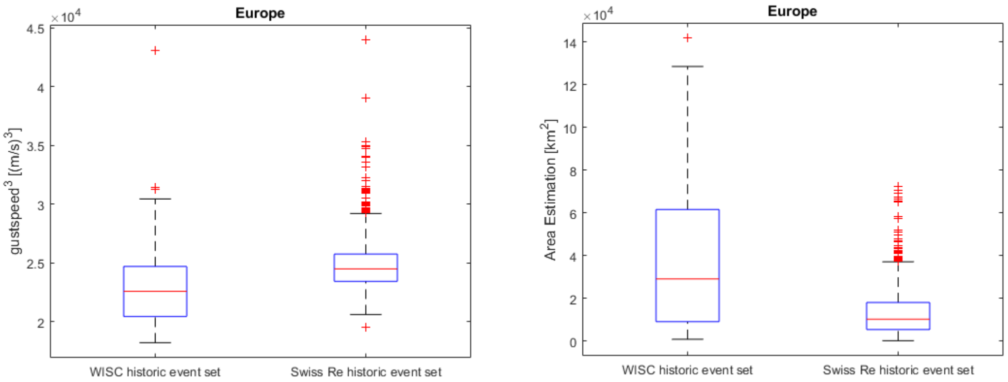


Figure 6 The cube of the gust speed and affected area estimation distributions for WISC historic event set and Swiss Re event set.

Additionally, the WISC dataset can be used to reconfirm the benefit of the enhancement of scenario footprints created by Swiss Re (see section 3.3.1). The SSIs of the Swiss Re scenario footprints aligns much better with SSIs of the WISC footprints than the Swiss Re raw footprints (Figure 1), confirming the benefit of the enhancement.

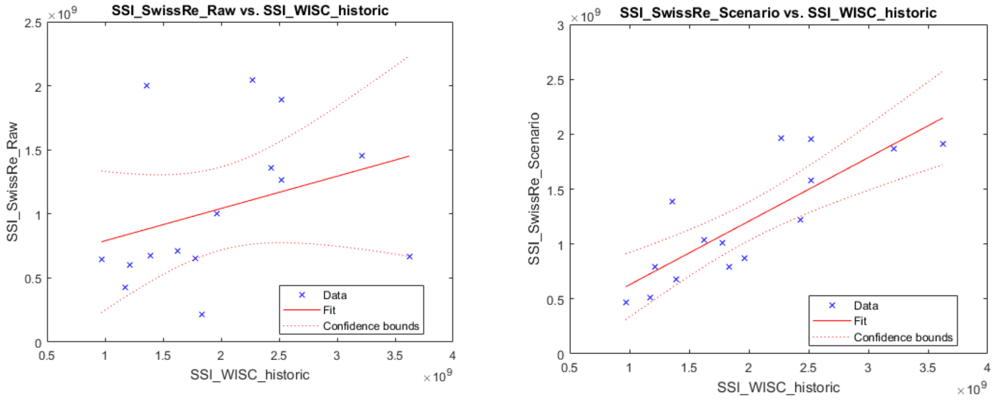


Figure 7 The SSI of events calculated with the Swiss Re footprint on the y-axis and the matching SSI calculated with the WISC footprint on the x-axis. For the left panel, the SSI of the event was calculated with the raw footprint, for the right panel with the enhanced scenario footprint.

All of the 15 compared scenario events happened after 1960 and eleven of them after 1980, in the time period of ERA-Interim. The WISC footprints are a good source to verify Swiss Re's NOAA 20th Century Reanalysis based footprints, which are originating from a consistent data source for all its 130 years, but a data source that has a lower resolution.

3.5.3 Comparison WISC exposure data with CLIMADA's default exposure database

As an illustration, the distribution of the WISC and CLIMADA exposure is shown in Figure 8. The WISC exposure has a flat distribution over Europe with a high concentration of exposure in the metropolitan areas like London, Paris or Berlin. The CLIMADA exposure spreads assets further out from city centers and does not show as harsh a difference between highly and lowly populated areas.

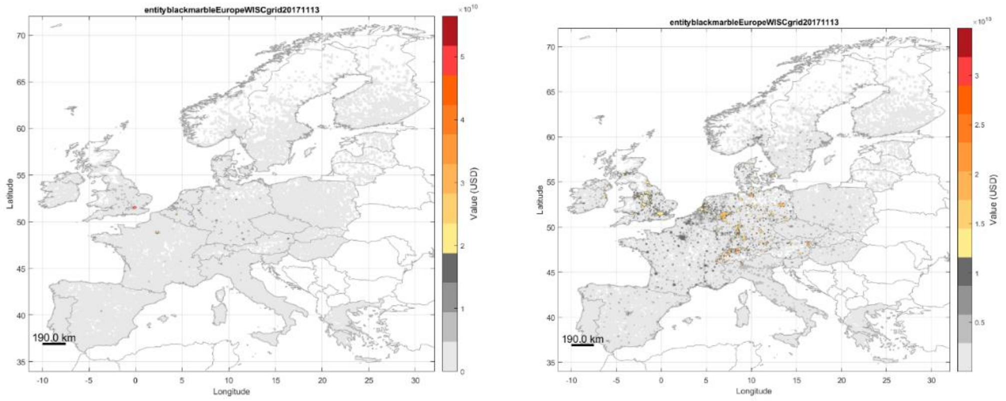
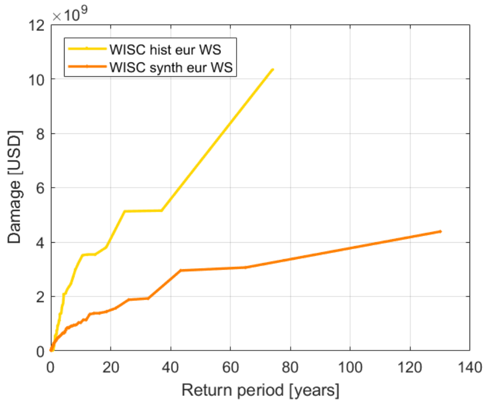


Figure 8 The exposure database of WISC containing rebuilding costs (left) and the CLIMADA exposure dataset, representing a proxy for asset values as of today (right).

3.5.4 Comparison of Damages

It is important to differentiate between the event damage and the annual aggregate damage when comparing the different event sets. Similar to the low SSI the WISC synthetic event set also produces low damage per event compared to the historic event set (Figure 9). When aggregating the events to an annual damage, the synthetic event set shows a higher average annual damage than the historic event set, driven by aggregating many small storms each year (Figure 10).



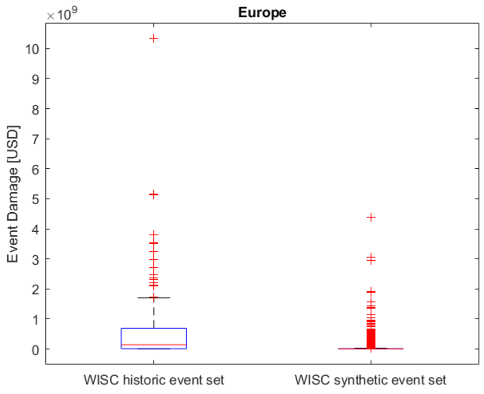


Figure 9 Event Damages of the WISC historic (yellow) and synthetic (orange) event set in Europe, calculated with the CLIMADA exposure dataset, shown as exceedance frequency curve (left). The same data shown as boxplot in the right panel.

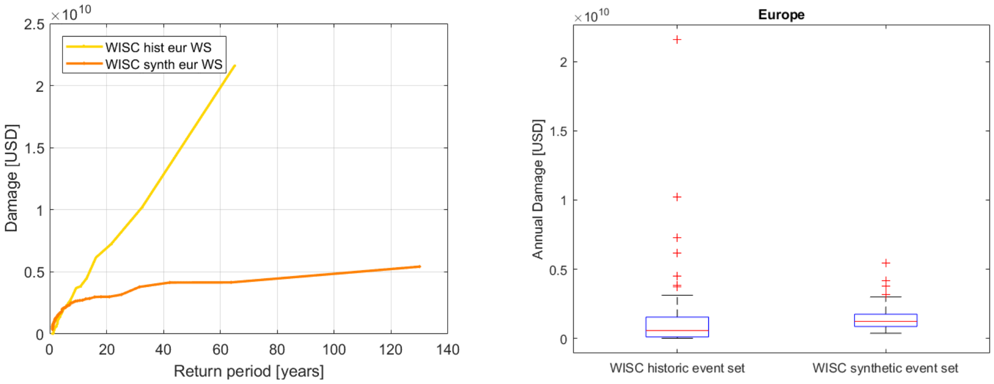


Figure 10 Annual Damages of the WISC historic and synthetic event set in Europe, calculated with the CLIMADA exposure dataset, shown as exceedance frequency curve (left) and same data shown as boxplot in the right panel.

The comparisons have so far been made on the European level, highlighting the consequence of the different spread of area affected in the two event sets. If a smaller region like the Netherlands is used as geographical extent, the smaller size of the events in the synthetic event set loses its relevance and the synthetic event set results in damages in a similar range as the historic event set. Figure 11 shows the annual damage of the two events sets for the exposure of the Netherlands and the correspondent exceedance frequency curves are looking similar. In the distribution of the event damages of each event set in Figure 12 it is shown that on the scale of the Netherlands the reason for the similar annual expected damage is not only the higher number of storms but also a similar distribution of event damages.

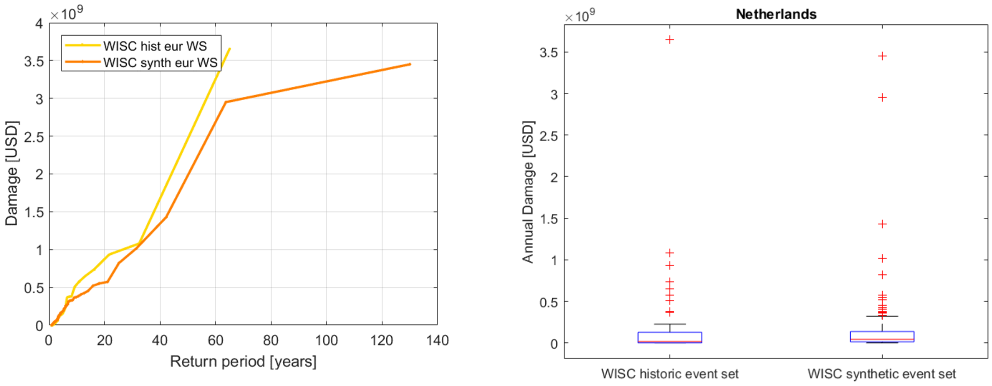


Figure 11 Annual Damages of the WISC historic and synthetic event set in the Netherlands, calculated with the CLIMADA exposure dataset, shown as Exceedance frequency curve (left) and the same data shown as boxplot (right).

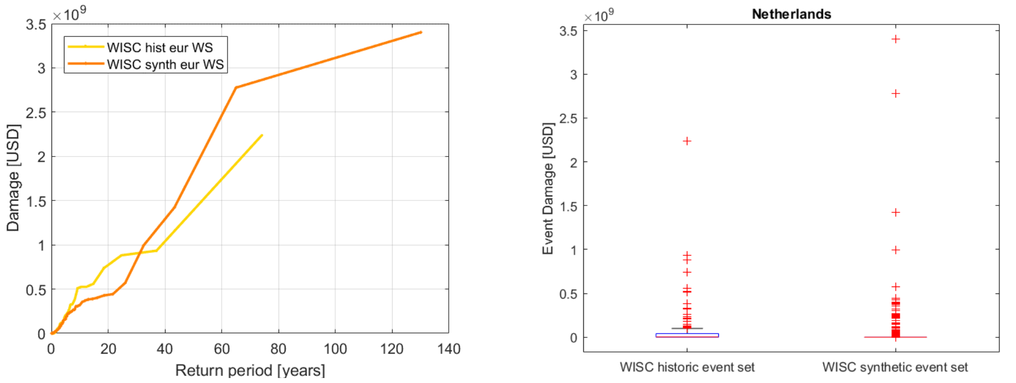


Figure 12 Event Damages of the WISC historic and synthetic event set in the Netherlands, calculated with the CLIMADA exposure dataset, shown as Exceedance frequency curve (left) and the same data shown as boxplot (right).

3.6 Conclusion

The WISC historic and synthetic events sets are both suitable to calculate winter storm damage in Europe. For calculating the damage of high impact events and especially for geographically large portfolios the WISC historic event set provides reliable hazard intensities. The WISC synthetic event set can be used to assess the risk for frequent events and aggregated annual damage. Based on the lower severity in the synthetic event set, we caution its use for rare events.

The WISC historic event set can be used to carry out sanity checks and verifications of the data, methods and decisions used in the hazard part of European winter storm models operational in the insurance industry, as shown in section 3.4.2 and 3.5.2.

3.7 Feedback and comments

The hazard footprints as provided by WISC form an independent set of data to cross-validate and further develop existing European winter storm models. For a comprehensive risk view, including rare high impact events as well as frequent events driving the annual aggregate damages, the risk results of both WISC historic and synthetic event set could be combined qualitatively. In order to quantitatively combine, one might consider to manually adjust the frequency or the severity of single events in the synthetic set to generate a combined event set containing both rare high impact events (mainly from the historic set) as well as sufficient number of frequent events (from the synthetic set).

Further research is still needed to better understand ‘real extremes’, i.e. very rare extreme European winter storms as well as to establish a comprehensive pan-European synthetic hazard event set fit for a variety of applications. Further development might focus also on dependent perils, such as associated (extreme) rainfall and storm surge, not least in the light of the discussion around compound events.

The authors would like to thank the WISC consortium and project team for making all the data and documentation fully open-access and deem the documentation key to enable and support further and wide use. In the same spirit, all data and methods as used in the probabilistic modeling platform CLIMADA and its European winter storm module are publicly available with no restrictions.

4 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 Welker[1], Thomas Röösli[2,3], and David N. Bresch[2,3]

Published in Natural Hazards and Earth System Sciences, 21, 279–299, 2021
DOI: https://doi.org/10.5194/nhess-21-279-2021

With access to claims, insurers have a long tradition of being knowledge leaders on damages caused by 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: an 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 assessment of rare events, such as a 250-year-return-period windstorm causing CHF 75 million in damages, including an evaluation of the uncertainties. Our study emphasizes 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] 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

4.1 Introduction

Severe windstorms are responsible for widespread socioeconomic 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 damage due to windstorms amount to 30% of the total amount of building damage from natural hazards in this region. For comparison, damage due to hailstorms and flooding amount to 41% and 28 %, respectively (all numbers from 2018; GVZ, 2018; 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 damage 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 CHF 500 billion (Swiss Francs) (in 2018). GVZ is an independent institution of the canton of Zurich under public law (GVZ, 2021).

Windstorm damage events in the canton of Zurich have been recorded in GVZ’s database since 1981. For example, the 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 the 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 was due to a very local, but extremely intense convective storm on 2 August 2017 with measured maximum gusts of more than 180 km h^{-1} 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 have been 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 provide 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 & 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 (Westcott *et al.*, 2020). However, only very few impact models are available as open source with free access for users in both the scientific and 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, 2019), whereas maximum wind gust speeds are frequently used as the hazard component to assess windstorm risk (e.g. Klawa & 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; Prahl *et al.*, 2015; Koks & Haer, 2020). 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.*, 2020), based on the gross domestic product (GDP; Geiger *et al.*, 2018), or on building data from OpenStreetMap (Koks & Haer, 2020). The sparse availability is why in some research studies loss ratios were used instead of information on exposure (Donat *et al.*, 2011b).

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 & Bresch, 2019). 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.*, 2017; Walz & 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 is 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 it provides the corresponding wind gust footprints at improved spatial resolution and covers more windstorms over a period longer than the 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, Röösli *et al.* (2018) found that the synthetic hazard event set is not suitable for this purpose. Therefore, we instead propose 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 4300 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 assessments. 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. 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.

4.2 Data and methods

After a description of the insurance claims data (Sect. 4.2.1) and the windstorm hazard event sets used (Sect. 4.2.2), we introduce the GVZ and the CLIMADA risk assessment models applied for damage modelling (Sect. 4.2.3) and conclude this section with a brief recapitulation of the risk assessment metrics employed in this study (Sect. 4.2.4).

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. "Historic windstorm hazard event set" in 4.2.2). In total, 18 events are associated with WISC windstorms based on that definition (see also Table 2). 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 normalized to present-day exposure levels. In this study, the applied normalization considers the general inflation on the basis of the Zurich construction price index (City of Zurich, 2020). Hereinafter, both insured and modelled windstorm damages are including occasional deductibles – so called "gross damages" – to ease comparison.

4.2.2 Windstorm hazard event sets

Atmospheric models provide information about winter windstorm events that can be used as a 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. "Historic windstorm hazard event set") and constructed a probabilistic extension based on it (Sect. “Probabilistic windstorm hazard extension”). In addition, we derived wind gust footprints from measurements for a selection of present windstorm events (Sect. “Observed footprints for current windstorms”). The additional windstorm hazard event sets published by WISC, that are however not considered in this study, are briefly summarized in Sect. “Other WISC hazard event sets”.

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 s gusts, with maxima determined for a 72 h time window. This relatively long time window was chosen, because it is widely used in the insurance sector (Maisey *et al.*, 2017). However, it also implies that the footprints of directly successive events (i.e. with a time difference of less than 72 h) 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 do not often represent the exact time and 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 2). 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, 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.

Table 2 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”)

Other WISC hazard event sets

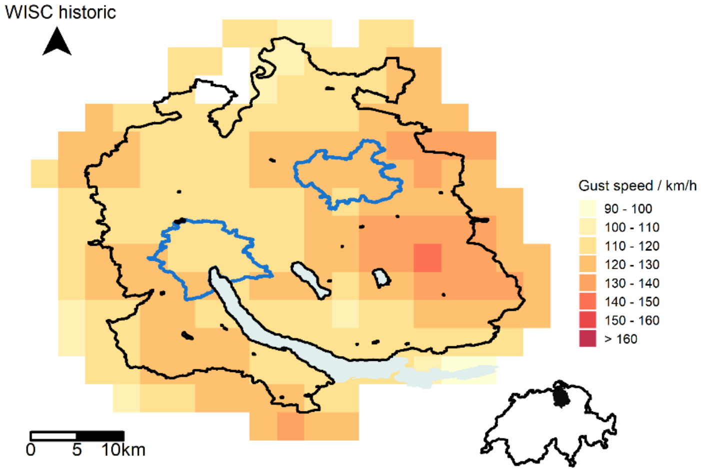
There are two additional windstorm hazard event sets published by WISC that are however not analysed in detail in this study.

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 & 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

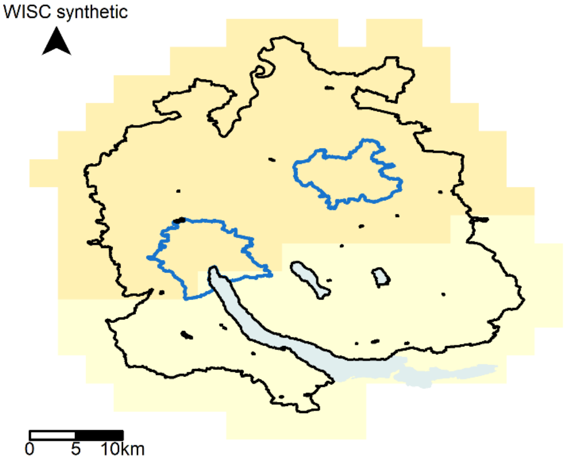
in the period 1985–2011 based on the climatic conditions of that period. The modelling framework developed five ensembles. The dataset contains wind gust footprints for around 23 000 synthetic windstorms: i.e. three sets of 7660 events each. Each of the three sets covers 135 modelled years. The original 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 (Röösli *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 (Figure 25) nor the high intensities we would expect from very rare, high-impact windstorm events (Figure 13).

For a detailed description of all unused windstorm hazard event sets provided by WISC, we refer to the documentations available online at WISC products (WISC, 2019) and WISC hazard event set description (Hamish Steptoe, 2017).

(a)



(b)



(c)

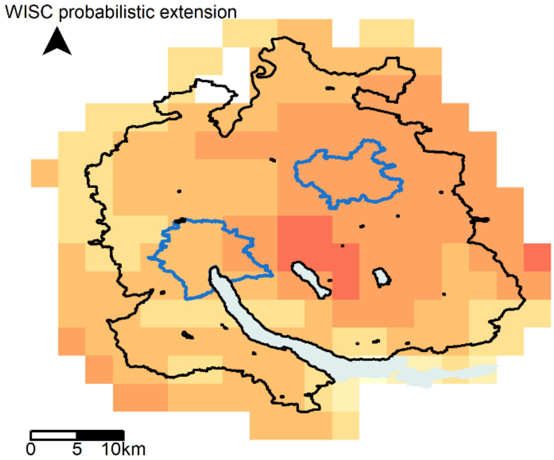


Figure 13 Maximum wind gusts for every grid cell in the canton of Zurich (i.e., windstorm footprints) for the most damaging events in (a) “WISC historic”, (b) “WISC synthetic”, and (c) “WISC probabilistic extension”. The urban areas of the two main cities Zurich (left) and Winterthur (right) are marked in blue.

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 or 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 3ms^{-1} (normally much less) according to the probabilistic alteration of wind speeds in Eq. (8), with a scale parameter α = 0.0225 and a power parameter β = 1.15 (choice explained further below):

$$\begin{aligned}
windspeed_{scenario\,1} &= windspeed_{original} + \alpha * windspeed_{original}{}^{\beta}\\
windspeed_{scenario\,2} &= windspeed_{original} - \alpha * windspeed_{original}{}^{\beta}\\
windspeed_{scenario\,3} &= windspeed_{original} + \alpha * \sqrt[\beta]{windspeed_{original}}\\
windspeed_{scenario\,4} &= windspeed_{original} - \alpha * \sqrt[\beta]{windspeed_{original}}\\
windspeed_{scenario\,5} &= windspeed_{original} - \frac{\alpha}{2} * windspeed_{original}{}^{\beta} - \frac{\alpha}{2} * \sqrt[\beta]{windspeed_{original}}
\end{aligned} \tag{8}$$

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; formula used by Dawkins *et al.*, 2016; further information in Lamb & Frydendahl, 1991; Leckebusch *et al.*, 2008). Similar to 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 and in Eq. (8)) 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 minimizes the difference in the cumulative distribution functions for events that have a return period of>75 years.

WISC probabilistic extension includes footprints for 4118 probabilistic windstorm events, along with the 142 original windstorm events in WISC historic (Table 2), 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 the case of WISC historic).

Encouragingly, the hazard event set WISC probabilistic extension shows considerably higher wind gust speeds in the canton of Zurich compared with WISC synthetic (Figure 13). 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.

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. 4.2.3). 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, 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.

4.2.3 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.”GVZ damage model”). 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. “CLIMADA impact model”).

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 & Bresch (2019). In this study, the windstorm hazard assessment is based on the winter windstorm footprints described in Sect. 4.2.2. 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, or business interruption.

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 an 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 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^{-1}, and only buildings affected by such gusts were considered in the following modelling steps.

Figure 26 shows the spatial distribution of all insured buildings in the canton of Zurich as well as of the total sum insured at the 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, 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 & Bresch, 2019).

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 categorized 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 1000 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.

CLIMADA impact model

The windstorm damage model in the open-source risk assessment platform CLIMADA relies on open data only, and that is why it deviates 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 the 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.*, 2020). The resulting values are then distributed to building footprints from OpenStreetMap (OpenStreetMap, 2021). 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 minimizing 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^{-1} ($20ms^{-1}$) and above and in the GVZ damage model for 90 km h^{-1} ($25ms^{-1}$) and above.

4.2.4 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 the 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.

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:

$$AAD = \frac{sum\ of\ all\ event\ damages}{time\ range\ covered\ by\ event\ set} = \sum_{event\ i} event\ damage_i * annual\ frequeny_i \tag{9}$$

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 sampling uncertainty.

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, 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 parameterized 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 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 sampling 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 the 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 "Probabilistic windstorm hazard extension" in Sect. 4.2.2) transforms part of the sampling uncertainty of the hazard event set WISC historic into an uncertainty of the parameters α and β in Eq. (8). 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 the case of the other damage event sets. Thus, for the purpose of comparing the uncertainties of the different damage event sets, we suggest using the sampling uncertainty of WISC historic as the best illustration of the uncertainty of WISC probabilistic extension.

However, for certain applications in the insurance industry the tail view of WISC probabilistic extension is an important feature of the dataset. The sampling uncertainty of WISC historic is too large to provide, for instance, a comparison criterion between two different exceedance frequency curves from different models. Therefore, we propose illustrating the probabilistic content of WISC probabilistic extension by using bootstrapping of all probabilistic damage events. In this way, a "probabilistic envelope" around the best-guess exceedance frequency curve can be determined (see also Sect. 2.4.2). This way of illustration shows how the problem could be addressed in practice, knowing well that it does not illustrate the full uncertainty. In contrast to the sampling uncertainty, the probabilistic envelope could represent something like the "represented uncertainty". In the approach applied, we firstly bootstrapped (random sampling with replacement, number of samples is 100) the historic damage events and then used these samples to create an ensemble of probabilistic damage event sets. Secondly, for each new probabilistic damage event set, we randomly bootstrapped (number of samples is 20) the equivalent of 500 years of windstorm events and built an exceedance frequency curve for each sample. From this set of double-bootstrapped damage event sets (total number of samples is 2000), we then calculated the span between the 5th percentile and the 95th percentile for each exceedance frequency to illustrate the envelope of the probabilistic content.

4.3 Results

4.3.1 Single events

The damage due to Lothar–Martin is by far the largest windstorm event damage in GVZ’s insurance claims database (Figure 27a): 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-year period of insurance claims data and the 75-year 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 (Figure 27b). 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 (“Observed footprints for current windstorms” in Sect. 4.2.2) is suitable for present and probably also for future windstorm events.

4.3.2 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 3). 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 (Figure 27a), (ii) the higher damages of events in the 5-year-return- period range (Table 3), 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.

Table 3 Annual average damage (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 GVZ damage 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)	1.4	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	-

4.3.3 Assessment of risks due to extreme windstorm events

Figure 14 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 sampling uncertainty of the estimate for the return period of Lothar–Martin based on WISC historic (yellow ribbon, 25 to > 500 years) incorporates both the estimate for the insurance claims data (blue ribbon) and 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 Figure 14). Contrary to this, the 250-year-event damage amounts to only about CHF 75 million in the 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 33 billion (yellow ribbon). As WISC probabilistic extension is based on the same historic information, this sampling 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 and the estimate based on WISC probabilistic extension.

An interesting feature illustrated in Figure 14 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. Evident “jumps” in the modelled damage (e.g. at return periods of approximately 30, 70, and 90 years) result from the discrete categorization of the individual windstorm events and the assumed degrees of impact as applied in GVZ’s damage modelling approach (“GVZ damage model” in Sect. 4.2.3).

The red ribbon in Figure 14 shows a possibility of illustrating the probabilistic envelope for the modelled damages based on WISC probabilistic extension and the GVZ damage model, according to a bootstrapping approach as described in Sect. 2.4.3. As expected, the probabilistic envelope for WISC probabilistic extension is much smaller than the range of sampling uncertainty for WISC historic (yellow ribbon).

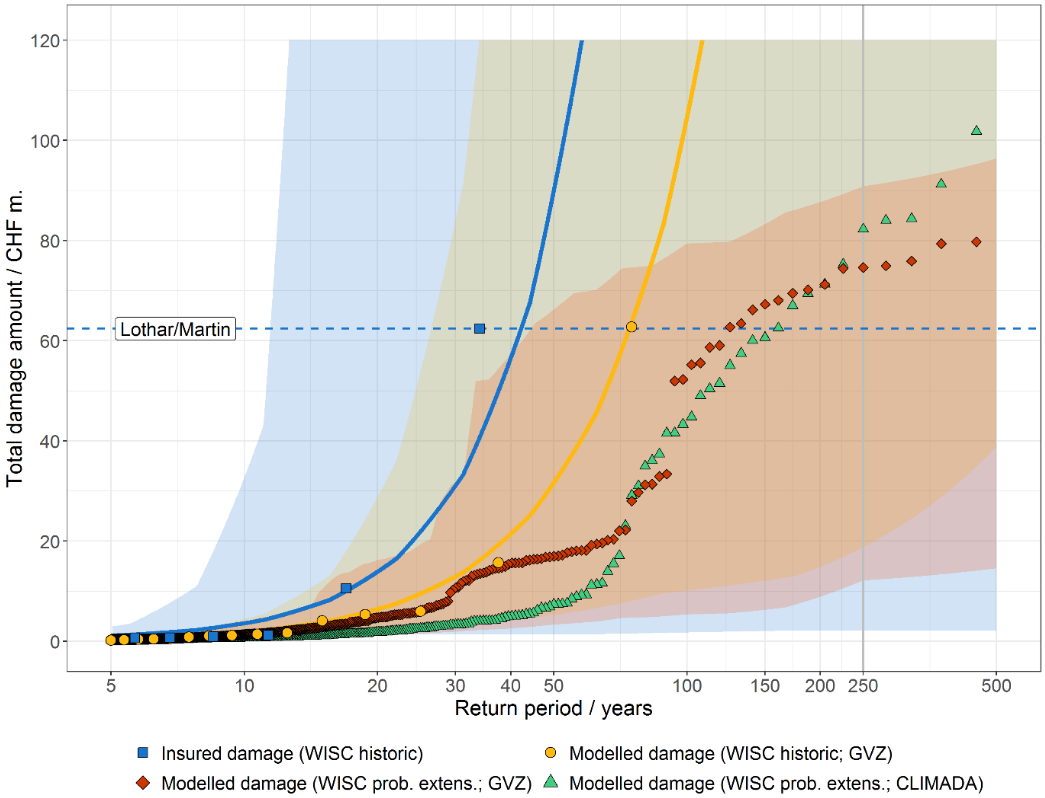


Figure 14 Exceedance frequency curves for building damages in the canton of Zurich based on different data sources. The blue squares indicate the insured damages according to GVZ's database (excluding the additional windstorms in 2017 and 2018), the blue solid line represents a GPD fitted to the insured 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 red ribbon shows the probabilistic envelope for the modelled damages based on "WISC probabilistic extension" and the GVZ damage model computed by applying a bootstrapping approach as described in Sect. 2.4.3. 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.

4.3.4 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 Figure 15 and Figure 27, and Sect. 4.3.1). 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 3 calculated using the GVZ damage model were also calculated using the CLIMADA impact model and the results can be found in Table 5. In summary, it can be stated that the setup of the two damage models applied works well and replicates the order of the events, provides a reasonable modelled damage for historic events (compared to insurance claims data), and both RMSDs are sufficiently good.

The exceedance frequency curve of the modelled damages based on WISC probabilistic extension and the CLIMADA impact model (green triangles in Figure 14) 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 Figure 15, where in Figure 15a 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 the 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 5) 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 the case of CLIMADA (Figure 14), 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.

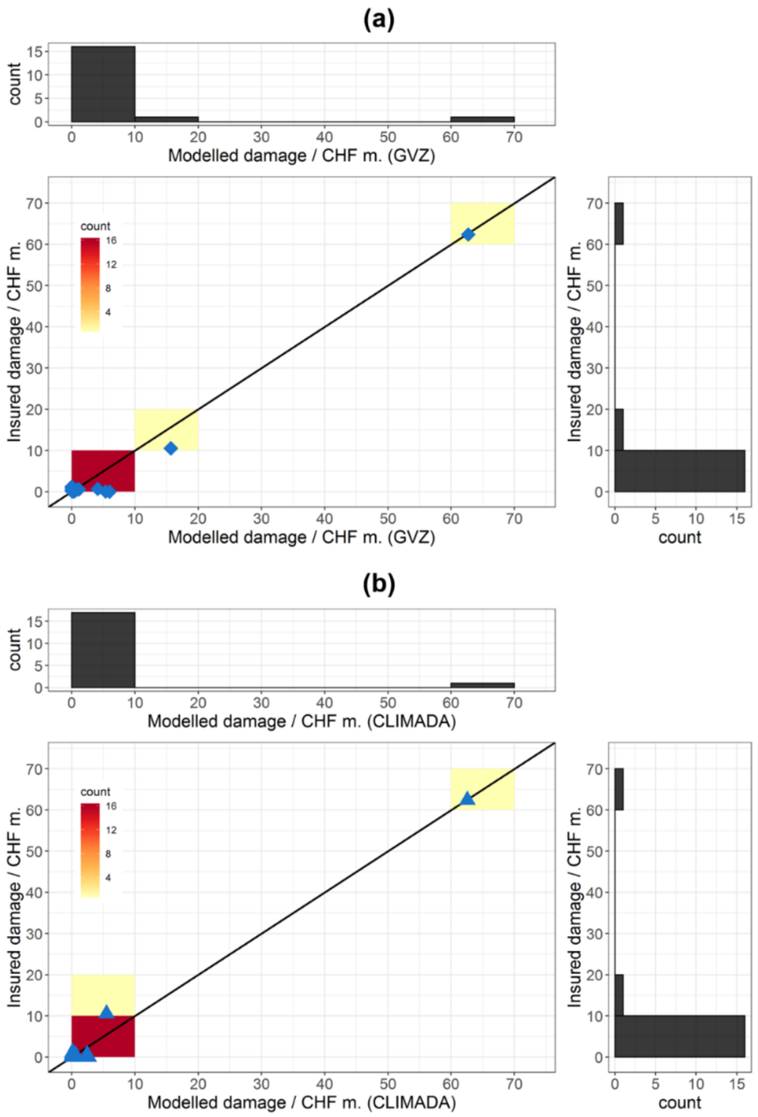


Figure 15 2d-histograms for the normalised insured total damages in the canton of Zurich versus the modelled total damages based on (a) the GVZ damage model (diamonds) and (b) the CLIMADA impact model (triangles), respectively, for all windstorms with damage > 0 in the hazard event set "WISC historic". Marginal histograms are shown in the top and right panels.

4.3.5 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 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 ("Observed footprints for current windstorms" in Sect. 4.2.2). The 95th percentile of the wind gust speeds at building level in the affected region of the canton of Zurich, which is also used in GVZ's damage model to categorize windstorm events (“GVZ damage model” in Sect. 4.2.3), is used as a rapid indicator of the range of possible damages. This process is illustrated in Figure 16. 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 visualized 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 (Figure 13). Thus, this windstorm is potentially about 1.5 times as damaging as Lothar–Martin.

Figure 16 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 (“GVZ damage model” in Sect. 4.2.3). 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^{-1}) again result from the discrete categorization 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 Figure 16) generally increases with increasing wind gust speed. Accordingly, the number of available wind gust footprints decreases with increasing wind gust speed.

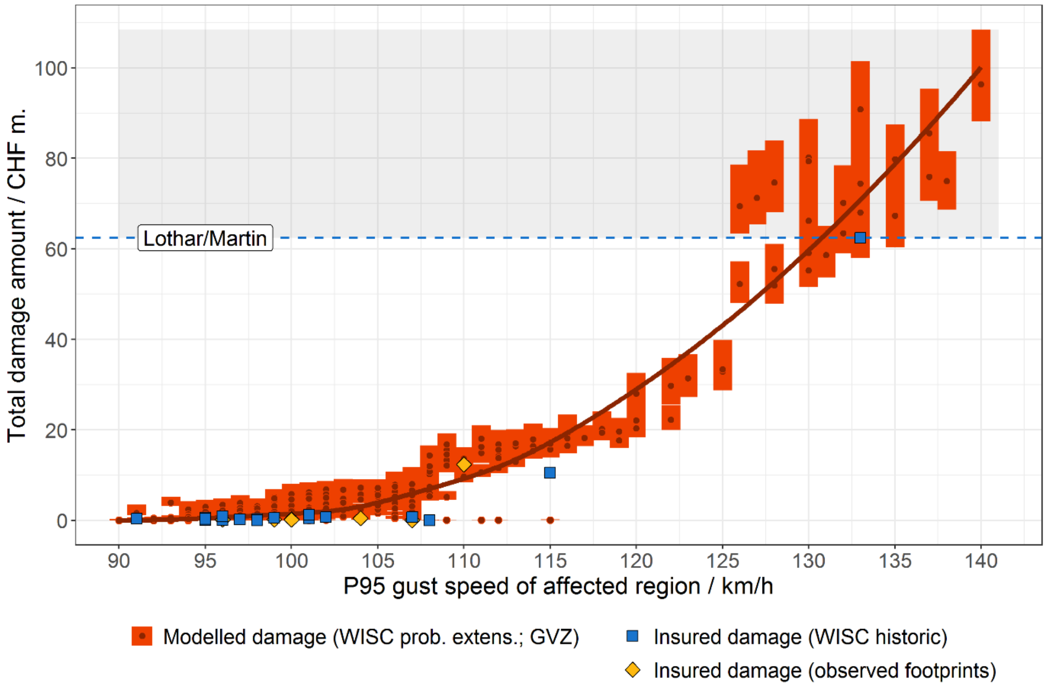


Figure 16 Total damage modelled using the GVZ damage model and the hazard event set “WISC probabilistic extension” versus the 95th percentile of the corresponding gust speeds in the affected region of the canton of Zurich (median of 1’000 random damage modelling as red points; range of modelled damages indicated as red bars). The 95th percentile of the gust speeds is shown, because the 95th percentile is used in GVZ’s damage model to categorise windstorm events (Sect. 2.3.1). The relationship between wind gust speed and modelled total damage is further approximated by a locally estimated scatterplot smoothing (LOESS) and a bootstrap method (i.e., random resampling with replacement, number of samples = 1’000; median of confidence interval given as solid red line). Furthermore, the relationship between gust speeds and normalised insured total damages based on “WISC historic” and independent, interpolated wind gust observations (selection of windstorms in 2017 and 2018, including winter windstorm Burglind) are given as blue squares and yellow diamonds, respectively. The domain for unprecedented windstorm damages − i.e. beyond Lothar-Martin − is shaded grey.

4.4 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 this 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 aware of the fact 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 anan 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 damages associated with Lothar and Martin amount to approximately EUR 5.8 billion and 2.5 billion, respectively (PERILS AG, 2021). 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 of Anatol (3 December 1999), Lothar, and Martin was estimated to be between 22 and 45 years (Zimmerli & Renggli, 2015). 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 damages for building damage 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 damages from all natural hazards of CHF 16 million and additionally yearly damages by fire of CHF 42 million (all numbers from 2018; GVZ, 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 sampling uncertainty (shown as confidence intervals in Figure 14). 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 cannot however considerably be reduced compared to WISC historic, because it relies on the same historic information. The fact that the probabilistic envelope for the modelled damages based on WISC probabilistic extension (red ribbon in Figure 14) does not cover the full range of the sampling uncertainty for the modelled damages based on WISC historic (yellow ribbon) shows two things: on the one hand, it shows the tail view, which is possible with the help of WISC probabilistic extension for certain applications in the insurance industry for instance; on the other hand, it reveals the limitations of the statistical perturbation, which is used in the generation of WISC probabilistic extension, to fully represent the sampling uncertainty of the underlying historic data. Despite this mismatch, it can nevertheless be important to study the sensitivity of the 250-year-returnperiod 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. In future studies, the information from dynamical models, which are run for many model years, would help to further reduce the sampling uncertainty compared to this study.

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 & Haer, 2020), 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 & Ruck, 2008; 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 vulnerability assumed in this study and the corresponding hazard intensity only consider 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 & 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 mountaintops).

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 Figure 16). The assumed degree of impact was derived according to the respective severity category of the windstorm. This severity categorization 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 smooth damage modelling (Figure 14). 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 Figure 16 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 the middle of the 1980s (Figure 27d). 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 ERAInterim 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 & 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).

4.5 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 of the sensitivity of the risk to 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 & Aznar-Siguan, 2019). 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; Westcott *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.

5 Impact forecasting of building damage from winter windstorms in Switzerland

Thomas Röösli[1,2], Christof Appenzeller[2] and David N. Bresch[1,2]

Revised version published as: "Towards operational impact forecasting of building damage from winter windstorms in Switzerland" in Meteorological Applications 28:e2035.
DOI: https://doi.org/10.1002/met.2035

5.1 Abstract

National meteorological and hydrological services issue warnings for severe weather events, typically based on stakeholder agreed fixed thresholds of meteorological parameters such as wind speeds or precipitation amounts. Yet societal decisions on preventive actions depend on the expected impacts of the weather event. In order to better inform such preventive actions, meteorological services are currently working towards including expected impacts into their warnings. We developed an open-source impact forecasting system for building damage due to windstorms in Switzerland. It combines a numerical ensemble weather prediction model with exposure and vulnerability data. This system forecasts expected building damage in Swiss Francs with two days lead time on a 500 m grid or aggregated to administrative regions. We compare the forecasted building damage with insurance claims in the Canton of Zurich. For the majority of days with severe winter windstorm damage the forecasted damage was in the right order of magnitude, with one missed event and one false alarm. For thunderstorms and foehn storms, the rate of missed events and false alarms is much higher, most likely related to the limited meteorological forecast skill. Such impact forecasts can inform decision-makers on preventive actions, such as allocating emergency response and other assets. Additionally, impact forecasts could also help communicating the severity of the upcoming event to the general public as well as indirectly help meteorological forecasters with taking warning decisions.

---

[1] Institute for Environmental Decisions, ETH Zurich, Zurich, Switzerland
[2] Federal Office of Meteorology and Climatology MeteoSwiss, Zurich, Switzerland

Keywords: Numerical weather prediction, impact modeling, impact-based warning, impact forecast, building damage

5.2 Introduction

Weather extremes cause disasters worldwide, with over 2 million deaths and over 3 trillion US$ economic damage associated with weather, climate and water related hazards in the last 50 years (WMO, 2020). With ongoing Climate Change and socio-economic developments a further increase of such impacts is expected (Bouwer, 2019).

Some of the negative impacts of weather extremes could be prevented since many weather extremes were correctly forecasted, but preventive measures were not taken (WMO, 2015a). For most National Hydrological or Meteorological Services (NHMS) warnings from such hazards are part of their mission (WMO, 2015a). NHMS use their available observations and numerical weather prediction models to forecast the weather hazard. The warnings are issued when the predicted hazard intensity, such as temperature extremes, wind gusts, rain or flood height, reaches a certain predefined, users agreed threshold or have a rare frequency of occurrence based on historic records. However the understanding and effectiveness of such threshold based warnings is often limited. Ideally the communication should include the impacts of approaching weather extremes to trigger more preventive measures (WMO, 2015a).

Impact information focuses on the consequences of the weather rather than the weather itself, by communicating the risk of an impact. For this purpose, it is important to incorporate the exposure as well as vulnerability in addition to the hazard, to arrive at the well-established formulation for risk of impact (IPCC, 2012; WMO, 2015a; Aznar-Siguan & Bresch, 2019). Exposure represents the population, or a socio-economic resource, or asset that could be affected by the hazard; vulnerability the susceptibility of the specific exposure to be affected by the hazard (WMO, 2015a). This risk of an impact communicates useful and directly actionable information to the recipient.

The impact information can be integrated into a warning system with a varying degree. The World Meteorological Organization (2015) differentiates between three paradigms. In the first paradigm, so-called hazard warnings (HbW), only the hazard information and no impact information are considered as described as weather warnings above. In the second paradigm, named impact based warnings (IbW), the vulnerability information is used in addition to the hazard to formulate potential impacts. In the third paradigm, the risk of impact is assessed using both vulnerability and exposure information arriving at impact forecasts (IFc) and impact warnings (IW). In this study, we focus on the third, most comprehensive, paradigm.

It is useful to differentiate impact forecasts and warnings in two additional dimensions. Firstly, the formulation of the risk of impact can be qualitative descriptions, quantitative calculations or a combination thereof. Secondly, the recipient of the information could be both the general public and individual decision-makers. These two dimensions mostly align in the current activities of NHMS. One direction is focused on providing qualitative impact warnings to the general public, whereas another is focused on providing quantitative impact forecasts as targeted decision support to individual stakeholders (Uccellini & Ten Hoeve, 2019).

Qualitative impact warnings issued for the general public are often communicated as levels on a three to five step color scale. An example is the UK Met office warning system that differentiates three warning levels and that considers qualitative impact descriptions both in the warning definition and the communication of the warning (Neal *et al.*, 2014; Lattimore, 2019). The benefits of communicating such combinations of warning levels and impact information have been assessed in survey-based studies: Weyrich *et al.* (2018) studied the perception and understanding of such warnings using hypothetical events. They found that both impact information and behavioral recommendations better communicated the warning content compared to meteorological information. Additionally, Weyrich *et al.* (2018) stress the point that for the best perception of the weather situation the communication of behavioral recommendation as well as a description of the impact was needed. In a recent real-time study involving actual weather events, these findings were put into question, but during the study period no “very severe” weather event took place and the explanatory power is thus limited (Weyrich *et al.*, 2020).

The focus of this paper is quantitative impact forecasting, which directly models socio-economic impacts with an individual stakeholder focus. Using specific and localized exposure data, the impact forecasts and warnings are issued in the metric commonly used and best understood by the stakeholder. Uccellini and Ten Hoeve (2019) propose a closer collaboration between NHMS, that have the knowledge about weather forecasts, and core partners, that decide on preventive measures. Merz *et al.* (2020) summarized the current state-of-the-art in impact forecasting for disaster risk management. He concludes that the impact forecasting provides “richer information to manage crisis situations”. With collaborations between different hazard disciplines and research-user interactions, impact forecasting can have additional benefits in a changing system, where extreme weather events are expected to change as do exposure and vulnerability due to a rapidly changing society (Merz *et al.*, 2020).

The framework of modelling risk as a combination of exposure, vulnerability and hazard is widely used in the insurance industry and in climate change risk assessments (Schwierz *et al.*, 2010; IPCC, 2012; Aznar-Siguan & Bresch, 2019). The movement to include such a framework for the production of impact forecasts and warnings can profit from these other efforts by exchanging methods and experience. Most of such natural catastrophe risk models are proprietary, but a selection of open-source or free tools are available (among others: Aznar-Siguan and Bresch, 2019; Oasis, 2018).

Most NHMS in Europe plan to incorporate impact information into their warning systems. The practical side of implementing IbW was studied in 32 European NHMS, where the NHMS self-assessed their views and their status with regards to IbW (Kaltenberger *et al.*, 2020). Most NHMS plan to transition towards IbW over the next 5 years. A bit less than half plan to use impact forecasting for individual users according to Kaltenberger *et al.* (2020). However, challenges remain on the practical side, which need to be resolved for a successful implementation. Two thirds of the NHMS think they lack the IT infrastructure to produce impact forecasting. Almost two thirds of the NHMS do not systematically collect impact data and also do not collaborate with partners to do so, but some collect field surveys after disasters (Kaltenberger *et al.*, 2020). Additionally, there might be legal obstacles: although three quarters of the NHMS report not being legally prevented from venturing into impact warnings, a third sees the responsibility for informing about impacts with another authority and 17% of NHMS face some sort of legal preventions.

Collaboration with partners is an important part of issuing IbW or IFc and IW. NHMS need to start a dialog with the recipients about better communication, but also about decision-making in a warning situation and about sharing of impact data for a verification of the warnings (WMO, 2015a; Uccellini & Ten Hoeve, 2019). Additionally, the collaboration and due coordination with other warning providers is important (Weyrich *et al.*, 2019). The recipients of warnings prefer to consult one platform to be informed not only about meteorological but all natural, socio-natural and anthropogenic hazards (Dallo *et al.*, 2020). An example of such a collaboration between all relevant providers of warnings is the Natural Hazard Partnership UK (Hemingway & Gunawan, 2018) or the Steering Committee on Intervention in Natural Hazards in Switzerland (Federal Office for the Environment Switzerland, 2020). Such collaborations are described as transdisciplinary research (Pohl *et al.*, 2017). It is important to plan sufficient resources to maintain the collaboration throughout the project (Fischer *et al.*, in preparation).

In this paper, we focus on the quantitative IFc of one particular hazard type: winter windstorms (Section 5.2.1). We study building damages as an example of socio-economic impact (see Section 5.2.2).

5.2.1 Impact modelling and impact forecasting of winter windstorms

Impact models for storm damages are successfully applied for risk assessments (e.g., Koks & Haer., 2020; Welker *et al.*, 2021), climate change risk (e.g., Schwierz *et al.*, 2010; Donat *et al.*, 2011) and single event case studies (Stucki *et al.*, 2015).

Merz *et al.* (2020) gathered the efforts in impact forecasting of natural hazards in various fields in a review. For meteorological hazards, there are various efforts, but they are rarely linked to official warnings by NHMS to the general public. In the following, we will summarize the efforts for forecasting the impacts of storm events. According to Merz *et al.* (2020), there are storm impact forecasting systems for insurance losses in the private domain e.g. proprietary models run by insurance companies (Pinto *et al.*, 2019). In the public domain, there are studies that show the skill of impact forecasting for storm impacts on a theoretical level (Pardowitz *et al.*, 2016a; Pantillon *et al.*, 2017), but do not focus on the communication of these forecasted impacts as warnings to specific users or the general public.

A successful implementation of a socio-economic impact model in an operational setting (as a mixture between IbW, IFc and IW) was illustrated by vehicle overturning model in the UK (Hemingway & Robbins, 2020). The model uses wind speed and direction as hazard information and combines it with roadways as exposure and overturning probabilities per windspeed as vulnerability to arrive at a risk map illustrating the vehicle overturning risk. Weather forecasters within the NHMS can consult the map for warning decisions. The output was compared to reported impacts on one event and the model performed well (Hemingway & Robbins, 2020).

Such individualized forecasting systems and the resulting dialog with core partners are summarized by the American NHMS as impact-based decision support services (Uccellini & Ten Hoeve, 2019). An analysis involving interviews with emergency management of aviation, transportation and energy sector revealed that with the implementation of impact-based decision support services the costs and recovery time of severe storm events could be reduced (Lazo *et al.*, 2020).

Presenting an yet another form of validation of IFc and IW, the reception of IbW in the UK was studied after storm Doris by surveys of the general public (Taylor *et al.*, 2019). Taylor et al. (2019) call for a better education of the public about IbW and additionally highlight that institutional trust plays a big role in the effective communication of warnings.

A few successful implementations of impact forecasting systems are known (Lazo *et al.*, 2020; Hemingway & Robbins, 2020), but the implementations are often not shared with the public, so other institutions cannot directly benefit from their development. Additionally, there has been no systematic comparison of impact forecasts with recorded impacts over a longer time span, but only for single events.

5.2.2 Study Focus “Building damage in Switzerland”

In Switzerland, storms are one of the most damaging weather related disasters, next to flood and hail (Imhof, 2011; WMO, 2020). The storm

Burglind/Eleanor hitting Europe on January 3rd 2018 was the most damaging winter windstorm hitting Switzerland since Lothar in December 1999. It caused damage to infrastructure estimated to 165 Mio CHF, interruptions in traffic and the electricity grid, and felled over 1.3 Mio cubic meters of wood (Scherrer *et al.*, 2018). Next to winter windstorms, thunderstorms and foehn are another cause of storm damage to buildings in Switzerland. The main impacts of storms in Switzerland as documented in reports and newspapers are: damage to buildings and infrastructure, interruption of rail and road traffic, electricity blackouts, forest damage and loss of life during or after the event (WSL & BUWAL, 2001; Scherrer *et al.*, 2018). As a proof of concept for an impact forecast, building damages due to storms is a good choice, due to the availability of building damage data from the public, mandatory building insurance sector and the availability of impact models for this hazard.

The building insurance sector presents itself as a model user for a user-specific impact forecast system. The cantonal building insurance of the canton of Zurich GVZ compulsorily insures all buildings (with a few exceptions) in the canton of Zurich against damage due to natural hazards and fire. The canton of Zurich is located in north-eastern Switzerland. The annual average building damage of winter windstorms in the canton of Zurich is estimated at around CHF 1.4 million (Welker *et al.*, 2021), calculated using GVZ’s proprietary windstorm damage model on the basis of freely accessible climatological windstorm footprints. According to its own statements, it would be useful for the GVZ to know roughly the expected damage before a severe event. Already now, GVZ uses its proprietary damage models directly after the occurrence of natural damage events to estimate the expected building damage.

In the event of a major storm event, GVZ needs to handle and assess claims from several thousand clients in a few days, a multitude of the regular caseload. An impact forecast could enable a better logistical planning of the claims handling, which reduces the time and effort for GVZ and its clients. GVZ needs to allocate resources and infrastructure in the case of severe damage events. For example, GVZ can decide to include an external phone service to handle the client calls and the claims adjusters need to be sent to the affected houses and their reports to be handled. Afterwards, repairs are made and the costs incurred are checked by the GVZ and the insured damages are finally paid. GVZ starts this process as early as possible. At the moment the logistical planning of the claims handling is supported by the application of their windstorm damage model directly after the event.

There is currently no impact forecasting system for building damages due to storms in Switzerland, to our knowledge, also not of any other meteorological hazard. Prevention efforts or preparations to efficiently deal with the damages could benefit from IFc. Additionally, NHMS working towards IbW or impact warnings in Switzerland and other countries can thus benefit from such a co-developed and open-source impact forecasting system.

We introduce an open source system to forecast socio-economic impacts of weather events. In this paper we show the data of 3.25 years of daily forecasted building damages in Switzerland (January 2017 – April 2020) and a case study of the event Burglind/Eleanor January 3rd 2018. We will answer the following questions: (1) Can an impact model developed for climatological risk assessments turned into an impact forecast system of building damages due to storms? (2) Under what conditions does the impact forecasting system work or not work? (3) Who can benefit from the output of such an impact forecasting system? To this end, we will compare the forecasted building damages with the damage database of an insurance company. We discuss the relevance for NHMS warning decisions as well as further development needs for incorporating socio-economic impact forecasting into NHMS warning decisions.

5.3 Methods and Data

To forecast building damages in Switzerland and verify this impact forecast, we combined data and methods from different fields. For the meteorological wind gust forecast, we used the operational numerical weather prediction model of Switzerland's NHMS MeteoSwiss (more info in section 5.3.1). We replicated the warning decision process of the operational forecaster on duty by constructing a simple automatized algorithm (section 5.3.2) For the impact calculations we used a storm damage model within the open-source risk assessment platform CLIMADA (more in section 5.3.3). For the verification of the forecasted building damages, we use damage records of the cantonal building insurance of the canton of Zurich GVZ (more in section 5.3.4).

5.3.1 Weather forecast

MeteoSwiss, the NHMS of Switzerland, operates numerical weather prediction models in different setups to produce weather forecasts. The most important setup for warning decisions is “COSMO-2E”, an ensemble setup of the COSMO weather model (COSMO, 2020) with the domain of the alpine region, a spatial resolution of 2.2 km, 60 vertical layers and 21 ensemble members (MeteoSwiss, 2020). Forecast runs are initialized twice a day and run for 5 days into the future. In our study, we look at the maximum wind gust velocity in m/s of each day (over 24 hours, i.e., 00:00 UTC – 24:00 UTC) for each grid point and each of the 21 ensemble members. We focus on the lead time of 2 days (i.e., maximum wind gust of a day is combined of maximum hourly wind gusts with a lead time of 48 hours – 72 hours). This lead time is relevant for warning decisions.

5.3.2 Hazard based warnings

MeteoSwiss is issuing weather warnings for wind in Switzerland. Forecasters issue a warning level between 1 and 5 for each of the 167 warning regions based on the weather forecast, thresholds for the different warning levels and their expert judgment. For the goal of comparing HbW with IFc, we decided to mimic the warning decision process of the operational forecaster on duty by a simple automatizing only based on the weather forecasts and the threshold for the warning levels. The thresholds for wind gusts are set differently for low elevation and for high elevation above 1600 meters above sea level. The thresholds for low elevation (high elevation) are 70 km/h (100 km/h) for level 2, 90 km/h (130 km/h) for level 3, 110 km/h (160 km/h) for level 4, and 140 km/h (200 km/h) for level 5 (Natural Hazards Portal Switzerland, 2021).

The warning “decision process” in our simple model is done in three steps. Firstly, for each grid point and each ensemble member of the weather forecast a warning level is assigned based on the elevation dependent thresholds. Secondly, every grid point is assigned the median warning level calculated from all ensemble members. Thirdly, each region is assigned the median warning level of all its contained grid points. Note that alternative definitions could be used.

5.3.3 Impact model

The risk of building damage due to storms, as one example of socio-economic impact of weather, can be calculated as a combination of hazard, exposure and vulnerability (IPCC, 2012; WMO, 2015a). CLIMADA provides a python platform to conduct risk analysis based on such a general framework (Aznar-Siguan & Bresch, 2019; Bresch & Aznar-Siguan, 2021). In the context of a climatological risk analysis of storms, Welker *et al.* (2021) presented an open-source implementation of such a model for building damages for Switzerland. The exposure and vulnerability from Welker *et al.* (2021) were used in this study, whereas the hazard component is replaced by the weather forecast (section 5.3.1).

The hazard is represented as a combination of intensity and probability (Aznar-Siguan & Bresch, 2019). Each day and each ensemble member of the weather forecast is defined as one event. For each event we know the intensity (maximum wind gust velocity) and the probability (occurrence probability of each ensemble member, in our case 1/21 for each member). For more details about the hazard definition, see section 5.3.1.

The exposure represents the value of buildings in Switzerland (Figure 17). In this study, we use a proxy for buildings values an exposure layer estimated by the LitPop-Methodology (Eberenz *et al.*, 2020). For spatial verification on postal code level within the canton of Zurich, the exposure for the canton of Zurich is further downscaled with building footprints from open street map (details see Welker *et al.*, 2021)).

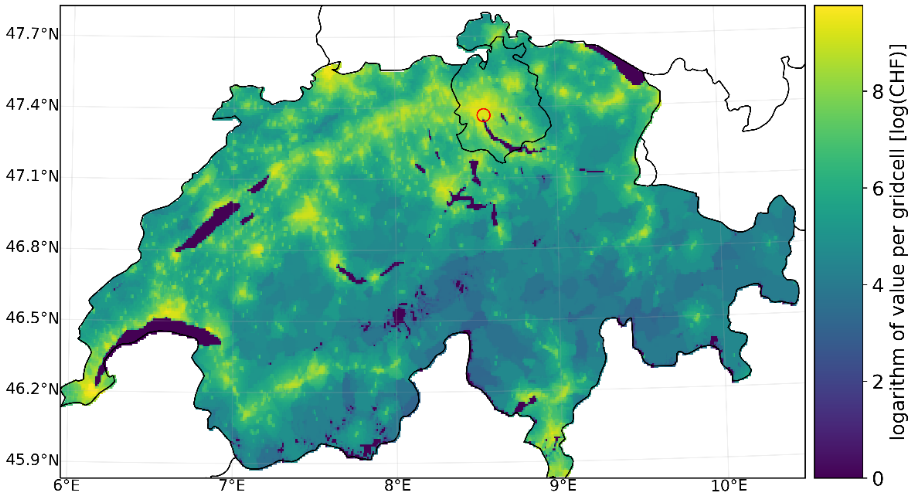


Figure 17 Exposure map of Switzerland. Spatial distribution of asset exposure value in Swiss Francs [CHF] derived from a total national value disaggregated according to nightlight intensity and population density (methodology described in Eberenz et al., 2020), borders of the canton of Zurich is drawn as a black line, red circle indicates the city of Zurich at the northern tip of lake Zurich.

The vulnerability is represented by a function relating wind gust velocity to proportional damage. The shape of this function was first published by Schwierz *et al.* (2010) and scaled for the current modelling setup by Welker *et al.* (2021).

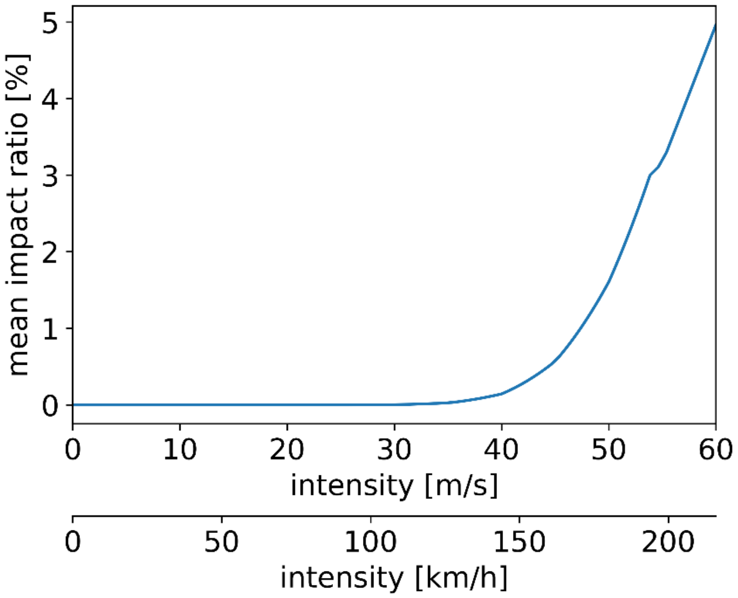


Figure 18 Impact function as defined in Welker et al. (2021). Hazard intensity, the wind gust velocity in m/s on the horizontal axis, proportional damage associated with different levels of hazard intensity on the vertical axis.

The risk modelling platform CLIMADA combines the hazard intensity, the impact function and for each grid point of the exposure. The result is a forecasted building damage dataset that stores an entry for each ensemble member and for each exposure grid point combined with its probabilities. From this data set, different summarizing plots and numbers can be produced to represent the risk of building damages for decision-makers. We present two main plots in this study: (1) the average impact for a certain day per grid cell, as well as (2) the empiric probability distribution of the total building damage aggregated over Switzerland. The numerical values represent mean forecasted building damages aggregated over a certain region.

The format of these outputs were developed to reproduce established formats used by weather forecasters within MeteoSwiss. This implementation of IFc can also serve as an illustration for operational weather forecasters on duty, who will base future warning decisions not only on meteorological forecasts but also on socio-economic impact forecasts. The graphs, numbers and terminology are designed in the style of meteorological forecasts to provide a familiar environment to the forecaster.

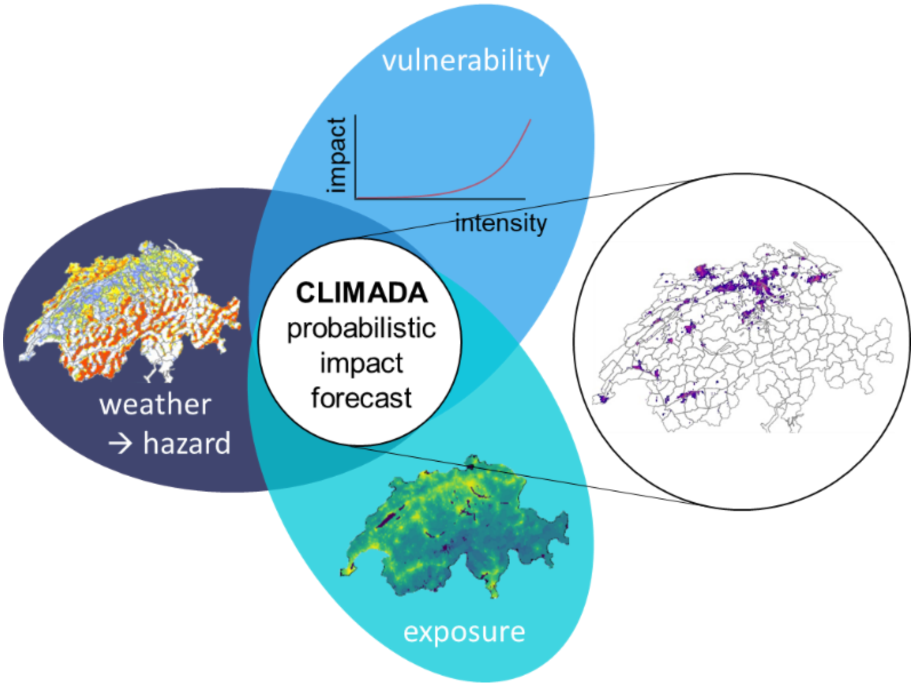


Figure 19 Schematic illustration of the impact forecasting system implemented in CLIMADA. The risk of impact is calculated spatially explicit based on weather forecasts as hazard, exposure and vulnerability information. CLIMADA facilitates the production of different summarizing risk metrics and plots. For details on CLIMADA see Aznar-Siguan and Bresch (2019). In the course of these study the CLIMADA Illustration adapted from (IPCC, 2012)

5.3.4 Building damage records

In Switzerland, building insurance is mandatory and in the canton of Zurich GVZ insures (almost) all buildings. The claims data of GVZ are a complete record of building damages in the canton of Zurich. The claims data are proprietary, but for this study, we were able to get aggregated data. One dataset is the total daily building damage for the canton of Zurich caused by wind for January 2017 – April 2020. The second data set is building damage per postal code in the canton of Zurich for one selected event (storm Burglind/Eleanor hitting Switzerland on January 3rd 2018). The third dataset covers the building insurance sector for 19 of 26 Swiss cantons that handle their mandatory building insurance with one public insurance, as reported by Scherrer *et al.* (2018). It contains the building damages per canton for Burglind/Eleanor. These building damage records provide context for the forecasted building damages.

5.4 Results:

We are able to forecast building damages caused by windstorms for Switzerland. We will show the content of our building damages forecast in three ways. First, the result for the Storm Burglind/Eleanor are shown, which hit the Alpine region and Switzerland on January 3rd 2018 (section 5.4.1).Second, we will show results of the spread of the impact forecast caused by meteorological uncertainty (section 5.4.2).

Third, using the daily building damage records from the public building insurance company for January 2017 – April 2020 we show a temporal and spatial verification of the aggregated impact forecasts u and highlight strengths and shortcomings (section 5.4.3).

5.4.1 Burglind/Eleanor impact forecast

Burglind/Eleanor hit Switzerland on January 3rd 2018 and MeteoSwiss issued a warning level 3 of 5 for most of Switzerland on January 1st (see Figure 20a). Our replicated, simple automatic HbW system (section 5.3.2) shows a more patchy distribution of warning levels over Switzerland and generally a lower warning level (Figure 20b). In the definition of the warning levels used be the forecaster, possible impacts are described. With regards to building damage, a warning level 3 warns that “damage to individual roofs” is possible (Natural Hazards Portal Switzerland, 2021). Neither the MeteoSwiss warning nor our automatic HbW system provides further information, where such an impact might occur.

Our impact forecasting system described in section 5.3.3 forecasted mean building damages of close to 50 million CHF for January 3rd 2018 based on a weather forecast run initialized on January 1st 2018. The IFc per grid cell shows a concentration of building damages in the northern and western part of Switzerland (Figure 20c). In Figure 20c), there are also clusters of high forecasted building damages at the locations with high exposure values (compare Figure 17). This lower pane in Figure 4 is the main output of the impact forecasting system that is in a semi-operational status since October 2019.

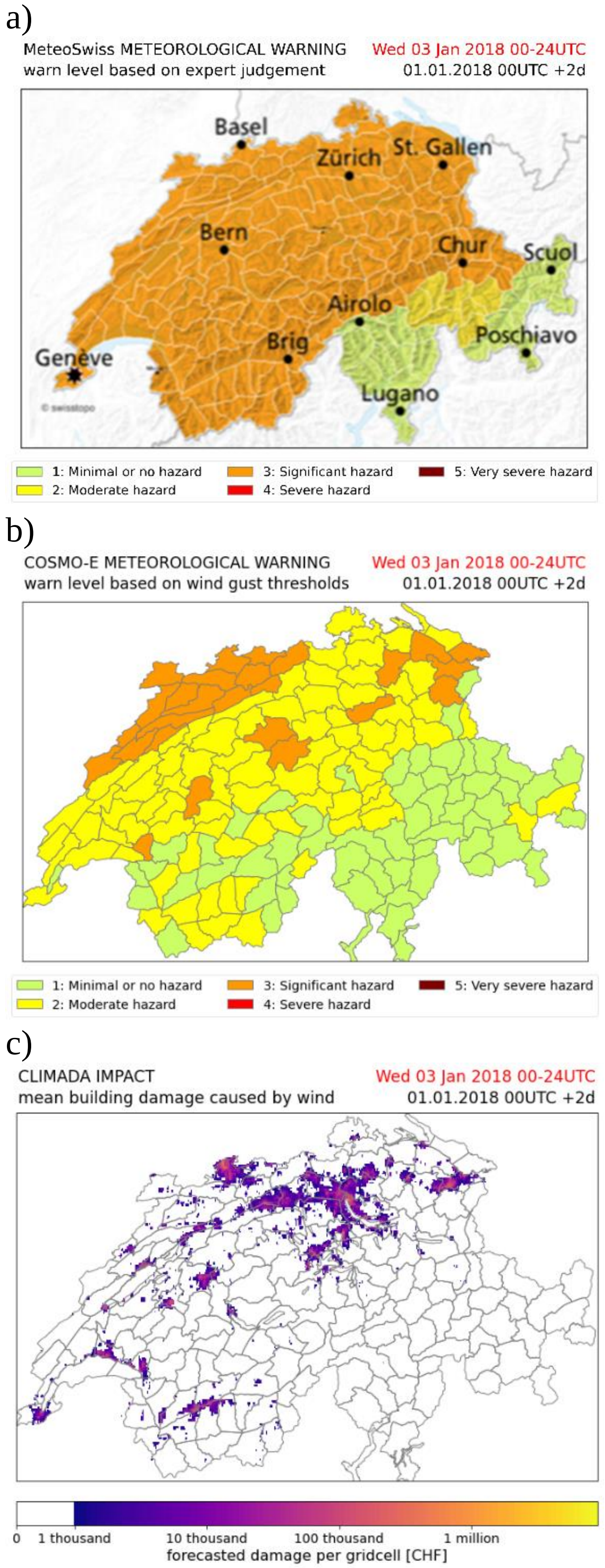


Figure 20 Hazard-based and impact-based wind warnings of the storm Burglind/Eleanor hitting Switzerland on January 3rd 2018, at a lead time of two days. a) Warning levels issued by MeteoSwiss based on weather forecast and expert judgement (adapted from Scherrer

et al., 2018). b) Simple automatic HbW system based on fixed thresholds and the ensemble median COSMO wind gust forecast. c) Mean forecasted building damage per grid cell in CHF. Building damages below 1000 CHF per grid cell are not shown, higher damages shown in a color scale from blue to yellow.

5.4.2 Meteorological uncertainty of impact forecast

The building damages are forecasted based on 21 ensemble members of the COSMO-2E model. The spread of the forecasted building damages for Burglind/Eleanor between the ensemble members is quite large. With the lowest being below 100’000 CHF and the highest over 600 Mio CHF. The distribution is skewed, with a fatter tail towards the side of higher damages. This results from the non-linearity of the impact function (Figure 18) and the inhomogeneity of underlying assets. The spread and empirical distribution is illustrated as a histogram with logarithmic bins in Figure 21. The distribution represents the uncertainty of the meteorological forecast, as exposure and vulnerability are held constant and the meteorological forecast is the only varying part of the impact forecast system.

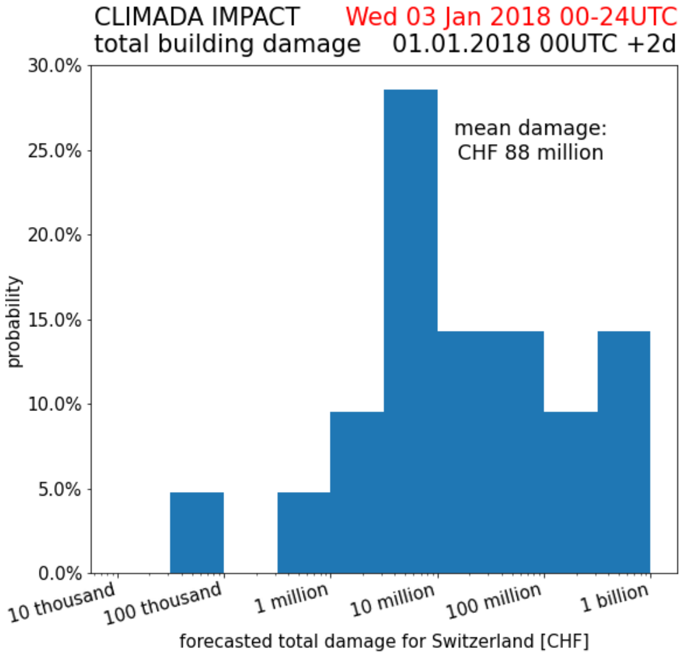


Figure 21 Histogram of the forecasted building damages for Switzerland for each of the 21 ensemble members in Swiss francs for the storm Burglind/Eleanor hitting Switzerland on January 3rd 2018, based on the meteorological forecast initialized 2 days earlier on January 1st 2018. Bins for forecasted building damages are on a logarithmic scale horizontally and probability of each bin on the vertical axis.

5.4.3 Temporal and spatial forecast assessment

To assess the skill of such a building damage forecast, we compare the forecasted building damages with the recorded building damages by the cantonal building insurance of the canton of Zurich GVZ (see section 5.3.4). For such an analysis, several cases are needed. Using the daily building damage records for January 2017 – April 2020 we show a temporal verification of the aggregated impact forecasts during this time period. Using a postal code resolved building damage record for Burglind/Eleanor, we verify the spatial component of the impact forecast also.

To understand how the forecast of Burglind/Eleanor differed from forecasts for other days we produce a scatter plot of recorded and forecasted building damages (Figure 22). Burglind/Eleanor is clearly identifiable as the event with the highest recorded building damage in the covered time period. Most days are located in the lower left corner with forecasted and reported building damages lower than CHF 1 Million. Beside Burglind/Eleanor, there are 17 other events with reported and/or forecasted building damages higher than CHF 1 Million. Depending on their location on the graph, they are qualitatively labelled as successful impact forecasts, misses or false alarms (“success”: impact forecast and reported damage no further than factor 3 apart, “miss”: impact forecast smaller than a third of reported damage, “false alarm”: impact forecast bigger than three times the reported damage).

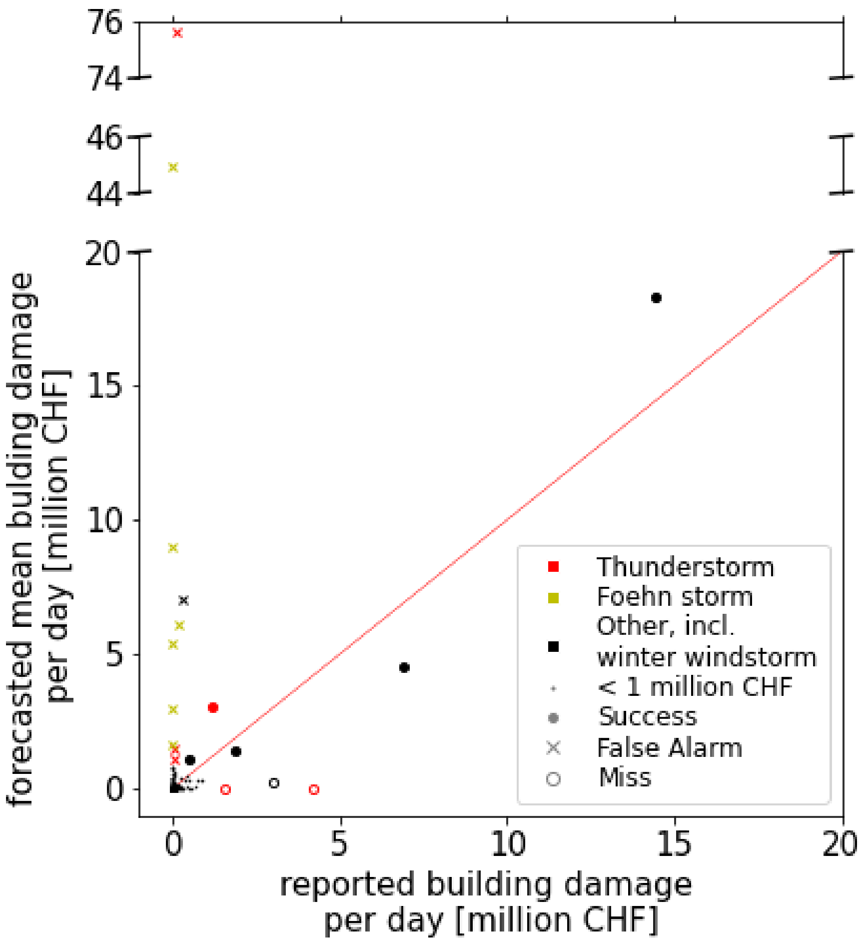


Figure 22 Scatterplot of recorded (horizontal axis) and forecasted (vertical axis) building damages for the canton of Zurich. Each point represents one out of 1211 days from January 2017 to April 2020. The horizontal axis represents building damages as recorded by the cantonal building insurance of the canton of Zurich GVZ. The vertical axis represents the mean forecasted building damages for the canton of Zurich based on the weather forecast with two days lead time (please mind the two gaps in the vertical axis). Foehn storm days are marked in yellow, days with thunderstorms are marked in red and all other events in black. The red line marks the 1-1 line, where forecasted and recorded building damages are exactly equal. Marker shapes are chosen according to the qualitative forecast rating (Full circle "success", empty circle "miss", cross "false alarm", and small points for days when neither recorded nor forecasted building damages reached CHF 1 million). Burglind/Eleanor is a clearly identifiable single event in the right half of the plot with the highest reported building damages. The yellow outlier with forecasted damages of CHF 45 million is a foehn event, for which the COSMO model has a known bias. The red outlier with mean forecasted damages of CHF 76 million was mainly caused by one outlying ensemble member, whilst the median forecasts damage for that day amounted to less than CHF 1000.

The events with reported and/or forecasted building damages higher than CHF 1 Million can be categorized into three types depending on the weather phenomena (Table 4). For the categorization the catalogue of the (Sturmarchiv Schweiz, 2021) was used. The thunderstorms are marked as red markers in Figure 22 and the impact forecast is mainly rated as “miss” or even a “false alarm” with only one successful impact forecast. The yellow markers in Figure 22 (Foehn storm, southerly wind events), are all “false alarms” with sometimes quite high forecasted impacts. All other days are marked as black markers, all black markers with forecasted or reported impacts over CHF 1 Million were categorized as winter windstorm events. The impact forecast of four out of six winter windstorm events can be rated as “success” with one “false alarm” and one “miss”.

Table 4 List of days, when either the reported building damages or the forecasted building damages for the canton of Zurich with 2 day lead time are larger than 1’000’000 CHF. The table also provides event classification (Category), name, and an impact forecast rating (“success”: impact forecast and reported damage no further than factor 3 apart, “miss”: impact forecast smaller than a third of reported damage, “false alarm”: impact forecast bigger than thrice the reported damage). The entries are sorted by the magnitude of reported damage. The observation period is from January 2017 to April 2020.

Event date	**Reported damage, mio CHF**	**Impact forecast, leadtime 2 days, mio CHF**	**Category**	**Name**	**Impact Forecast Rating**
03/01/2018	14.41	18.35	Winter windstorm	Burglind	Success
10/02/2020	6.92	4.55	Winter windstorm	Sabine	Success
02/08/2017	4.21	0.00	Thunderstorms		Miss
04/02/2020	3.02	0.23	Winter windstorm	Petra	Miss
11/02/2020	1.84	1.39	Winter windstorm	Sabine	Success
30/05/2018	1.55	0.00	Thunderstorms		Miss
01/08/2017	1.20	3.05	Thunderstorms		Success
16/01/2018	0.51	1.12	Winter windstorm	Evi	Success
12/11/2017	0.27	7.01	Winter windstorm	Numa	False Alarm
04/03/2017	0.17	6.09	Foehn storm		False Alarm
10/07/2017	0.08	75.62	Thunderstorms		False Alarm
04/04/2018	0.07	1.47	Foehn storm		False Alarm
24/04/2019	0.06	1.10	Foehn storm		False Alarm
07/03/2019	0.01	9.02	Foehn storm		False Alarm
17/12/2019	0.00	2.99	Foehn storm		False Alarm
11/12/2017	0.00	44.95	Foehn storm		False Alarm
19/10/2019	0.00	1.61	Foehn storm		False Alarm
20/12/2019	0.00	5.36	Foehn storm		False Alarm

The data of forecasted building damages are available on a high spatial resolution. Comparing recorded building damages for individual regions to forecasted building damages for the event Burglind/Eleanor illustrates a verification of this spatial content of the presented impact forecasting system. The comparison of forecasted and recorded building damage shows no correlation on the level of postal codes (Figure 23b). The spatial distribution of damages can be better forecasted on the level of cantons (Figure 23a), than on the levels of postal codes (Figure 23). In the mechanism where local building damage occurs, there is a lot of randomness involved, which cannot be represented in our impact model.

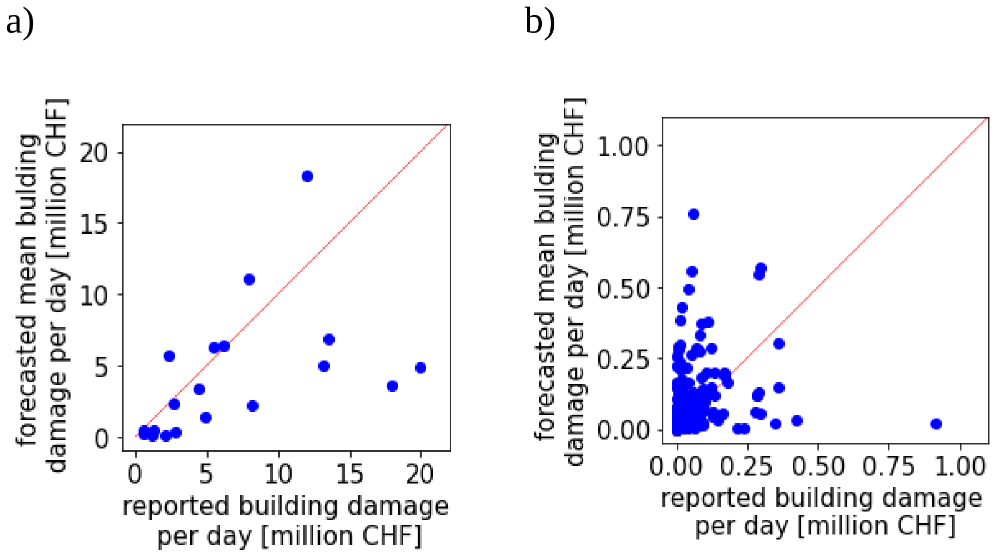


Figure 23 Same as Figure 22 but for the event Burglind/Eleanor, aggregated on different geographical scales. a) Each point represents one of 17 cantons within Switzerland. The horizontal axis represents building damages as recorded by the public building insurers of the individual cantons. The vertical axis represents the mean forecasted building damages for the canton of Zurich based on the weather forecast with two days lead time. b) Each point represents one of 243 postal code regions within the canton of Zurich. The horizontal axis represents building damages as recorded by the cantonal building insurance of the canton of Zurich GVZ. The vertical axis represents the mean forecasted building damages for the canton of Zurich based on the weather forecast with two days lead time.

5.5 Discussion

Forecasting socio-economic impacts of winter windstorms in Switzerland based on a regional weather predictions model works. The use of an impact model in combination with the weather forecast produces forecasted building damages in Swiss Francs [CHF] on a spatial grid. With that, an individualized impact forecast can be provided to a stakeholder through combining the weather information with stakeholder-specific exposure and vulnerability information. We will discuss the assessment and uncertainty of the impact forecast in general (Section 5.5.1 and 5.5.2) and from the perspective of a building insurer (Section 5.5.3) in particular. Finally, we will discuss these results to with regards to impact warnings (Section 5.5.4) and suggest some practical implications (Section 5.5.5).

5.5.1 Impact forecast and different windstorm phenomena

Four severe winter windstorm events are clearly identifiable in the set of forecasted building damages aggregated over the canton of Zurich during 1211 days, with one false alarm and one miss. There are two main explanations for these successful forecasts: Firstly, winter windstorms are well represented in the weather forecasts. Secondly, the vulnerability of the impact model was calibrated using data from winter windstorm events (Welker *et al.*, 2021).

False alarms, as in the case of winter windstorm event Numa on November 12th 2017 (Table 4), are to be expected as part of such a forecasting system. Due to the lead time of two days, the storm can still change its movement or intensity. Such changes are well represented in the ensemble forecast. And even though the reported damage of Numa was much smaller than the mean forecasted impact, it was well within the spread of impact forecasts of all ensemble members (minimum forecasted building of all ensemble members: 0 CHF, maximum: 145 million CHF).

The missed winter windstorm event Petra on February 4th 2020 (Table 4) needs further study, especially the meteorological forecast, because no ensemble member forecasted a damage close to the reported damage. In all other cases, the reported damages of the winter windstorms are well within the ensemble spread of the forecasted damages and several times smaller than the ensemble member with the highest forecasted damage.

In contrast to the winter windstorms, the impact forecasting system produces a larger ratio of misses and false alarms for foehn events and thunderstorms. The reasons for this discrepancy are discussed in the following paragraphs.

Thunderstorms occur on a much smaller spatial and temporal scale than winter windstorms. Their location and intensity is not well represented in a weather forecast with a two days lead time. The variability of the impact forecasts is enlarged for thunderstorms, by the interaction of the smaller spatial scale of the area with damaging gust with the inhomogeneous distribution of values in the exposure layer. Additionally, it is possible that rain, hail, and flood damages occur during thunderstorms that are not covered in the impact forecasting system, nor in the shown recorded building damages, which are restricted to wind damages. Wind damages of a single building are sometimes attributed to another hazard type if these hazard types co-occurred. The outlier in Figure 6 is discussed further below. For thunderstorms, the impact forecast might get better with a shorter lead time of several hours.

Foehn events occur in the alpine valleys and high wind speeds and gusts can even stretch northwards and reach the urban regions in Zurich. In the studied 1’211 days there have been 8 days where the impact forecast in the canton of Zurich reached more than 1 Mio CHF whilst foehn winds were detected in the alpine valleys. The reported damages were at least one magnitude but mostly several magnitudes smaller than the forecasted ones. There are two plausible explanations for this high rate of false alarms: Either, there is a bias in the forecast model that predicts too high gust speeds in the canton of Zurich during foehn events. It is a known problem for the COSMO model forecast of MeteoSwiss to predict too high winds during foehn events in the canton of Zurich by overestimating the spatial extend of foehn events (Buzzi, 2012). The other plausible explanation is that the calibration of the vulnerability is not transferable from winter windstorms to foehn events. This would mean that the forecasted gust speed has a different relationship to building damages depending on the underlying weather phenomena. As the overestimation of the spatial extend is a known problem for foehn events in COSMO, it is likely that the transferability of the vulnerability plays a minor part. But we did not further investigate, as this might question warrant a study of its own.

Two false alarms occurred with forecasted building damages more than double the damages of Burglind/Eleanor (see outliers in Figure 6). In the case of the thunderstorm event (July 10th 2017, Table 4, red outlier in Fig 6), one of the 21 ensemble members predicted high gust speeds up to 58 m/s over most the populated area: the city of Zurich. The impact forecast of this one member leads to enormous damages over 1.5 billion CHF in the canton of Zurich, contributing to a major part of the 76 million CHF mean forecasted damage. The median forecasted damage is less than 1 thousand CHF. Thunderstorms were actually occurring on July 10th 2017 over the canton of Zurich, leading to heavy rainfall, but not as heavy gusts. Whether such a thunderstorm gust event as represented in the highest ensemble member is a realistic scenario, and with what return period such events occur would need further study. As the operational COSMO model at MeteoSwiss uses perturbation of physical tendencies and soil moisture perturbation to increase the ensemble spread of the weather forecast, it is plausible that the gust speeds of this ensemble member reach unrealistic values due to these perturbations (Guy deMorsier, pers. communication, March 31, 2021). Alternatively, a limitation in the numerical representation of the COSMO model could have been reached in that particular members run. What can be learned is that impact forecasting systems need to establish a handling of such outliers. In case of the foehn storm (December 11th 2017, Table 4, yellow outlier in Figure 22), several members predicted high impacts in the city of Zurich and the densely populated shore of lake Zurich with two days lead time. Neither the observed damages nor measured gust speeds reached the level of these ensemble members. This can be explained by the bias in the gust forecast of foehn events described above.

Post-processing aims to remove the bias of NWP forecasts by using predictive statistical relationships between the forecast output of an NWP model and observations and hence might increase the skill of weather forecasts and impact forecasts (WMO, 2015b). In the presented impact forecasting system, it might solve the problem of overestimation of impacts in foehn storms by correction of the wind gust forecast of the southerly winds in the canton of Zurich. The aggregation of the impacts over an area is an important feature in impact forecasts. The post-processed forecasts need to preserve the information, which extremes could occur simultaneously at different points, and which extremes are possible at different points, but exclusively.

5.5.2 Uncertainty of impact forecasts

Even for successful impact forecasts of winter windstorm events, the uncertainty represented in the ensemble spread is larger than expected. The uncertainty is accentuated with the highly nonlinear parameterized impact function that gives a value in Swiss Francs (Figure 21). Two days before the storm event Burglind/Eleanor, the impact forecasts cover a large range due to the meteorological uncertainty represented in the ensemble forecast. The forecasted building damages aggregated over Switzerland range from a small event (around 100’000 CHF) and one of the most damaging events ever recorded (more than 600 Mio CHF, Eidg. Forschungsanstalt und Bundesamt für Umwelt, 2001). This illustrates that the exact impact cannot be known two days in advance, which is not surprising.

This represented uncertainty originates from the meteorological forecast, as the other two elements of the impact, the exposure and the vulnerability, are held constant in the present study. There are two main processes governing this meteorological uncertainty. One considers the large-scale weather forecast, the other the single gust on the small scale. They can be shown with the range of the IFc and with the potential skill scores at different geographical aggregation levels.

There is uncertainty in the large-scale weather forecast about the location and intensity of the storm event. Already two day in advance the weather forecast reliably predicts a severe large scale weather system over central Europe (Pardowitz *et al.*, 2016a). However, large uncertainty remains regarding exact location and intensity of the gusts. The forecast model represents this uncertainty as good as possible in the difference of the ensemble members. A small change in high gust intensities can lead to a substantial increase in the forecasted damages due to the exponential shape of the impact function. This leads to a large range between the damage forecasts of different ensemble members. This represented uncertainty routinely spreads from almost zero to a multitude of the mean forecasted damage. Still this represented uncertainty does not always capture the full uncertainty e.g. in the case of winter windstorm event Petra on February 4th 2020 (Table 4) the reported damage was more than 10 times larger than the mean forecasted building damage and almost 3 times larger than the forecasted building damage of the most severe ensemble member. The unrepresented uncertainties are discussed in more details below.

On the small scale, the process of strong wind velocities of high atmospheric layers mixing down to the ground as wind gusts and damaging houses has a large random component. This randomness adds further to the uncertainty. Some aspects of the wind gust can be explained by the topography and surface roughness, but there is always a randomness involved on the single block or even house level. Independent of the lead time, it is impossible to know which houses will be affected by the wind gusts, as we deal with a turbulent flow. This randomness is not represented in the meteorological forecast nor in the impact model. This is clearly shown by the failure of the damage forecast to predict the damage on the smallest scale - the postal code level (Figure 23b). On a cantonal level, the aggregation over a larger geographical area helps to smooth the forecasted damages and the agreement between forecasted and reported damages is better (Figure 23a).

Using these presented building damage forecasts for societal decisions on preventive actions is decision-making under large uncertainties. Dealing consciously with represented quantitative uncertainties and unrepresented qualitative uncertainties is an important part of that process. One of the important limitations is that the model input incorporates the meteorological uncertainty but otherwise uses deterministic components in the impact model. Pardowitz *et al.* (2016) showed an increase in skill of an impact forecast if the impact model is also probabilistic. The aim of this impact forecasting system was to portray the implications of the forecasted weather in a most straightforward way. This is achieved firstly by transforming the wind gust forecast and its represented uncertainty into building damages and secondly by focusing on the mean forecasted building damage as the range of the represented uncertainty is very large and very volatile. Representing additional uncertainties would dilute that information. However, it is important to always keep in mind the unrepresented uncertainties, either of the meteorological forecast (exemplified with the missed event of winter windstorm Petra) or of the exposure and vulnerability. The unrepresented uncertainties of the exposure and vulnerability include: the uncertainty in the estimation of building values, the randomness of the wind gusts hitting a specific house, uncertainties in the relationship between gust speed and damage degree, and uncertainty in the economic valuation of past damages in the calibration process. Finally, it should be noted that one aim of the modelling approach is to establish an impact based warning system for specific stakeholders. Instead predicting the mean damage with the full range ensemble spread a probability forecast to overpass a certain damage threshold, defined by the stakeholder, would provide an alternative approach.

5.5.3 Usability of impact forecasts

A building insurance company for example can use such impact forecast to better prepare before a storm event. They have the option to initiate an external phone service to handle the client calls and to mobilize claims adjusters and maybe even to pre-allocate them in places where high building damages are expected. The communication of the forecasts in building damages – a metric that the building insurer is familiar with considering unit and scale – helps to facilitate such decisions. The use of exposure and vulnerability allows for a familiar localization of the forecasted impacts. Areas of higher aggregated damages, due to the higher exposure or higher wind speeds, are highlighted (Figure 20b) and can be prioritized for first actions by the building insurance sector.

The impact model for building damages in the canton of Zurich was developed as part of a collaboration between the cantonal building insurance of the canton of Zurich GVZ and the authors (Welker *et al.*, 2021). The co-development of the impact forecasting system increases the trust of the recipient in the forecasts and allows a better recognition of the involved uncertainties. During this process, the advantages and limitations of such a model were discussed, especially they are aware of unrepresented qualitative uncertainties. Such an exchange helps the user with the interpretation of the impact forecasts during their decision-making process. This is especially valuable in the stressful situation of a potentially arriving storm event.

5.5.4 Towards impact warnings for general public

The impact forecast shown in Figure 20b is directly usable as impact warning a building insurer, as discussed, but not for the general public. There are two main shortcomings. Firstly, a member of the general public, e.g. single house owner would be “warned” differently depending whether his/her house is located in an urban or rural area because of their single risk perspective on the exposure, compared to the portfolio perspective of a building insurer. Secondly, as a cautionary remark: a person interested in traffic interruption, forest damages or any other impact will not see the relevant exposure nor vulnerability represented in Figure 20b. This discrepancy is hard to understandably disclaim and could lead to misunderstanding of the warning content.

The presented impact forecast could still be indirectly valuable for NHMS by providing an additional source of information for the decision process lead by the meteorologist on duty who issue warnings to the general public. NHMS collaborate with specific partners like emergency services, who have to plan their resources and benefit from the aggregated focus of this impact forecast. Half of NHMS in Europe have or plan to have impact based warnings for specific partners (Kaltenberger *et al.*, 2020). Additionally, country-wide or canton-wide building damages are regularly reported in the media after storm events. It can be hypothesized that users in the general public get a better perception of the upcoming weather situation, if the warning text references such commonly used aggregate metrics of impacts.

5.5.5 Practical implications

A number of additional practical implications can be derived from this case study for NHMS that have the production of IbW or IFc as a strategic goal. The learnings consider IT-infrastructure for the production of IFc and verification of IW.

Interestingly two thirds of NHMS self-assessed that they lack the IT-infrastructure to run impact models (Kaltenberger *et al.*, 2020). The presented system does only require a minimum of resources compared to numerical weather prediction models and should be useable with the infrastructure that NHMS and even partners or clients already have access to. The development in open data access and application programming interfaces (API) to NWP data will accelerate the uptake of impact forecasting by partners and clients.

For NHMS forecast verification is important to improve their own forecasting tools (WMO, 2015b). If forecasted impacts become part of their services, they need to either build their own impact database or relay on collaboration with specific partners, like building insurers or emergency services, to obtain impact data for verification. Access to that data is important because most NHMS do not have their own impact database. The perception of the warning could be verified with regular surveys of the public as it is practiced in the UK (Taylor *et al.*, 2019; Lattimore, 2019).

5.6 Conclusion and Outlook

We presented an impact forecasting system for building damages from winter windstorms. It combines a wind gust forecast of the operational ensemble weather forecast model COSMO as hazard with exposure and vulnerability in the open source risk assessment platform CLIMADA to forecasts building damages in Swiss Francs with two days lead time. We compared the forecasted impact with reported building damages of the canton of Zurich. Of the investigated 1’211 days, there were six days with forecasted or recorded building damages from winter windstorms over 1 million CHF. Of those days, four were forecasted in the right order of magnitude with one missed event and one false alarm. For other weather phenomena as thunderstorms and foehn storms, the rate of missed events and false alarms is much higher. The building insurance sector can use the building damage forecasts to better prepare for a winter windstorm event. Additionally, such a system could be used by any organization who is interested in an aggregate impact view for their preventive decisions.

The forecasted building damages contain many uncertainties and a user of that information for societal decisions on preventive actions must be aware of them. One of the important limitations of the presented impact forecasting system is that it incorporates the meteorological uncertainty but otherwise uses deterministic components. This setup highlights the information of the meteorological forecast including its uncertainty. The user needs to have a qualitative understanding of the additional unrepresented uncertainty.

From the current state of impact warnings for one or few specific stakeholders to impact warnings for the general public is still a long way. For NHMS to get a better understanding of impacts, transdisciplinary research projects with individual stakeholders could certainly strengthen the experience to tackle impact warnings for the general public. Such stakeholders could be any organizations that needs aggregated impact information to facilitate their decisions making process, e.g., emergency services. Using a software tool such as CLIMADA to co-create an impact model as proposed in this paper allows to structure this process (Fischer *et al.*, in preparation; Pohl *et al.*, 2017). This opens the use of such specific impact forecasts as additional inputs for the warning decisions process in the NHMS. Additionally, it could widen the possibilities of partnerships between NHMS and core partners, because proficient partners could run and maintain the impact forecasting system themselves.

Ideally, impact warnings for the general public should be aggregated from a multitude of quantitative impact forecasts that in combination cover most socio-economic impacts relevant for the general public. The warning decision process and content could then be structured primarily around the type of expected socio-economic impacts (e.g. disruption in traffic, ...) and only secondarily provide the detailed meteorological information such as specific threshold numbers. There are still too few examples to demonstrate the applicability of such a methodology. It is unclear if all relevant impacts can be represented with an impact forecast and if the NHMS have the needed competence to operationally issue and verify such impact forecasts. If NHMS would acquire this competence, e.g., through the collaboration with partner organizations, they could extend their role as trusted sources for meteorological information (Taylor *et al.*, 2019) to the broader spectrum of the impact warnings.

Goals like better preparedness, reduced damage or faster claims handling, give meaning to the decision-making process based on impact forecasts. To have a better picture of the net benefit of using such a forecast in decision-making, it is important to include the cost structure of the decision-maker’s options. For example, the benefit of early allocation of claims adjusters in the case of a severe event outweighs the cost manifold in the case of the building insurance sector. Such a cost structure increases the net benefit of the impact forecasting system. The model CLIMADA allows option appraisals for damage and cost reductions (Bresch & Aznar-Siguan, 2021). For the interested user, a full implementation of not only the forecasted impacts but also of adaptation and mitigation options into the impact forecasting system is possible.

Using an open-source impact model and sharing implementations open source and open-access does support the development of transferable solutions. Especially with increasing availability of raw forecasting data in open data initiatives and simplified data access via API (e.g. https://opendata.dwd.de), this will help accelerate the uptake of impact forecasting. The impact forecasting system presented in this paper is available open-source and does now lend itself to support these next development steps.

6 Synthesis

The four studies in chapters 2 - 5 presented new findings about impacts of winter windstorms in Switzerland. These findings can inform decisions about how society deals with winter windstorm risk in general, shortly before an upcoming event and after an event. The developed impact model and the tools presented in chapters 4 and 5 help generate straight-forward information for decision-makers.

This synthesis chapter reviews the findings, provides a deeper discussion of a few select topics, and suggests future work. First, the achievements of each of the main chapter 2 - 5 are summarized in Section 6.1.

Uncertainty is part of all presented studies. Especially, there is a considerable amount of uncertainty in the modelling results as provided in chapters 4 and 5. Section 6.2 summarizes and categorizes the different sources of uncertainty and suggests a way to more explicitly represent uncertainty within the presented impact model going forward. Additionally, the role of uncertainty in communication for decision-making support is discussed.

Incorporating impacts into warning systems is a goal that many national weather services work towards. There have been many attempts to provide structure to that undertaking, and section 6.3 highlights the importance of exposure in warning systems, which incorporate impacts.

Section 6.4 highlights the synergies between risk assessments (featured in chapter 3 and 4) and impact forecasting (featured in chapter 5) and suggests a closer collaboration between these separate research fields in the future.

An outlook into the next development steps needed, research topics and practical implications is presented in section 6.5.

6.1 Achievements

The most important achievements of the four studies are summarized and complemented with additional observations or insights acquired during the work on the studies. The order of the subsection follows the order of the chapters 2 - 5.

6.1.1 Effecting a review of the impacts of Burglind/Eleanor

The socio-economic impacts of the event Burglind/Eleanor occurring in January 2018 were collected as part of a post-event analysis. Burglind/Eleanor was the most severe winter windstorm event hitting Switzerland in almost two decades. The impacts were widespread and included infrastructure damage, forest damage and interruptions to traffic and power supply. Burglind/Eleanor was less severe both in meteorological terms and concerning socio-economic impacts than the "reference" event regarding severe winter storms in Switzerland: Lothar in 1999. Still it was an extraordinary event and MeteoSwiss and other organisations contacted during the research for chapter 2 were analysing the event in hindsight to generate learnings with respect to dealing with future events. Many of the contacted organisations also showed interest in the produced report in order to include the meteorological background into their own analysis.

MeteoSwiss was discussing internally and in the report if warning level three was the right choice or if warning level four would have been more fitting. The forecasted gust speeds were at the boundary between the definitions of warning level three and four. In the conversations with organisations contacted during the research for chapter 2, the author of the thesis had the impression that people felt well warned by the high presence of the event in the media before the event, independent of the warning level. This corresponds to the increased effort invested in MeteoSwiss' distribution channels and the increased usage numbers of those channels. The independence of the warning's reception from the warning level is also reported in a survey about the warnings of storm Doris in the UK (Taylor *et al.*, 2019).

Gathering impact data also highlighted problems about impact data in general. Shortly after the event, the impacts had not been assessed quantitatively and only rough estimates were available. With time, these estimations got more and more precise, as they were replaced with quantitative impact assessments or got more conclusively attributed to the event. Even at the editorial deadline, two months after the event, some impact assessments were still ongoing (e.g. the assessments of building damages), whilst some others were not further assessed and remained at the level of rough estimates. This experience aligns with the general reported scarcity of socio-economic impact data.

What was very interesting to see was the different evaluation of the impacts of Burglind/Eleanor depending on the sector. The felled wood in the forests represented the largest storm damage of the last decade, but since the amount of felled wood was well below an annual harvest, it was expected that the felled wood could be sold at regular market prices. Retrospectively, the annual harvest in 2018 was 11% higher than in previous year due to Burglind/Eleanor. Increased bark beetle infestation due to drought in summer also played a role in this small price difference (BAFU, 2020). There is also an interesting difference between road and rail traffic. Incidents in road traffic were 10 times higher than on a comparable day. Incidents in rail traffic attributed to Burglind/Eleanor were accumulating to only 30% of the number of incidents occurring on any regular day. This hints at a different vulnerability of the two traffic systems. A potential explanation could be that the surroundings of rails are better maintained to prevent trees falling on the infrastructure compared to roads. Members of the general public also have individual perspectives and evaluations regarding the impacts, especially those that may have suffered from large individual losses. This is visible in the comments on the MeteoSwiss blog, where people did not agree with the stated assessment of the severity of Burglind/Eleanor. The comparison of the aggregated impacts of Burglind/Eleanor with the aggregated impacts of Lothar did not reflect their own experience due to their single risk perspective (Users of MeteoSwiss, 2018).

6.1.2 Reviewing a new winter storm database in a partner case study

The **W**indstorm **I**nformation **S**ervi**C**e (WISC, a C3S Sectoral Information Service project) produced datasets of pan-European gust footprints: A historic dataset containing around 140 winter windstorm events covering 75 years and a synthetic dataset containing 7’660 winter windstorm events in 135 modelled years. The historic dataset sets new standards in terms of a high spatial resolution of 4 kilometres, covering a long historic period and being openly and freely available. In chapter 3, it was shown that the contained storms have similar characteristics to other datasets previously used in industry and research. The synthetic dataset containing probabilistic storms has shortcomings by containing storms with too small spatial extents compared to the historic dataset and other industry and research datasets.

One goal of the case study was to present the use of these datasets in the insurance industry. In chapter 3 it is shown that the main benefit of these datasets for the industry partner Swiss Re was to compare their proprietary dataset with an independent counterfactual. Their interest to replace their established impact model with a new dataset was limited. During the discussions with Swiss Re it has been discovered that a better use case of the new datasets provided by WISC would be a smaller insurance company that did not have the resources to develop their storm impact model until WISC provided openly accessible datasets of winter storm gust footprints.

Both these points, the shortcomings of the synthetic dataset and a case study of a company without an established impact model for winter windstorm risk of similar quality were addressed in the next study.

6.1.3 Building a new winter windstorm risk model

The risk assessment for building damages from winter windstorms is presented in a collaboration with the cantonal building insurance of the canton of Zurich GVZ. The proprietary impact model of GVZ was presented as well as an open source impact model implemented on the CLIMADA platform. The results from impact modelling are compared to the claims-based risk assessment and show the benefit of impact modelling for such risk assessment, especially regarding rare events. The biggest source of uncertainty is the sampling uncertainty. The events in a dataset are interpreted as a sample of an underlying distribution of events. The knowledge about the underlying distribution is limited especially for rare events, as only a limited sample is available. The limitations are mostly governed by the length of the observed time period, resulting in differing sampling uncertainty for the different data sources. These sampling uncertainties were represented using statistical resampling. The presented probabilistic dataset allows the assessment of risk for previously unexperienced extremes.

For the probabilistic gust footprints, there are two ranges of uncertainties. One is the full sampling uncertainty from sampling the underlying historic events, which is also an indicator of the sampling uncertainty of the resulting probabilistic event set. The other is the uncertainty represented in the probabilistic events due to statistical perturbations of the wind field. This uncertainty has a smaller range than the full sampling uncertainties (These ranges are illustrated in Figure 14 in chapter 4). During the review process, there was an interesting discussion about which range of uncertainty to highlight. One reviewer asked to highlight the full sampling uncertainty, whereas another reviewer with an industry perspective asked to highlight the represented uncertainty. This shows a different appetite for considering uncertainty, depending on the perspective and use of such datasets. Other aspects of the uncertainty are discussed in Section 6.2.

6.1.4 Building an impact forecasting system for winter storms

A forecasting system for socio-economic impacts based on weather forecasts is introduced. It forecasts building damages due to windstorms based on gust forecasts. The impact forecasting system has been deployed successfully as a semi-operational prototype and provides building damage forecasts in real-time with a lead time of two days for the whole of Switzerland at 500 meter resolution. The comparison between forecasted and reported building damages shows that the system can successfully forecast the impacts of the most severe winter windstorm events in the studied period, despite the two-day lead time of the forecast. Other weather phenomena show higher rates of false alarms or misses. The presented forecasting system can directly be used as a decision support tool in the building insurance sector to better prepare for upcoming storm events, e.g. to plan and better allocate resources for claims-adjustment and claims handling. It also constitutes one example of incorporating impacts into warning systems. The learnings will shape the discussion on how national meteorological services can better incorporate socio-economic impact into their warnings.

The presented impact forecasting system provides the flexibility to represent all the possible degrees of incorporating impacts into warning systems. The Forecast class in the risk assessment platform CLIMADA is structured with the components hazard, exposure and vulnerability.

If a component should not be considered in the warning, it can be set to neutral. The exposure can be set to neutral by setting their values equal to one in the model, as the components are combined via multiplication in CLIMADA (Equations (5) and (7)). The impact functions representing the vulnerability can be set to neutral if it is defined as step function resulting in zero or one to represent hazard thresholds, instead of the normally used continuous functions. Specifically, the Forecast class in CLIMADA can now represent the full spectrum of WMO paradigms (WMO, 2015a).

Hazard-based warnings: As shown in chapter 5, hazard-based warnings can be technically represented in CLIMADA. The hazard represents the maximum wind gust at each location and each ensemble member. The exposure is set to neutral with all values set to one. The impact function is defined as a step function resulting in zero or one with varying thresholds defined for each location (e.g. region-specific or height-depending thresholds). The main result in CLIMADA is a matrix indicating if the threshold is reached at each location and for each ensemble member. This matrix can be used to inform warning decisions. E.g. by providing a level of confidence needed (in form of a percentage of the ensemble members) a warning level can be defined for polygons (see Figure 20a in chapter 5) or individually for each location. Hence it could a possible tool for an operational warning system that is targeted toward the greater public.

Impact-based warnings take into account hazard and vulnerability. Hazard and exposure are defined exactly the same as above. The vulnerability now represents an impact function e.g., for building damages due to gusts (Figure 18 in chapter 5). The main result in CLIMADA is a matrix with the expected loss ratio at each location and for each ensemble member. These forecasted loss ratios can be used as input to a warning. This information represents the single risk perspective e.g., every house owner that is exposed to same hazard level will receive exactly the same information. In mountainous regions, the forecasted gust speeds are higher and as a result the expected loss ratios are also higher, luckily there are almost no buildings there. In the data or visually the mountainous regions still stand out, this can be mitigated by incorporating exposure (see below and section 6.3.2).

Impact forecasts and *impact warnings* take into account hazard, exposure and vulnerability; they explicitly use the locations of buildings via the exposure information and provide a focus on locations with high expected impacts as shown in chapter 5. Hazard and vulnerability are defined exactly the same as directly above. The exposure now represents the value of buildings at each location in Swiss francs (Figure 17 in chapter 5). The main result in CLIMADA is a matrix with the expected building at each location and for each ensemble member. These forecasted building damages can be used as a warning at each location (see Figure 20c in chapter 5) or aggregated e.g., in polygons. This information represents the portfolio risk perspective. It support decisions around the allocation of resources, so they e.g., correspond to the magnitude of the expected impacts or are directed to locations with the highest expected impacts. The exposure does not have to contain buildings or other asset values, but can also represent population, vulnerable groups or natural resources.

Merz *et al.* (2020) defined the goal of bringing impact models up to the same quality and dependability as existing hazard models. The implemented Forecast class in the risk assessment platform CLIMADA is an important stepping stone in that direction. The presented impact forecasting system is a decision support tool ready to be used for building damages from winter windstorms. It is provided open-source and -access, follows software development standards like continuous integration and provides a template that is easily adaptable for other hazards, regions and sectors at risk, including population and vulnerable groups. Its integration in the platform CLIMADA render future translations of methodologies from risk assessments to impact forecasting a simpler undertaking.

6.2 Uncertainty

Decision-making around risks is decision-making under uncertainty. In this section, the uncertainties in the decision-making support tools presented in chapter 4 and 5 are explained and categorized. This should help decision-makers to understand the uncertainties of the information they receive and additionally help researchers to find ways to further reduce uncertainties or better represent them quantitatively in the results.

Taylor *et al.* (2015) differentiate between first order and second order uncertainty in the context of communicating seasonal weather forecasts to users. They defined them as follows: “First-order uncertainty refers to the likelihood of an event happening according to a particular forecast and is also referred to as aleatory uncertainty, probability or risk. Second-order uncertainty, also known as epistemic uncertainty, Knightian uncertainty or ambiguity, refers to ‘uncertainty about the uncertainty’” (Taylor *et al.*, 2015). The decision support tools presented in this thesis provide simple and straightforward information for part of the first order uncertainty to decision-makers. In chapter 4, the presented impact model does not only provide an assessment of the risk to the user about the probability of Lothar/Martin-like damage or about the expected damage reached every 250-years: it provides a range of uncertainty based on the sampling (i.e. aleatory) uncertainty of the underlying datasets. In chapter 5, the impact forecasting system does not only display the expected building damage based on a deterministic wind gust forecast, but it portrays the probability-weighted mean damage of an ensemble forecast and illustrates the empirical distribution of the impact forecast ensemble. For both these decision support tools, however, the second order uncertainty is not quantitatively assessed. This section focusses on extending the quantification of the first and the second order uncertainty.

Discussing and transparently revealing the first and second order uncertainty is important for users of the decision support tools, as they can use that information in their decision-making process. Both of the presented decision support tools provide a quantitative indication of part of the first order uncertainty, next to listing and discussing additional sources of uncertainty. In chapter 4, the spread in the exceedance frequency curves is illustrated using resampling. It represents the sampling uncertainty of the underlying data source. In chapter 5, the spread and empirical ensemble distribution of the ensemble forecast is shown. It represents the meteorological uncertainty as it is represented in the weather forecast model. For other sources of uncertainty, especially uncertainty in the exposure and vulnerability components no quantitative indication is provided. This simplification can be useful in the decision-making process and is justified if the decision-maker is aware of the unrepresented uncertainties (e.g., a building insurer knows about uncertainties of impact models). It is more important to represent these uncertainties quantitatively if other decision-makers (e.g., the forecaster on duty or a member of the public) use the impact forecasts. This could be implemented in the present model setup with a sensitivity analysis (Kropf *et al.*, 2021).

It is possible to expand the impact model, especially the exposure and vulnerability components, to represent more uncertainty. Such a setup allows to answer two questions: Does the quantitative representation of these additional uncertainties improve the usefulness of the forecast? How does the uncertainty in exposure and vulnerability compare to the uncertainty of meteorological forecasts? A methodology to represent uncertainty in exposure and vulnerability is described and its potential to answer the two questions is discussed in section 6.2.1. In the context of chapter 5, further statistical possibilities to analyse the uncertainty with the ensemble of the impact forecasts are discussed in section 6.2.2. And additional insights on how decisions are taken under uncertainty for impact forecasts and warnings are shared in section 6.2.3.

6.2.1 Representing uncertainty with an ensemble of opportunity

In impact models, in contrast to weather models, it is not common to use an ensemble approach to represent uncertainties. There are very few open-access impact models for winter windstorm risk. Still they could be used to form an ensemble of opportunity (Zumwald *et al.*, 2020) to represent part of the uncertainty in the impact model. Instead of using a deterministic representation of exposure and vulnerability, one would use an ensemble of the available implementations of exposure and vulnerability.

For alternative exposure estimations, it would be possible to use the openly shared methodology of Koks and Haer (2020) that build an exposure layer bottom-up using building outlines from OpenStreetMap (2021). A second option would be to build an exposure layer by using a population dataset and assigning a certain value per person as in Welker *et al.* (2016). In Aznar-Siguan and Bresch (2019) an exposure layer based on nightlight intensity is used. Switzerland also uses a fixed value per household for other natural risk assessments (BAFU, 2021b) which could be used with building outlines to arrive at a further exposure layer. These exposure layers could easily be used additionally to the LitPop exposure layer used in chapters 4 and 5, to form an ensemble of opportunity.

For vulnerability, it would be possible to use the calibrated impact function of Koks and Haer (2020). Additionally Prahl *et al.* (2015) compare different functions to calculate loss ratios caused by winter windstorms. These four functions could be calibrated in CLIMADA and used as impact functions. An ensemble of opportunity could be formed with these impact functions, additional to the impact function used in chapter 4 and 5.

These different components could be combined to arrive at an ensemble of modelled impacts for each storm event in chapter 4 and each ensemble member in chapter 5. The spread of such an (expanded) ensemble would then represent part of the uncertainties in the impact model (Zumwald *et al.*, 2020).

Does the quantitative representation of these additional uncertainties improve the usefulness of the forecasts? According to Pardowitz *et al.* (2016), the forecast of loss ratios has more skill if not only the weather forecast but also the impact model is probabilistic. It is to be expected that this will also be the case for impact forecasts calculated in CLIMADA. Koks and Haer (2020) performed a sensitivity analysis of their impact model and reported – to now surprise – that their results are most sensitive to the parameterisation of their impact function. From the findings of both these studies it follows that it is especially important to consider the uncertainty of the impact functions in the ensemble of opportunity. In the proposed ensemble of opportunity, the impact functions would be as diverse as possible allowing for different minimum gust speed that leads to impact and different shapes of the impact functions above this threshold.

How does the uncertainty in exposure and vulnerability compare to the uncertainty of meteorological forecasts? For the answer to this question, it is important to have in mind that the exposure and vulnerability components of the listed models were calibrated to provide a best guess of the impact. The ensemble of opportunity would then represent an ensemble of best guesses. The ensemble of the weather forecast on the other hand, is designed to have a wide enough spread to capture all possible outcomes. This difference makes a quantitative comparison of the uncertainties in the different components difficult when an ensemble of opportunity is used. Two of the functions investigated by Prahl *et al.* (2015) provide a probabilistic result of the loss ratios with the goal to represent the size of the spread and not only the best guess. Given a large enough set of impact data, these functions could be calibrated to capture the spread of past outcomes. This would allow for a better quantitative comparison of the first order and second order uncertainty of the different components of the impact forecasting system. With this comparison, it could be known which component contributes the most to the uncertainty: hazard, exposure, or vulnerability. Decision-makers could be informed more in depth about the uncertainty of the decision support tools, and future research could be prioritized to focus on the most uncertain component.

The two questions from above could also be asked in the context of chapter 4: Does the quantitative representation of these additional uncertainties improve the usefulness of the risk assessment? How does the uncertainty in exposure and vulnerability compare to the sampling (i.e., aleatory) uncertainty of hazard information? The answers in the context of chapter 4 would be quite similar to the context of chapter 5. The risk assessment is expected to be more robust if uncertainty is explicitly represented with an ensemble of opportunity. Regarding the second question, the sampling uncertainty in chapter 4 is designed to capture all possible exceedance frequencies. The two probabilistic functions investigated by Prahl *et al.* (2015) would need to be calibrated to capture the spread of past outcomes. This would allow a comparison, of the uncertainties in hazard, exposure, or vulnerability in the context of the risk assessment.

6.2.2 Impact forecasting system

The ensemble members of the weather forecast represent the uncertainty of the weather forecast. In chapter 5, the empirical distribution of the ensemble members is shown as an illustration of the meteorological uncertainty. In weather forecasting, sometimes a parameterized model (often a simple statistical distribution) is fitted to the ensemble predictions and verification data to arrive at a better description of the uncertainty (e.g., Wilks and Hamill, 2007). The advantages of such a methodology include that it relates the forecasts to past impact data, and that the problem of single outliers in the ensemble is smoothed during this process. The disadvantage is that enough relevant impact data is needed for the fitting, and that an assumption about the type of distribution has to be made, which has an impact on the resulting uncertainty. As the best choice of distribution depends on the focus of the analysis (Wilks & Hamill, 2007), it is important to take into account the requirements of the decision-making process. The decision-making process will define if the focus is on either mean expected impact or for example worst case scenarios. Additionally, the decision could focus on one specific meteorological phenomenon, e.g., only winter windstorm events, or on all impact forecasts from wind gusts. These choices will have an influence on the represented uncertainty.

As long as such a methodology is not applied, it is nonetheless important to discuss the uncertainty in the context of verification data and not only focus on the meteorological uncertainty represented by the ensemble members. Such a qualitative assessment is shown in chapter 5, with a simple rating of the impact forecast of past events. With that rating, the number of successful forecasts of severe damage events can be compared with false alarms and misses. In decision-making, the ratio of false alarms is an important measure of uncertainty (Taylor *et al.*, 2015).

An alternative way to deal with the outlier problem in the empirical distribution is the use of post-processed gust speeds instead of direct model output. The statistical methods applied in post-processing also result in a smoothing of single ensemble member outliers in the gust forecast. Yet one should be aware that such an approach might over-correct for outliers (overconfidence) and lead to underestimation of extreme outcomes.

6.2.3 Warning decisions under uncertainty

Independent of the methodology of quantifying the first and second order uncertainty, the resulting assessment needs to be interpreted. Neither the perfect weather model nor the impact model exist and as a result, a perfect impact forecast will not exist in the near future either. As a result, there are shortcomings if the interpretation of the impact forecast is automated. There are learnings from the handling of uncertainty with weather forecasts by professional forecasters (see section 1.6.2). The forecaster on duty incorporates the quantified and unquantified uncertainties, but also known biases into their mental model too, and then takes decisions based on this extended knowledge base. This method of interpretation is very crucial to the decisions under imperfectly represented uncertainties.

In the context of impact forecasts for specific decision-makers (e.g., building insurers as in chapter 5), either the provision of an automated output metric suffices (in chapter 5, the shown output metric is mean forecasted impact) or an interpretation has to be done. Most probably there will be cases where an interpretation is necessary. In these cases, either the decision-maker has to be educated to achieve enough understanding of the shortcomings of the underlying weather and impact forecast to be able to make the decision, or the forecaster on duty has to be involved in decision-making process to provide their interpretation. This interaction would add an additional task for the forecaster on duty in high-impact situations.

The organization in which the decision-making takes place might also directly interface to the forecast provider via an application programming interface (API) and either fetch the impact information (e.g. impact maps) or even run the impact model within the organisation and only fetch the meteorological data (e.g. ensemble footprints) and handle exposure and vulnerability in-house. To allow for such setups in the future, any design of an impact forecasting system should be structured to support such arrangements going forward, by developing the impact model as a stand-alone application (as being the case with CLIMADA).

6.3 The role of exposure

In the context of risk and impacts, exposure plays a crucial role. This is also true for incorporating impacts into the warning system. In impact forecasts, the choice of exposure defines the metric of the impact forecast. In this section, two particular aspects of the role of exposure in warnings systems are highlighted.

6.3.1 A new paradigm

In the WMO Paradigms (WMO, 2015a), the hazard is featured in the first paradigm, whilst the focus lies on vulnerability in the second paradigm. The exposure is only included in the last paradigm, which focuses on the impact. In the context of incorporating impacts into decision support tools for specific partner organisations of National

Hydrological and Meteorological Services (e.g. emergency services) or other users, this order is not intuitive. A user often does not have a quantitative understanding of their relevant vulnerability to a hazard, if any understanding at all. The logical first step to incorporate impacts would be a combination of hazard and exposure. The exposure is normally quantitatively documented (e.g. geo-referenced location and further specification of critical infrastructure) or at least can be quantified without the sparsely available impact data. Thus, a fourth paradigm might be proposed, the hazard exposure combination. It could be named "exposure-based warnings", "EbW". An example would be the number of people living in an area affected by a level 3 hazard intensity, e.g. allowing the early allocation of resources to the most-affected locations.

Exposure-based warnings take into account hazard and exposure. Technically speaking, such a system can be represented by a step-function shape of the impact function (resulting to zero below a level 3 hazard intensity, and to one at and above this level). The hazard represents the maximum wind gust at each location and each ensemble member. The exposure would represent the population count at each location. The main result in CLIMADA is a matrix with the number of affected people at each location and for each ensemble member. E.g. by providing a level of confidence needed (in form of a percentage of the ensemble members), the expected number of affected people could be shown individually for each location or aggregated for polygons. Such an implementation would also be forward-compatible to incorporate more refined vulnerability information, towards a fully-fledged impact forecast and impact warnings (see 6.1.4).

6.3.2 Single risk and portfolio risk perspective

The exposure normally contains two types of information: the location and the value (denoting e.g. number of people in a given area or replacement value of buildings and/or infrastructure) of the object at risk. The values in the geo-referenced exposure layer represent the spatial pattern and thus provide decision support for the portfolio risk perspective. A neutral exposure value (e.g. exposure value set to one at each location) allows the forecast system to illustrate the single risk perspective (see 6.1.4). This comes normally at the cost, that the type of impact is not recognized from the pattern of the presented information.

In Hemingway and Robbins (2020), the single risk perspective and the location information are combined. Their presented vehicle overturning model illustrates the risk of vehicles overturning due to wind in a single risk perspective. Their model does not take into account the traffic density (e.g., number of cars). The traffic density would be needed to illustrate the portfolio risk perspective that e.g., a road emergency service might need, without it single points cannot be aggregated properly. Still the single risk is only displayed at the locations of highways whilst the rest of the map is blank. The pattern of the exposure locations strongly underlines that this warning system focuses on the impact on traffic.

For building damages, impact-based warnings for a single risk perspective can be calculated (see 6.1.4). From the forecasted loss ratios per grid point and ensemble member, e.g. the probability of reaching a certain loss ratio can be displayed, similar to an illustration shown in Pardowitz *et al.* (2016). Now, it is possible to only display the loss ratio for locations that have a large enough value per grid point in the LitPop exposure layer (Figure 24). This mask is applied with the goal to exclude e.g., the unpopulated mountain areas (a better distinction between unpopulated and populated areas could be achieved with a higher resolution exposure). Unfortunately, it is not as clear which type of impact this warning information is focused on as with the vehicle overturning model. Still a similarly fashioned illustration will underline the impact focus for other types of socio-economic impacts like dangers in forests, and road- and rail traffic delays, even if they focus on the single risk perspective.

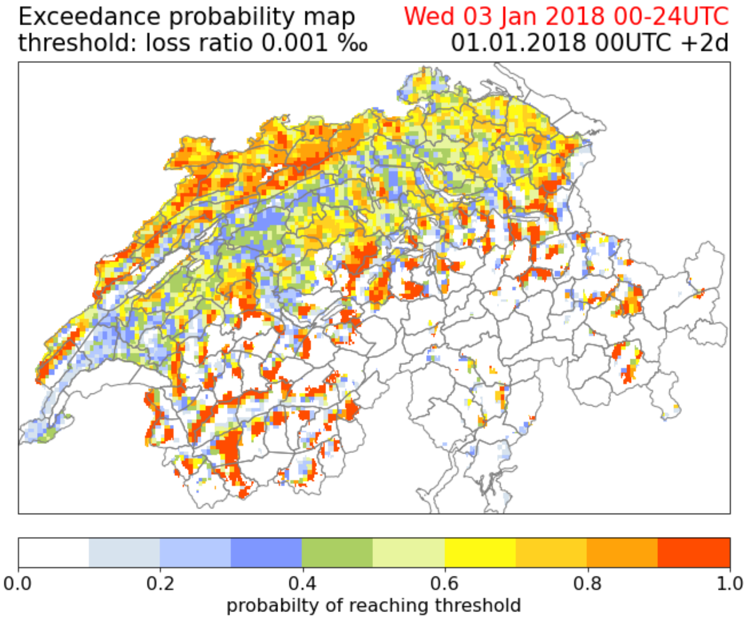


Figure 24 Impact-based warnings of the storm Burglind/Eleanor hitting Switzerland on January 3rd 2018, at a lead time of two days. The probability of exceeding a loss ratio of 0.001 ‰ for building damages from wind is portrayed, but only for populated locations (simple selection by only showing the top 66% most valuable grid points of the LitPop exposure).

6.4 Win-win of impact forecast and risk assessments

Repurposing of impact models developed for risk assessment for impact forecasts may generate synergies that benefit both goals. E.g., the impact models presented in chapters 3 and 4 build on the assumption that the majority of storm damage risk in Europe and in the canton of Zurich could be modelled based on a winter windstorm hazard set. Chapter 5 now justifies this assumption: on the one hand, by confirming that 80% of the building damage due to the seven biggest storm events in the more than 3 years was caused by winter windstorms. On the other hand, the weather forecast model data was shown to often misrepresent thunderstorms and to overestimate the impact of Foehn storms. Both these problems could potentially be present in reanalysis data as well. Additionally, the assumption that wind damage is primarily caused by winter storms makes sense for large scale damages, but on a sub-cantonal level, thunderstorm damage needs to be included to best represent the local damage burden.

The two research fields should collaborate more deeply as they benefit from each other’s learnings. Sharing models openly and using shared platforms (such as CLIMADA) does enhance the interoperability of models and the cooperation of actors of these two fields.

6.5 Outlook

The findings and achievements of this thesis are only a starting point for impact forecasting of weather events in both the academic as well as the applied field. This section suggests new research topics or practical implications to advance the topic of impact modelling for risk assessments and weather warnings. The outlook is structured in five sections. It quickly touches again on the overarching topic of uncertainty (6.5.1). Then a possibility to model impacts based on probabilistic gust speeds is proposed (6.5.2), followed by overarching topics: impact data (6.5.3), risk assessment (6.5.4), and impact forecasting systems (6.5.5) before ending with an outlook on options appraisals for impact and cost reduction (6.5.6).

6.5.1 Uncertainty of exposure and vulnerability

Both chapter 4 and 5 propose in their outlook section to further study the uncertainty of the impact model. As this topic is so prominent, it has been discussed in detail in section 6.2. The uncertainty of exposure and vulnerability can be represented using an ensemble of opportunity (section 6.2.1). Such an ensemble could be used to answer the question: Does the quantitative representation of these additional uncertainties improve the usefulness of forecasts? How does the uncertainty in exposure and vulnerability compare to the uncertainty of meteorological forecasts?

6.5.2 Probabilistic hazard intensity for building damage models

In the impact model as used in this thesis, the hazard intensity is represented by gust speed. Both in chapters 4 and 5 these intensities are derived through gust parameterisation in weather models which report the gust speed at each grid point on a 2.2 km or 4.4 km resolution over the whole of the domain (Switzerland). The gust parameterisation is normally calibrated to reflect the mean gust speed, whilst in reality gust speed follows a distribution(Ágústsson & Ólafsson, 2004). From analysis of building damage claims and from the representation of the vulnerability in impact functions, we know that only a certain percentage of the exposed buildings is actually affected. If the distribution of the gust speeds per grid cell would be known, the relevant percentile could be drawn form that distribution to be used in the impact model. Two gust parameterisation presented by Brasseur (2001) and by Born *et al.* (2012) provide a probabilistic gust parameterisation approach that define the above mentioned distribution of gust speed. To the best knowledge of the author of this thesis, such probabilistic gust parameterisations have only been validated using gust measurements, but their usage in an impact model has not been investigated. In an experimental setup a weather model, either in forecast or in reanalysis configuration, the two mentioned gust parameterisations would have to be implemented to output their probabilistic distribution of gusts. An impact model would have to be set up to either consider a specified percentile of that distribution or use the distribution to convolute with the distribution of building values for the impact calculation. Such a convolution could be combined with the stochastic approach to sample affected buildings introduced with the proprietary building damage model of the cantonal building insurance of the canton of Zurich GVZ in chapter 4. Considering probabilistic gust speeds in the hazard component would increase the represented uncertainty in the impact model. Additionally, it could be tested whether the resulting mean or median impacts provide a more reliable estimation of the risk as the previous deterministic model. The non-linearity of the impact function does to some extent mimic this effect in an implicit fashion already, hence any such test would also entail a proper re-calibration of the whole setup.

6.5.3 Impact data

Impact data are a crucial element in the development of the presented decision support tools based on impact models. Besides their broad use in calibration, impact data are also a crucial ingredient in communicating capabilities shortcomings of such tools. Especially when incorporating impacts into weather warnings, impact data are an indispensable element also for verification. The available public datasets introduced in section 1.4 do not provide data on a high enough spatial resolution, nor for all relevant impact types, nor do they cover a large enough set of events. Therefore a more systematic and harmonized collection of such impact data and consolidation of existing impact data into one database is a prerequisite to further development of impact models, in particular for warning applications.

The path towards such a database is laid out by international guidelines (JRC EU expert working group on disaster damage and loss data, 2015) and exemplified in running projects. The project CESARE in Austria, to which the author of this thesis contributed as a project member, is an example also relevant in the Swiss context. Important steps in realizing a comprehensive impact database include: (1) convening all relevant stakeholders, including potential providers and users of such a database, and including their knowledge and their needs in the design process early on, (2) defining a structure and naming convention to consolidate existing databases, (3) ensuring a systematic and regular collection of impact data in the future and (4) provisions to guarantee for operational usability and longterm sustainability of the database.

National Hydrological and Meteorological Services (NHMS) and other warning agencies are best positioned to take a leading role in this process, as they require these data for operationalizing and evaluating impact-based warning or impact forecast products. It is important to use the time before the next “Burglind/Eleanor”-size event to operationalize a more systematic collection and curation of impact data, not least to issue reports at least as comprehensive as the one presented in chapter 2.

6.5.4 Risk assessment

Climate services are a fast-growing field and new and more extensive datasets will become available in the near future. The methodology for a comparison between risk assessments based on claims or modelled damages and their uncertainties (as presented in chapter 4) are transferable to new datasets of winter windstorm events and also to other hazard types.

One example to look out for is the PRIMAVERA dataset for winter windstorms. It will provide probabilistic event footprints based on 1700 years of climate model simulations and also includes footprints based on mid-century climate change scenarios (Lockwood *et al.*, 2020). Such open-access datasets in combination with open-source impact models have the potential to set a new standard in risk assessments, not least for legal requirements of insurance or physical risk disclosure (e.g., Task Force for Climate-related Financial Disclosure, Westcott et al., 2020), as laid out in chapter 4.

The CLIMADA platform and the risk assessment implemented specifically in chapter 4 showcase such an easily adaptable decision support tool. Open-access datasets for other hazard types are available (e.g. flood: Sauer *et al.*, 2021) and readily available on the mentioned platform.

6.5.5 Impact forecasting system

With this thesis, proof of concept for incorporating impacts in weather warnings has been established. Many learnings are transferable to other impact forecasting endeavours. However, further research in general and development in particular is often required still to switch any particular warning system from hazard-based warnings towards incorporating impacts for relevant hazards and socio-economic impacts. For this, more examples that cover a wider range of applications and studies for other hazard types would be helpful. Further to that, organizational constraints and cultural barriers in adopting new warning paradigms (WMO, 2015a) shall not be underestimated when designing and managing such evolution of any particular warning system. The following sections suggest further examples and list what aspects they could explore and provide guidance for.

Other impacts of winter windstorms

Impact data for socio-economic impacts other than building damages of winter windstorms is not as readily available. Nevertheless, the findings and general approach of impact forecasting can be transferred to other socio-economic impacts. With the current definition of the windstorm hazard, only exposure and vulnerability have to be changed to simulate other socio-economic impacts of winter windstorms. According to chapter 2, potential impact categories include forest damages (impact metrics such as number of trees or m^3 of wood felled) and traffic and electricity interruptions (impact metric e.g. hours of disruption, transport kilometres lost, number of houses without electricity). For forests, the impact functions published by Feuerstein *et al.* (2011) describing the vulnerability of diseased/unstable treestands, strong tree stands as well as edge trees, as well as leafy and bare branches can serve as a starting point. A special focus has to be given to the exposure, as forests are constantly growing and changing, and species, age and height have an influence both on the exposure and on the vulnerability. For interruptions to traffic or electricity, operational and maintenance management play an important role next to the physical weather risk. Thus, the collaboration with service providers will be a key aspect in the development of such an impact forecasting system. For such collaborations it’s important to plan with enough time for the interaction between the project partners in order to properly co-design and -develop a warning system for proper use (Fischer *et al.*, under review).

Other hazards

The presented methodology and the implementation are compatible with all other hazard types. A first candidate for an additional hazard type relevant in Switzerland is rainfall and subsequent pluvial flooding. This could be brought to use within an application to assess and forecast the impact of heavy rain on emergency service operations. The study “Starkniederschläge und Einsatzplanung von Schutz & Rettung Zürich” by the Federal Office for Civil Protection (2019) already established a threshold-based vulnerability and exposure, that is ready to be implemented in the forecast class in CLIMADA.

In general, bringing more stakeholders to the table would be beneficial for the acceptance of impact forecasting for natural hazard warnings in Switzerland. Taylor *et al.* (2019) highlighted the importance that users understand that impact based warnings are indeed impact based and not hazard based. As Switzerland is using a multi-hazard platform, a mutual move to incorporating impacts might be advisable to be able to inform users accordingly. This would mean that starting initial projects with other warning providers like the Federal Office for the Environment (FOEN) for hydrological hazards or the Institute for Snow and Avalanche Research (SLF) for avalanche risk would be strategically advisable. Early dialogue with PLANAT (the National Platform for Natural Hazards with the objective to advance risk management in Switzerland) might also open avenues for co-design and development with public and private actors.

Compound events

One particular advantage of using weather forecasts as a hazard in impact forecasting is its potential to provide congruent representations of multi-hazard and compound phenomena (Zscheischler *et al.*, 2018). The interaction of multiple hazards in a compounding event can increase or decrease vulnerability, exposure, and subsequently change the magnitude and nature of impacts (Zscheischler *et al.*, 2020; Hillier *et al.*, 2020). The phenomenon of winter storms is not only accompanied by strong gusts, but also heavy precipitation and ensuing floods, landslides and even possibly avalanches following heavy snowfall. E.g., for the Swiss rail company SBB, all of these hazard types are relevant for their service and a collaboration with them could analyse the benefit of a compound event perspective compared to a single hazard perspective for impact forecasting could be illustrated and the interaction between the hazard types and its influence on the interruptions could be analysed. First steps in this direction are undertaken, with the CLIMADA platform having been coupled to the RAMMS avalanche model of the Institute for Snow and Avalanche Research SLF (Ortner *et al.*, 2020).

Time-dependent impacts

Weather forecasts provide hazard information with a precise timing of the occurrence. This could be used to combine such hazards with time-dependent exposure and vulnerability information to arrive a time-dependent impact forecasts. Perrels *et al.* (2015) build a detailed quantitative model on the influence of bad weather conditions on road accidents in Finland. They found that freezing and thawing lead to a higher crash risks in the early winter months, than in late winter, which could inform a time-dependent impact function. Additionally, the traffic density is changing based on the day of the week and time of day, which could inform a time-dependent exposure.

This concept, if successful, would be adaptable to many societal impacts e.g., weather dependent impacts related to travel and leisure activities. For example, the danger in forests - reflected in the behavioural recommendation to stay away from forests during strong winds (Natural Hazards Portal Switzerland, 2021) - could potentially lead to higher impacts due to increased exposure during time periods with high leisure activity like weekends compared to time periods with lower leisure activity such as during night time.

Using qualitative information to configure a quantitative model

Using moderated stakeholder dialog and expert workshops, exposure and vulnerability could well be defined in a transdisciplinary collaboration in case the otherwise-needed quantitative impact data is not available for calibration and verification (compare section 1.6.3 and Souvignet *et al.*, 2016). This would be especially useful for impacts with little data available and for impacts that are less easy to quantify. It would be interesting to study the acceptance and attributed trustworthiness of such impact forecasts by conducting surveys or interviews with experts, forecasters, specific decision-makers and members of the public, both before, during development and after implementation of such a warning system.

Get to know the user, also for general public

NHMS need a detailed knowledge of the broad panel of (potential) users to provide impact forecasts catering to their needs. This is true for decision-makers in partner organisations of the NHMS as well as for members of the general public. In a future implementation of impact-based warnings or impact forecasts for members of the public, it could be crucial both to provide a reasonable default configuration and ensure that each user – or user segment – is able to specify which impacts are particularly relevant for them. Already today, MeteoSwiss provides information about expected impacts and behavioural recommendations to each warning type and level. In a first step, the user could select which of the expected impacts and behavioural recommendations are most relevant to them. If possible, this could be done specifically for each location a user wishes to receive warning notifications for. The most relevant information would then be featured more prominently in warning notifications, e.g., by simply changing the order in the list. Further down the line, the user profiles constructed from such selections could be extended based on, e.g. car ownership, personal mobility, age, housing, etc. to provide even more tailored impact information. Additionally, the user profiles could help the NHMS to find and prioritize future development needs to provide the most relevant impact information and behavioural recommendations.

6.5.6 Options appraisal

Both decision support tools presented in chapters 4 and 5 model the impacts of winter windstorms event based and spatially explicit. For the interested user, damage and cost reductions through modelled adaptation and mitigation options could readily be implemented on the CLIMADA platform, as done already for Economics of Climate Adaptation studies worldwide (Bresch & Aznar-Siguan, 2021). Such an implementation would allow for providing the cost-benefit ratio and other inputs into a multi criteria analysis or option appraisal. In the case of impact forecasts, looking at option appraisal for a user means a deeper conversation about the possible options applicable prior to extreme weather events. This conversation allows the testing of different strategies using the forecast scenarios of previous events. Next to the strategic benefits of such an endeavour another possible outcome are individualized behavioural recommendations tailored to the user that could speed up the decision on preventive options in the short time available prior to an event.

7 Conclusions

This thesis developed, presented and discussed decision-support tools around the socio-economic impacts of winter windstorms in the alpine region. The tools provide straight-forward and usable risk assessments in the metric of the socio-economic impact. The computational tools are implemented in the event-based and probabilistic risk assessment platform CLIMADA. The risk of the socio-economic impacts is modelled as a combination of hazard, exposure, and vulnerability. The hazard is based on meteorological or climatological data on the location, intensity and probability of winter windstorm events. The exposure represents the value at risk and is typically defined specifically for a respective application or use-case. Exposure data includes the spatial extend, location and distribution of the values. The vulnerability is defined by an impact function linking the wind gust intensity with damage ratios. The model output is calibrated and validated using data on observed socio-economic impacts (e.g., building damage). These prototypes are shared open-source and open-access to allow future research on risk assessments as well as allow the uptake of these methodologies by decision-makers in society. For this, the methods and results are presented and discussed in technical reports and scientific publications. Complementarily, the use and interpretation of modelled socio-economic impacts in decision-making are illustrated and discussed with applied examples.

In chapter 2, the impact of the winter storm Burglind/Eleanor (3 January 2018) were collected and reviewed to form an understanding of the socio-economic impacts of winter windstorms and the severity of individual events. Chapter 3 evaluates a new and openly available dataset of the intensities of historic and synthetic winter windstorm events by comparing it both to industry and research data. In chapter 4, the risk of building damage due to winter windstorms for the canton of Zurich, Switzerland is assessed based on a claims-based perspective and a probabilistic risk modelling approach and the associated uncertainties are discussed. In chapter 5, an impact forecasting system for building damages in Switzerland is build and deployed as a semi-operational prototype. The skill of the forecasted building damage is assessed in a comparison with insurance claims data.

Relevant learnings can be drawn from the implementations of the decision support tools and their results, both for research and application. The impact model helps derive straight-forward impact and risk information from climatological or meteorological data. The exposure plays an important role in defining the focus of the resulting information: In chapter 4, it represents the specified portfolio of an insurer and allows the assessment of the risk such as exceedance frequency curves. This portfolio-specific risk cannot robustly be derived only by analysing claims data nor can it be derived from pan-European analysis. In the context of warnings, the incorporation of exposure values provides a portfolio risk perspective, instead of the single risk perspective if no exposure values are provided. It additionally helps to underline the impact focus of the warning by showing a recognizable pattern in illustrations of the impact forecast.

Another key learning from this thesis underlines the need for systematic collection of high quality impact data of a wide spectrum of socio-economic impacts. Impact data are a crucial requirement for calibrating and evaluating impact forecasts. Collecting impact is a prerequisite, if the benefit of the presented decision support tools should be harvested in other applications.

In future projects, more components of the impact model should be defined probabilistically, e.g., a probabilistic representation of impact functions, that link hazard intensities not only with the best guess of expected damage degree but also with the spread of possible outcomes. With that, the uncertainty can be assessed in a quantitative way. Additionally, the second-order uncertainty of such modelling approaches can be highlighted by combining different implementations of exposure and vulnerability components of impact models in an ensemble of opportunity. The relevance of representing a fuller picture of the uncertainty can then be discussed in the context scientific findings as well as applied purposes.

The proof of concept for incorporating impacts like building damage in weather warnings has been demonstrated with this thesis. This prototype is a stepping-stone in bringing impact models up to the same quality and dependability as existing hazard models. This achievement will help to shape the current discussion in National Hydrological and Meteorological Services about incorporating socio-economic impacts into weather warnings. The presented and deployed prototype is built in a flexible structure. The implementation in CLIMADA can represent all degrees of incorporating impacts into warning systems – from hazard-based warnings to impact-based warnings to the shown impact forecasts. The system is also readily adaptable to other types of hazard such as e.g., heavy precipitation, and impact types such as e.g., forest damages and affected population. Impact forecasting for weather warnings should not fall behind the standards set by this thesis regarding the spatially explicit modelling using hazard, exposure and vulnerability.

Future research and applications can profit from the transparently documented and openly shared implementations. The full potential of the open-source tools presented here can be realised in combination with (1) the increasingly available climatological data in the context of "climate services" and (2) meteorological forecasts with open data-access and application programming interfaces (API) to numerical weather prediction data. The integration of forecasts and climatological risk in one platform can help foster a seamless exchange between the two fields, for example, the representation of new hazards and compound events could profit from this exchange. The impact forecasting system for building damages is readily available as a decision support tool in the building insurance sector. The open-source implementation lends itself to be extended into a full option appraisal tool by additionally modelling adaptation and mitigation options and the resulting damage and cost reductions.

8 References

Ágústsson H., Ólafsson H. 2004. Mean gust factors in complex terrain. *Meteorologische Zeitschrift* **13**:149–155. *Available at http://dx.doi.org/10.1127/0941-2948/2004/0013-0149*.

Andrews RJ., Quintana LM. 2015. Unpredictable, unpreventable and impersonal medicine: global disaster response in the 21st century. *EPMA Journal* **6**:2. *Available at https://doi.org/10.1186/s13167-014-0024-9*.

Aznar-Siguan G., Bresch DN. 2019. CLIMADA v1: a global weather and climate risk assessment platform. *Geosci. Model Dev.* **12**:3085–3097. *Available at https://gmd.copernicus.org/articles/12/3085/2019/*.

Aznar-Siguan G., Eberenz S., Steinmann C., Vogt T., Röösli T., Sauer IJ., Mühlhofer E., Hartman J., Ciullo A., Kropf C., Bresch DN., Schmid E., Guillod B., Stalhandske Z., Wüthrich J., Kam PM., Meiler S., Bungener R., Fairless C., Lüthi S., Bozzini V., Stocker D., Geiger T., Nesa V., Beck T., Zhu Q. 2021. *CLIMADA-project/climada_python: v2.1.0*. Zenodo. *Available at https://doi.org/10.5281/zenodo.4659173*

BAFU 2020. *Jahrbuch Wald und Holz 2019*. Bern, p. 106. *Available at https://www.bafu.admin.ch/bafu/de/home/themen/wald/publikationen-studien/publikationen/jahrbuch-wald-und-holz.html* (accessed April 17, 2021).

BAFU 2021a. *Jahrbuch Wald und Holz. Available at https://www.bafu.admin.ch/bafu/de/home/themen/wald/publikationen-studien/publikationen/jahrbuch-wald-und-holz.html* (accessed April 13, 2021).

BAFU 2021b. *EconoMe Objektparameter*. Bern, . *Available at https://econome.ch/eco_work/temp/doku_Objekte_1619024903.pdf* (accessed April 21, 2021).

Born K., Ludwig P., Pinto JG. 2012. Wind gust estimation for Mid-European winter storms: Towards a probabilistic view. *Tellus, Series A: Dynamic Meteorology and Oceanography* **64**.

Bouwer LM. 2019. Observed and Projected Impacts from Extreme Weather Events: Implications for Loss and Damage. In: Mechler R, Bouwer LM, Schinko T, Surminski S, Linnerooth-Bayer J eds. *Loss and Damage from Climate Change: Concepts, Methods and Policy Options*. Cham: Springer International Publishing, 63–82.

Brasseur O. 2001. Development and Application of a Physical Approach to Estimating Wind Gusts. *Monthly Weather Review* **129**:5–25. *Available at https://journals.ametsoc.org/view/journals/mwre/129/1/1520-0493_2001_129_0005_daaoap_2.0.co_2.xml*.

Bresch DN. 2016. Shaping Climate Resilient Development: Economics of Climate Adaptation. In: Salzmann N, Huggel C, Nussbaumer SU, Ziervogel G eds. *Climate Change Adaptation Strategies – An Upstream-downstream Perspective*. Cham: Springer International Publishing, 241–254.

Bresch DN., Aznar-Siguan G. 2019. *CLIMADA-python*. *Available at https://github.com/CLIMADA-project/climada_python* (accessed July 17, 2019).

Bresch DN., Aznar-Siguan G. 2021. CLIMADA v1.4.1: towards a globally consistent adaptation options appraisal tool. *Geoscientific Model Development* **14**:351–363. *Available at https://gmd.copernicus.org/articles/14/351/2021/*.

Bresch DN., Aznar-Siguan G., Bozzini V., Bungener R., Eberenz S., Hartman J., Mühlhofer E., Pérus M., Röösli T., Saurer I., Schmid E., Stalhandske Z., Steinmann C., Stocker D. 2020. *CLIMADA_python v1.4.1*. *Available at https://doi.org/10.5905/ethz-1007-252*

Buzzi M. 2012. COSMO-2 model performance in forecasting Foehn: a systematic process oriented verification. In: Lugano,. *Available at http://www.cosmo-model.org/content/consortium/generalMeetings/general2012/wg5-versus/buzzi_foehn.pdf* (accessed April 1, 2021).

Catto JL., Ackerley D., Booth JF., Champion AJ., Colle BA., Pfahl S., Pinto JG., Quinting JF., Seiler C. 2019. The Future of Midlatitude Cyclones. *Current Climate Change Reports* **5**:407–420. *Available at https://doi.org/10.1007/s40641-019-00149-4*.

CESARE 2019. *CESARE - CollEction, Standardization and Attribution of Robust disaster Event information*. *Available at* *https://projekte.ffg.at/projekt/3307382* (accessed April 13, 2021).

City of Zurich 2020. *Zurich construction price index. Available at https://www.stadt-zuerich.ch/prd/de/ index/statistik/themen/bauen-wohnen/wohnbaupreise/ zuercher-index-der-wohnbaupreise.html* (accessed January 14, 2020).

CLIMADA 2018. *CLIMADA manual. Available at https://github.com/davidnbresch/climada* (accessed May 9, 2021).

Compo GP., Whitaker JS., Sardeshmukh PD., Matsui N., Allan RJ., Yin X., Gleason BE., Vose RS., Rutledge G., Bessemoulin P., Brönnimann S., Brunet M., Crouthamel RI., Grant AN., Groisman PY., Jones PD., Kruk MC., Kruger AC., Marshall GJ., Maugeri M., Mok HY., Nordli Ø., Ross TF., Trigo RM., Wang XL., Woodruff SD., Worley SJ. 2011. The Twentieth Century Reanalysis Project. *Quarterly Journal of the Royal Meteorological Society* **137**:1–28. *Available at https://doi.org/10.1002/qj.776*.

COSMO. 2020. Consortium for Small-scale Modeling. *Available at http://www.cosmo-model.org* (accessed October 13, 2020).

Dallo I., Stauffacher M., Marti M. 2020. What defines the success of maps and additional information on a multi-hazard platform? *International Journal of Disaster Risk Reduction* **49**:101761. *Available at https://linkinghub.elsevier.com/retrieve/pii/S2212420920312632*.

Davies T., Cullen MJP., Malcolm AJ., Mawson MH., Staniforth A., White AA., Wood N. 2005. A new dynamical core for the Met Office’s global and regional modelling of the atmosphere. *Quarterly Journal of the Royal Meteorological Society* **131**:1759–1782. *Available at https://doi.org/10.1256/qj.04.101*.

Dawkins LC., Stephenson DB., Lockwood JF., Maisey PE. 2016. The 21st century decline in damaging European windstorms. *Natural Hazards and Earth System Sciences* **16**:1999–2007.

De Groeve T., Poljansek K., Ehrlich D. 2013. *Recording disaster losses: recommendations for a European approach.* LU:

Publications Office. *Available at https://data.europa.eu/doi/10.2788/98653*

Dee DP., Uppala SM., Simmons AJ., Berrisford P., Poli P., Kobayashi S., Andrae U., Balmaseda MA., Balsamo G., Bauer P., Bechtold P., Beljaars ACM., van de Berg L., Bidlot J., Bormann N., Delsol C., Dragani R., Fuentes M., Geer AJ., Haimberger L., Healy SB., Hersbach H., Hólm EV., Isaksen L., Kållberg P., Köhler M., Matricardi M., McNally AP., Monge-Sanz BM., Morcrette J-J., Park B-K., Peubey C., de Rosnay P., Tavolato C., Thépaut J-N., Vitart F. 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society* **137**:553–597. *Available at https://doi.org/10.1002/qj.828*.

Della-Marta PM., Liniger MA., Appenzeller C., Bresch DN., KöLlner-Heck P., Muccione V. 2010. Improved estimates of the European winter windstorm climate and the risk of reinsurance loss using climate model data. *Journal of Applied Meteorology and Climatology* **49**:2092–2120.

Donat MG., Leckebusch GC., Wild S., Ulbrich U. 2010. Benefits and limitations of regional multi-model ensembles for storm loss estimations. *Climate Research* **44**:211–225.

Donat MG., Leckebusch GC., Wild S., Ulbrich U. 2011a. Future changes in European winter storm losses and extreme wind speeds inferred from GCM and RCM multi-model simulations. *Natural Hazards and Earth System Science* **11**:1351–1370.

Donat MG., Pardowitz T., Leckebusch GC., Ulbrich U., Burghoff O. 2011b. High-resolution refinement of a storm loss model and estimation of return periods of loss-intensive storms over Germany. *Natural Hazards and Earth System Science* **11**:2821–2833.

Eberenz S., Stocker D., Röösli T., Bresch DN. 2020. Asset exposure data for global physical risk assessment. *Earth Syst. Sci. Data* **12**:817–833. *Available at https://essd.copernicus.org/articles/12/817/2020/*.

ECMWF 2021. IFS Documentation. *Available at https://www.ecmwf.int/en/publications/ifs-documentation* (accessed April 12, 2021).

EEA 2016. *Corine Land Cover Database 2012*. Copenhagen, Denmark,

ETH Zürich 2021. ECA Case Studies. *Available at https://wcr.ethz.ch/research/casestudies.html* (accessed May 9, 2021).

Etienne C., Beniston M. 2012. Wind storm loss estimations in the Canton of Vaud (Western Switzerland). *Natural Hazards and Earth System Sciences* **12**:3789–3798. *Available at https://nhess.copernicus.org/articles/12/3789/2012/*.

Federal Office for Civil Protection 2019. *Starkniederschläge und Einsatzplanung von Schutz & Rettung Zürich*. Bern, p. 82. *Available at https://www.babs.admin.ch/de/publikservice/downloads/gefrisiken.html* (accessed April 6, 2021).

Federal Office for the Environment Switzerland. 2020. LAINAT and GIN secretariats. *Available at https://www.bafu.admin.ch/bafu/de/home/amt/geschaeftsstellen-lainat-und-gin.html* (accessed November 23, 2020).

Feuerstein B., Groenemeijer P., Dirksen E., Hubrig M., Holzer AM., Dotzek N. 2011. Towards an improved wind speed scale and damage description adapted for Central Europe. *Atmospheric Research* **100**:547–564. *Available at http://dx.doi.org/10.1016/j.atmosres.2010.12.026*.

Fischer LJ., Wernli H., Bresch DN. under review. Widening the common space to reduce the gap between climate science and decision-making in industry.

Fischer LJ., Wernli H., Bresch DN. in preparation. Widening the common space to reduce the gap between climate science and decision-making.

Fleischhut N., Herzog SM., Hertwig R. 2020. Weather Literacy in Times of Climate Change. **12**:18.

Geiger T., Frieler K., Bresch DN. 2018. A global historical data set of tropical cyclone exposure (TCE-DAT). *Earth System Science Data* **10**:185–194.

Gettelman A., Bresch DN., Chen CC., Truesdale JE., Bacmeister JT. 2017. Projections of future tropical cyclone damage with a high-resolution global climate model. *Climatic Change*:1–11.

Gettelman A., Rood RB. 2016. *Demystifying climate models: a users guide to earth system models*. Springer Nature.

GIN 2019. *Overview of the GIN Platform*. *Available at https://www.info.gin.admin.ch/bafu_ gin/en/home/gin/overview.html* (accessed November 19, 2019).

GIS browser Zurich 2019. *GIS browser Zurich*. *Available at http://www.maps.zh.ch/* (accessed September 18, 2019).

Guha-Sapir D., Below R. 2002. *Quality and accuracy of disaster data: A comparative analyse of 3 global data sets.* 2002, . *Available at http://www.cred.be/sites/default/files/Quality_accuracy_disaster_data.pdf* (accessed April 19, 2021).

Guha-Sapir D., Checchi F. 2018. Science and politics of disaster death tolls. *BMJ* **362**:k4005. *Available at http://www.bmj.com/content/362/bmj.k4005.abstract*.

Guha-Sapir Debarati 2021. EM-DAT The International Disaster Database. *Available at https://www.emdat.be/* (accessed April 19, 2021).

GVZ 2018. *Annual Report*. Zurich: GVZ, . *Available at https://www.gvz.ch/_file/1228/01111018003-web-gvz-gb2018-210x297-es-anhang.pdf* (accessed February 21, 2020).

GVZ 2021. Homepage. *Available at https://www.gvz.ch/,* (accessed April 14, 2021).

Haas R., Pinto JG. 2012. A combined statistical and dynamical approach for downscaling large-scale footprints of European windstorms. *Geophysical Research Letters* **39**. *Available at https://doi.org/10.1029/2012GL054014*.

Hamish Steptoe 2017. *C3S WISC Event Set Description*. *Available at https://wisc.climate.copernicus.eu/wisc/documents/shared/C3S _WISC_Event Set_Description_v1.0.pdf,* (accessed April 12, 2021).

Hauge \AAshild Lappegard., Flyen C., Ven\aas C., Aall C., Kokkonen A., Ebeltoft M. 2018. *Attitudes in Norwegian insurance companies towards sharing loss data–Public-private cooperation for improved climate adaptation*p. 47. *Available at https://sintef.brage.unit.no/sintef-xmlui/handle/11250/2581670* (accessed April 13, 2021).

Hayes B., Whittaker D., Dixon R. 2018. *WISC Summary Report of Task 5.1-OASIS User Case Study*. *Available at https://wisc.climate.copernicus.eu/wisc/documents/shared/(C3S_441_Lot3_WISC_SC2-D5.1-CGI-RP-18-0101)%20(OASIS%20Case%20Study)%20(1.0).pdf* (accessed May 3, 2021).

Heim C. 2018. *Improving the Wind Gust Parameterization in COSMO-1. Available at Unpublished report*

Hemingway R., Gunawan O. 2018. The Natural Hazards Partnership: A public-sector collaboration across the UK for natural hazard disaster risk reduction. *International Journal of Disaster Risk Reduction* **27**:499–511. *Available at https://linkinghub.elsevier.com/retrieve/pii/S2212420917303370*.

Hemingway R., Robbins J. 2020. Developing a hazard-impact model to support impact-based forecasts and warnings: The Vehicle OverTurning (VOT) Model. *Meteorol Appl* **27**. *Available at https://onlinelibrary.wiley.com/doi/abs/10.1002/met.1819*.

Heneka P., Ruck B. 2008. A damage model for the assessment of storm damage to buildings. *Engineering Structures* **30**:3603–3609. *Available at http://dx.doi.org/10.1016/j.engstruct.2008.06.005*.

Hersbach H., Dee D. 2016. *ERA5 reanalysis is in production*. Reading, UK, . *Available at https://www.ecmwf.int/en/newsletter/147/news/era5-reanalysis-production* (accessed May 9, 2021).

Hewitt C., Mason S., Walland D. 2012. The global framework for climate services. *Nature Climate Change* **2**:831–832. *Available at http://dx.doi.org/10.1038/nclimate1745*.

Hewson TD., Neu U. 2015. Cyclones, windstorms and the IMILAST project. *Tellus, Series A: Dynamic Meteorology and Oceanography* **6**.

Hewson TD., Titley HA. 2010. Objective identification, typing and tracking of the complete life-cycles of cyclonic features at high spatial resolution. *Meteorological Applications* **17**:355–381. *Available at https://doi.org/10.1002/met.204*.

Hillier JK., Matthews T., Wilby RL., Murphy C. 2020. Multi-hazard dependencies can increase or decrease risk. *Nature Climate*

Change **10**:595–598. *Available at https://doi.org/10.1038/s41558-020-0832-y*.

Imhof M. 2011. *Analyse langfristiger Gebäudeschadendaten*. Bern: Interkantonaler Rückversicherungsverband, . *Available at https://docplayer.org/17951561-Analyse-langfristiger-gebaeudeschadendaten.html* (accessed April 11, 2021).

International Standards Organization 2009. *Risk Management: Principles and Guidelines*. International Standards Organization Geneva, Switzerland. *Available at https://www.iso.org/obp/ui#iso:std:iso:31000:ed-2:v1:en*

IPCC 2012. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. Cambridge: Cambridge University Press. *Available at http://ebooks.cambridge.org/ref/id/CBO9781139177245*

IPCC 2014. Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. In: Field CB, Barros VR, Dokken D, Mach K, Mastrandrea M, Bilir T, Chatterjee M, Ebi K, Estrada Y, Genova R, Girma B, Kissel E, Levy A, MacCracken S, Mastrandrea P, White I eds. *Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge, UK, and New York, USA: Cambridge University Press, 833–868.

JRC EU expert working group on disaster damage and loss data 2015. Guidance for Recording and Sharing Disaster Damage and Loss Data. *JRC Science and Policy Reports*:28. *Available at http://drr.jrc.ec.europa.eu/Portals/0/Loss/JRC_guidelines_loss_data_recording_v10.pdf.*

Kaltenberger R., Schaffhauser A., Staudinger M. 2020. "What the weather will do" – results of a survey on impact-oriented and impact-based warnings in European NMHSs. *Adv. Sci. Res.* **17**:29–38. *Available at https://asr.copernicus.org/articles/17/29/2020/.*

Karremann MK., Pinto JG., Von Bomhard PJ., Klawa M. 2014. On the clustering of winter storm loss events over Germany. *Natural Hazards and Earth System Sciences* **14**:2041–2052.

Klawa M., Ulbrich U. 2003. A model for the estimation of storm losses and the identification of severe winter storms in Germany.

Natural Hazards and Earth System Sciences **3**:725–732. *Available at http://apps.webofknowledge.com/full_record.do?product=UA&search_mode=GeneralSearch&qid=48&SID=W1f6NPcgesxznir7aU7&page=4&doc=32&cacheurlFromRightClick=no*.

Koks EE., Haer T. 2020. A high-resolution wind damage model for Europe. *Sci Rep* **10**:6866. *Available at http://www.nature.com/articles/s41598-020-63580-w*.

Kropf CM., Ciullo A., Meiler S., Otth L., McCaughey JW., Bresch DN. 2021. *Uncertainty and sensitivity analysis for natural risk and adaptation appraisal modeling with CLIMADA*

Kube M., Ambühl J., Appenzeller C., Binder P., Comment T., Félix C., Frei C., Gaia M., Germann U., Grüter E., Hering A., Keller F., Meier D., Nisi L., Panziera L., Reiniger T., Romang H., Reynolds S., Stoll M., Vogt S., Calpini B. 2016. *Optimierung der Warnung und Alarmierung vor Naturgefahren bei MeteoSchweiz*p. 136. *Available at https://www.meteoschweiz.admin.ch/home/service-und-publikationen/publikationen.subpage.html/de/data/publications/2016/4/optimierung-der-warnung-und-alarmierung-vor-naturgefahren-bei-meteoschweiz.html?query=Warnungen&topic=0&publicationYear=&pageIndex=0* (accessed April 9, 2021).

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

Lattimore C. 2019. 10 years of the Flood Forecasting Centre (England and Wales). From flood risk assessment to verification. In: Copenhagen,. *Available at https://meetingorganizer.copernicus.org/EMS2019/EMS2019-303.pdf* (accessed April 11, 2021).

Lazo JK., Hosterman HR., Sprague-Hilderbrand JM., Adkins JE. 2020. Impact-based decision support services and the socioeconomic impacts of winter storms. *Bulletin of the American Meteorological Society* **101**:E626–E639.

Leckebusch GC., Renggli D., Ulbrich U. 2008. Development and application of an objective storm severity measure for the

Northeast Atlantic region. *Meteorologische Zeitschrift* **17**:575–587.

Lockwood J., Palin E., Guentchev G., Roberts M. 2020. Using PRIMAVERA high-resolution global climate models for European windstorm risk assessment in present and future climates for the (re) insurance industry. In: *EGU General Assembly Conference Abstracts*.

Lorenz EN. 1963. Deterministic Nonperiodic Flow. *Journal of Atmospheric Sciences* **20**:130–141. *Available at https://journals.ametsoc.org/view/journals/atsc/20/2/1520-0469_1963_020_0130_dnf_2_0_co_2.xml*.

Maisey P., Becker B., Steptoe H. 2017. *WISC Storm Footprint (Gridded Windfield) Description*. *Available at https://wisc.climate.copernicus.eu/wisc/documents/shared/C3S_WISC%20Storm_Footprint_(Gridded_Windfield)_Descrpition_v1.0.pdf*

Merz B., Kuhlicke C., Kunz M., Pittore M., Babeyko A., Bresch DN., Domeisen DIV., Feser F., Koszalka I., Kreibich H., Pantillon F., Parolai S., Pinto JG., Punge HJ., Rivalta E., Schröter K., Strehlow K., Weisse R., Wurpts A. 2020. Impact Forecasting to Support Emergency Management of Natural Hazards. *Rev. Geophys.*. *Available at https://onlinelibrary.wiley.com/doi/abs/10.1029/2020RG000704*.

MeteoSwiss 2016. Die MeteoSchweiz App: Ab sofort noch übersichtlicher. *Available at https://www.meteoschweiz.admin.ch/home/aktuell/meteoschweiz-blog/meteoschweiz-blog-suche.subpage.html/de/data/blogs/2016/11/die-meteoschweiz-app--ab-sofort-noch-uebersichtlich.html?query=app&topic=0&timerange=&dateFrom=&dateTo=&pageIndex=0&tab=search_tab* (accessed May 3, 2021).

MeteoSwiss 2019. 20 Jahre danach – Was sich seit Lothar verändert hat. *Available at https://www.meteoschweiz.admin.ch/home/aktuell/meteoschweiz-blog/meteoschweiz-blog.subpage.html/de/data/blogs/2019/12/20-Jahre-*

danach%E2%80%93Was-sich-seit-Lothar-veraendert-hat.html (accessed April 9, 2021).

MeteoSwiss. 2020. COSMO-Prognosesysteme. *Available at https://www.meteoschweiz.admin.ch/home/mess-und-prognosesysteme/warn-und-prognosesysteme/cosmo-prognosesysteme.html* (accessed October 13, 2020).

Mitchell-Wallace K. (ed.) 2017. *Natural catastrophe risk management and modelling: a practitioner's guide*. Hoboken, NJ: John Wiley and Sons, Inc.

Mizielinski MS., Roberts MJ., Vidale PL., Schiemann R., Demory ME., Strachan J., Edwards T., Stephens A., Lawrence BN., Pritchard M., Chiu P., Iwi A., Churchill J., Del Cano Novales C., Kettleborough J., Roseblade W., Selwood P., Foster M., Glover M., Malcolm A. 2014. High-resolution global climate modelling: The UPSCALE project, a large-simulation campaign. *Geoscientific Model Development* **7**:1629–1640.

Mölter T., Schindler D., Albrecht AT., Kohnle U. 2016. Review on the Projections of Future Storminess over the North Atlantic European Region. *Atmosphere* **7**. *Available at https://www.mdpi.com/2073-4433/7/4/60*.

Munich Re 2002. *Winter storms in Europe (II): Analysis of 1999 losses and loss potentials*. Munich, Germany, . *Available at https://www.planat.ch/fileadmin/PLANAT/planat_pdf/alle_2012/2001-2005/Munich_Re_Group_2002_-_Winter_storms_in_Europe_II.pdf* (accessed May 10, 2021).

Munich Re 2011. *NatCatSERVICE: natural catastrophe know-how for risk management and research*. München: Münchener Rückversicherungs-Gesellschaft, . *Available at https://www.munichre.com/content/dam/munichre/contentlounge/website-pieces/documents/302-06733_en.pdf* (accessed April 13, 2021).

Natural Hazards Portal Switzerland 2021. Danger levels wind. *Available at https://www.natural-hazards.ch/home/dealing-with-natural-hazards/wind/danger-levels.html* (accessed February 17, 2021).

Neal RA., Boyle P., Grahame N., Mylne K., Sharpe M. 2014. Ensemble based first guess support towards a risk-based severe weather warning service: Ensemble severe weather forecasts. *Met. Apps* **21**:563–577. *Available at http://doi.wiley.com/10.1002/met.1377*.

Nurmi P., Perrels A., Nurmi V. 2013. Expected impacts and value of improvements in weather forecasting on the road transport sector. *Meteorological Applications* **20**:217–223. *Available at https://doi.org/10.1002/met.1399*.

Oasis 2018. *Oasis Loss Modelling Framework*. *Available at https://github.com/OasisLmf*

OpenStreetMap 2021. Open Street Map. *Available at https://www.openstreetmap.org* (accessed April 21, 2021).

Ortner G., Bruendl M., Bresch DN., Bühler Y. 2020. From Large Scale Hazard Mapping to Risk Assessment. In: *EGU General Assembly Conference Abstracts*. Online,.

Palmer TN. 2000. Predicting uncertainty in forecasts of weather and climate. *Reports on Progress in Physics* **63**:71–116. *Available at http://dx.doi.org/10.1088/0034-4885/63/2/201*.

Palmer TN., Mureau R., Molteni F. 1990. THE MONTE CARLO FORECAST. *Weather* **45**:198–207. *Available at https://doi.org/10.1002/j.1477-8696.1990.tb05619.x*.

Pantillon F., Knippertz P., Corsmeier U. 2017. Revisiting the synoptic-scale predictability of severe European winter storms using ECMWF ensemble reforecasts. *Nat. Hazards Earth Syst. Sci.* **17**:1795–1810. *Available at https://nhess.copernicus.org/articles/17/1795/2017/*.

Pardowitz T., Osinski R., Kruschke T., Ulbrich U. 2016a. An analysis of uncertainties and skill in forecasts of winter storm losses. *Natural Hazards and Earth System Sciences* **16**:2391–2402.

Pardowitz T., Osinski R., Kruschke T., Ulbrich U. 2016b. An analysis of uncertainties and skill in forecasts of winter storm losses. *Nat. Hazards Earth Syst. Sci.* **16**:2391–2402. *Available at https://nhess.copernicus.org/articles/16/2391/2016/*.

PERILS AG 2021. Industry Exposure and Loss Database. *Available at https://www.perils.org/losses* (accessed April 13, 2021).

Perrels A., Votsis A., Nurmi V., Pilli-Sihvola K. 2015. Weather Conditions, Weather Information and Car Crashes. *ISPRS*

International Journal of Geo-Information **4**:2681–2703. *Available at http://dx.doi.org/10.3390/ijgi4042681*.

Pinto JG., Pantillon F., Ludwig P., Déroche M-S., Leoncini G., Raible CC., Shaffrey LC., Stephenson DB. 2019. From Atmospheric Dynamics to Insurance Losses: An Interdisciplinary Workshop on European Storms. *Bulletin of the American Meteorological Society* **100**:ES175–ES178. *Available at https://journals.ametsoc.org/bams/article/100/6/ES175/343810/From-Atmospheric-Dynamics-to-Insurance-Losses-An*.

PLANAT 2018. *Management of Risks from Natural Hazards Strategy 2018*. *Available at https://www.planat.ch/fileadmin/PLANAT/Strategie2018/Strategie_en.pdf* (accessed May 3, 2021).

Pohl C., Krütli P., Stauffacher M. 2017. Ten Reflective Steps for Rendering Research Societally Relevant. *GAIA - Ecological Perspectives for Science and Society* **26**:43–51. *Available at http://www.ingentaconnect.com/content/10.14512/gaia.26.1.10*.

Poli P., Hersbach H., Dee DP., Berrisford P., Simmons AJ., Vitart F., Laloyaux P., Tan DGH., Peubey C., Thépaut J-N., Trémolet Y., Hólm EV., Bonavita M., Isaksen L., Fisher M. 2016. ERA-20C: An Atmospheric Reanalysis of the Twentieth Century. *Journal of Climate* **29**:4083–4097. *Available at https://journals.ametsoc.org/view/journals/clim/29/11/jcli-d-15-0556.1.xml*.

Porter KA., Jaiswal KS., Wald DJ., Greene M., Comartin C. 2008. Whe-Pager project: A new initiative estimating global building inverntory and its seismic vulnerability. In: *14th World Conference on Earthquake Engineering*. Beijing, China,.

Prahl BF., Rybski D., Burghoff O., Kropp JP. 2015. Comparison of storm damage functions and their performance. *Natural Hazards and Earth System Sciences* **15**:769–788.

Prahl BF., Rybski D., Kropp JP., Burghoff O., Held H. 2012. Applying stochastic small-scale damage functions to German winter storms. *Geophysical Research Letters* **39**:1–6.

Priestley MDK., Dacre HF., Shaffrey LC., Hodges KI., Pinto JG. 2018. The role of serial European windstorm clustering for extreme seasonal losses as determined from multi-centennial simulations of high-resolution global climate model data. *Nat. Hazards Earth Syst. Sci.*:16.

Raible CC., Kleppek S., Wüest M., Bresch DN., Kitoh A., Murakami H., Stocker TF. 2012. Atlantic hurricanes and associated insurance loss potentials in future climate scenarios: limitations of high-resolution AGCM simulations. *null* **64**:15672. *Available at https://doi.org/10.3402/tellusa.v64i0.15672*.

Reguero BG., Bresch DN., Beck M., Calil J., Meliane I. 2014. COASTAL RISKS, NATURE-BASED DEFENSES AND THE ECONOMICS OF ADAPTATION: AN APPLICATION IN THE GULF OF MEXICO, USA. *Coastal Engineering Proceedings* **1**:15. *Available at https://journals.tdl.org/icce/index.php/icce/article/view/7585*.

Roberts JF., Champion AJ., Dawkins LC., Hodges KI., Shaffrey LC., Stephenson DB., Stringer MA., Thornton HE., Youngman BD. 2014. The XWS open access catalogue of extreme European windstorms from 1979 to 2012. *Natural Hazards and Earth System Sciences* **14**:2487–2501.

Röösli T. 2021. *ThomasRoosli/climada_papers_building_damage_forecast*. Zenodo. *Available at http://doi.org/10.5281/zenodo.4696214*

Röösli T., Appenzeller C., Bresch DN. 2021a. Towards operational impact forecasting of building damage from winter windstorms in Switzerland. *Meteorological Applications* **28**:e2035. *Available at https://doi.org/10.1002/met.2035*.

Röösli T., Bresch DN. 2020. Probabilistic Windstorm Hazard Event Set for Europe. . *Available at http://hdl.handle.net/20.500.11850/406567*.

Röösli T., Bresch DN., Wüest M. 2018. *A comparison of the WISC events sets with both industry and research data. WISC Summary Report of Task 5.3 – ETH / Swiss Re Case Study*. *Available at https://wisc.climate.copernicus.eu/wisc/#/help/products#casestudies_section* (accessed May 3, 2021).

Röösli T., Welker C., Bresch DN. 2021b. *ThomasRoosli/climada_papers_winter_windstorms_model: Winter windstorm model*. Zenodo. *Available at https://doi.org/10.5281/zenodo.4442602*

Sauer IJ., Reese R., Otto C., Geiger T., Willner SN., Guillod BP., Bresch DN., Frieler K. 2021. Climate signals in river flood damages emerge under sound regional disaggregation. *Nature Communications* **12**:2128. *Available at https://doi.org/10.1038/s41467-021-22153-9*.

Scherrer S., Salamin C., Weusthoff T., Kaufmann P., Bader S., Röösli T., Aemisegger N., Gut M. 2018. *Der Wintersturm Burglind/Eleanor in der Schweiz*. Zurich: MeteoSchweiz, p. 35. *Available at http://www.meteoschweiz.admin.ch/home/service-und-publikationen/publikationen.subpage.html/de/data/publications/2018/6/der-wintersturm-burglind-eleanor-in-der-schweiz.html* (accessed April 11, 2021).

Schraff C., Reich H., Rhodin A., Schomburg A., Stephan K., Periáñez A., Potthast R. 2016. Kilometre-scale ensemble data assimilation for the COSMO model (KENDA). *Quarterly Journal of the Royal Meteorological Society* **142**:1453–1472. *Available at https://doi.org/10.1002/qj.2748*.

Schwierz C., Köllner-Heck P., Mutter EZ., Bresch DN., Vidale PL., Wild M., Schär C. 2010. Modelling European winter wind storm losses in current and future climate. *Climatic Change* **101**:485–514.

Shapiro MA., Keyser D. 1990. Fronts, Jet Streams and the Tropopause. In: Newton CW, Holopainen EO eds. *Extratropical Cyclones: The Erik Palmén Memorial Volume*. Boston, MA: American Meteorological Society, 167–191.

Shen G., Hwang SN. 2019. Spatial–Temporal snapshots of global natural disaster impacts Revealed from EM-DAT for 1900-2015. *null* **10**:912–934. *Available at https://doi.org/10.1080/19475705.2018.1552630*.

Skelton M., Fischer AM., Liniger MA., Bresch DN. 2019. Who is ‘the user’ of climate services? Unpacking the use of national climate scenarios in Switzerland beyond sectors, numeracy and the research–practice binary. *Climate Services* **15**:100113. *Available at https://www.sciencedirect.com/science/article/pii/S2405880719300548*.

Skelton M., Porter JJ., Dessai S., Bresch DN., Knutti R. 2017. The social and scientific values that shape national climate scenarios: a comparison of the Netherlands, Switzerland and the UK. *Regional Environmental Change* **17**:2325–2338. *Available at https://doi.org/10.1007/s10113-017-1155-z*.

Smits A., Klein Tank AMG., Können GP. 2005. Trends in storminess over the Netherlands, 1962–2002. *International Journal of Climatology* **25**:1331–1344. *Available at https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/joc.1195*.

Souvignet DM., Wieneke DF., Mueller L., Bresch DDN. 2016. Economics of Climate Adaptation (ECA) - Guidebook for Practitioners. :100. *Available at https://www.kfw-entwicklungsbank.de/ PDF/Download-Center/Materialien/2016_No6_Guidebook_ Economics-of-Climate-Adaptation_EN.pdf*.

S&P Global Ratings 2015. *The Heat Is On: How Climate Change Can Impact Sovereign Ratings*. *Available at https://www.spglobal.com/ratings/en/research/articles/151125-the-heat-is-on-how-climate-change-can-impact-sovereign-ratings-9425836* (accessed May 9, 2021).

Sprenger M., Schmidli J., Egloff L. 2018. The Laseyer wind storm - case studies and a climatology. *Meteorologische Zeitschrift* **27**:32. *Available at http://hdl.handle.net/20.500.11850/239023*.

Steppeler J., Doms G., Schättler U., Bitzer HW., Gassmann A., Damrath U., Gregoric G. 2003. Meso-gamma scale forecasts using the nonhydrostatic model LM. *Meteorology and Atmospheric Physics* **82**:75–96. *Available at https://doi.org/10.1007/s00703-001-0592-9*.

Stucki P., Brönnimann S., Martius O., Welker C., Imhof M., Von Wattenwyl N., Philipp N. 2014. A catalog of high-impact windstorms in Switzerland since 1859. *Natural Hazards and Earth System Sciences* **14**:2867–2882.

Stucki P., Brönnimann S., Martius O., Welker C., Rickli R., Dierer S., Bresch DN., Compo GP., Sardeshmukh., D P. 2015. Dynamical downscaling and loss modeling for the reconstruction of historical weather extremes and their impacts a severe foehn storm in 1925. *Bulletin of the American Meteorological Society* **96**:1233–1241.

Stucki P., Dierer S., Welker C., Gómez-Navarro JJ., Raible CC., Martius O., Brönnimann S. 2016. Evaluation of downscaled wind speeds and parameterised gusts for recent and historical windstorms in Switzerland. *Tellus, Series A: Dynamic Meteorology and Oceanography* **68**.

Sturmarchiv Schweiz. 2021. Sturmarchiv Schweiz - Swiss Severe Weather Database. *Available at https://www.sturmarchiv.ch/* (accessed April 1, 2021).

Swiss Re 2017. Natural catastrophes and man-made disasters in 2016: a year of widespread damages. *Sigma*:43. *Available at http://media.swissre.com/documents/sigma1_2011_en.pdf*.

Swiss Re 2021a. CatNet®. *Available at https://www.swissre.com/reinsurance/property-and-casualty/solutions/property-specialty-solutions/catnet.html* (accessed April 14, 2021).

Swiss Re 2021b. Swiss Re Homepage. *Available at https://www.swissre.com/* (accessed April 20, 2021).

Swisstopo 2019. *Digital height model*. Wabern, . *Available at https://shop.swisstopo.admin.ch/en/products/height_models/dhm25200* (accessed August 8, 2019).

Taylor AL., Dessai S., de Bruin WB. 2015. Communicating uncertainty in seasonal and interannual climate forecasts in Europe. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **373**:20140454. *Available at https://doi.org/10.1098/rsta.2014.0454*.

Taylor AL., Kause A., Summers B., Harrowsmith M. 2019. Preparing for doris: Exploring public responses to impact-based weather warnings in the United Kingdom. *Weather, Climate, and Society* **11**:713–729.

The Economics of Climate Adaptation Working Group 2009. *Shaping climate resilient development. A framework for decisionmaking*. *Available at https://ethz.ch/content/dam/ethz/special-interest/usys/ied/wcr-*

dam/documents/Economics_of_Climate_Adaptation_ECA.pdf (accessed May 9, 2021).

Thépaut J-N., Dee D., Engelen R., Pinty B. 2018. The Copernicus programme and its climate change service. In: *IGARSS 2018-2018 IEEE International Geoscience and Remote Sensing Symposium*. IEEE, 1591–1593.

Uccellini LW., Ten Hoeve JE. 2019. Evolving the national weather service to build a weather-ready nation. *Bulletin of the American Meteorological Society* **100**:1923–1942.

Ulbrich U., Leckebusch GC., Pinto JG. 2009. Extra-tropical cyclones in the present and future climate: a review. *Theoretical and Applied Climatology* **96**:117–131. *Available at https://doi.org/10.1007/s00704-008-0083-8*.

UNISDR 2015. *Sendai Framework for Disaster Risk Reduction 2015 - 2030*p. 37

UPSCALE 2020. *UPSCALE Project Overview*. *Available at http://proj.badc.rl.ac.uk/upscale* (accessed February 21, 2020).

Users of MeteoSwiss 2018. Comments to the MeteoSwiss reports Burglind/Eleanor. *Available at https://www.meteoschweiz.admin.ch/home/aktuell/meteoschweiz-blog/meteoschweiz-blog-suche.subpage.html/de/data/blogs/2018/6/wintersturm-burglind--der-umfassende-bericht.html?query=Burglind&topic=0&timerange=&dateFrom=&dateTo=&pageIndex=0&tab=search_tab* (accessed April 17, 2021).

Vautard R., Gobiet A., Sobolowski S., Kjellström E., Stegehuis A., Watkiss P., Mendlik T., Landgren O., Nikulin G., Teichmann C., Jacob D. 2014. The European climate under a 2\hspace0.167em°C global warming. *Environmental Research Letters* **9**:034006. *Available at https://doi.org/10.1088/1748-9326/9/3/034006*.

Vautard R., van Oldenborgh GJ., Otto FEL., Yiou P., de Vries H., van Meijgaard E., Stepek A., Soubeyroux J-M., Philip S., Kew SF., Costella C., Singh R., Tebaldi C. 2019. Human influence on European winter wind storms such as those of January 2018.

Earth Syst. Dynam. **10**:271–286. *Available at https://esd.copernicus.org/articles/10/271/2019/*.

VKG 2020. Relative frequency of causes of damage 2009-2018. *Available at http://www.vkg.ch/de/versicherung/rueckversicherung* (accessed February 25, 2020).

VKG 2021. Relative frequency of causes of damage 2010-2019. *Available at http://www.vkg.ch/de/versicherung/rueckversicherung* (accessed April 12, 2021).

Walz MA., Leckebusch GC. 2019. Loss potentials based on an ensemble forecast: How likely are winter windstorm losses similar to 1990? *Atmospheric Science Letters* **20**:e891. *Available at https://doi.org/10.1002/asl.891*.

Wanner H., Furger M. 1990. The Bise—Climatology of a regional wind north of the Alps. *Meteorology and Atmospheric Physics* **43**:105–115. *Available at https://doi.org/10.1007/BF01028113*.

Weidmann M. 2010. *Schadensverminderung an Gebäudehüllen unter extremer Windeinwirkung»*. Bern, p. 68. *Available at https://www.vkg.ch/media/1078/wind_d.pdf* (accessed April 6, 2021).

Welker C., Martius O. 2015. Large-scale atmospheric flow conditions and sea surface temperatures associated with hazardous winds in Switzerland. *Climate Dynamics* **44**:1857–1869. *Available at https://doi.org/10.1007/s00382-014-2404-1*.

Welker C., Martius O., Stucki P., Bresch D., Dierer S., Brönnimann S. 2016. Modelling economic losses of historic and present-day high-impact winter windstorms in Switzerland. *Tellus, Series A: Dynamic Meteorology and Oceanography* **68**.

Welker C., Röösli T., Bresch DN. 2021. Comparing an insurer's perspective on building damages with modelled damages from pan-European winter windstorm event sets: a case study from Zurich, Switzerland. *Natural Hazards and Earth System Sciences* **21**:279–299. *Available at https://nhess.copernicus.org/articles/21/279/2021/*.

Westcott M., Ward J., Surminski S., Sayers P., Bresch DN., Claire B. 2020. Be Prepared: Exploring Future Climate-Related Risk for

Residential and Commercial Real Estate Portfolios. *The Journal of Alternative Investments* **23**:24–34. *Available at https://jai.pm-research.com/content/23/1/24*.

Wever N. 2012. Quantifying trends in surface roughness and the effect on surface wind speed observations. *Journal of Geophysical Research: Atmospheres* **117**. *Available at https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2011JD017118*.

Weyrich P., Scolobig A., Bresch DN., Patt A. 2018. Effects of Impact-Based Warnings and Behavioral Recommendations for Extreme Weather Events. *Weather, Climate, and Society* **10**:781–796. *Available at https://journals.ametsoc.org/wcas/article/10/4/781/107420/Effects-of-ImpactBased-Warnings-and-Behavioral*.

Weyrich P., Scolobig A., Patt A. 2019. Dealing with inconsistent weather warnings: effects on warning quality and intended actions. *Meteorol Appl* **26**:569–583. *Available at https://onlinelibrary.wiley.com/doi/abs/10.1002/met.1785*.

Weyrich P., Scolobig A., Walther F., Patt A. 2020. Responses to severe weather warnings and affective decision-making. *Nat. Hazards Earth Syst. Sci.* **20**:2811–2821. *Available at https://nhess.copernicus.org/articles/20/2811/2020/*.

Wilks DS., Hamill TM. 2007. Comparison of Ensemble-MOS Methods Using GFS Reforecasts. *Monthly Weather Review* **135**:2379–2390. *Available at https://journals.ametsoc.org/view/journals/mwre/135/6/mwr3402.1.xml*.

WISC 2018. WISC - Windstorm Information Service. *Available at https://wisc.climate.copernicus.eu/wisc/#/* (accessed July 9, 2018).

WISC 2019. Products. *Available at https://wisc.climate.copernicus.eu/wisc/#/help/products* (accessed May 9, 2021).

WMO 2015a. *WMO Guidelines on Multi-hazard Impact-based Forecast and Warning Services*. Geneva: World Meteorological Organization, p. 24. *Available at https://library.wmo.int/index.php?lvl=notice_display&id=17257* (accessed April 1, 2021).

WMO 2015b. *Seamless prediction of the earth system: from minutes to months*. Geneva: World Meteorological Organization, p. 471. *Available at https://library.wmo.int/?lvl=notice_display&id=17276* (accessed April 11, 2021).

WMO 2018. *Guide to meteorological instruments and methods of observation*. Geneva: World Meteorological Organization.

WMO. 2020. *2020 STATE OF CLIMATE SERVICES: RISK INFORMATION AND EARLY WARNING SYSTEMS*. Geneva: World Meteorological Organisation, p. 47. *Available at https://library.wmo.int/index.php?lvl=notice_display&id=21777* (accessed April 1, 2021).

World Bank 2018. *Building the World Bank's Wealth Accounts: Methods and Data*. *Available at https://development-data-hub-s3-public.s3.amazonaws.com/ddhfiles/94641/wealth-methodology-january-30-2018_4_0.pdf* (accessed May 9, 2021).

WSL, BUWAL 2001. *Lothar. Der Orkan 1999. Ereignisanalyse*. Bern: Eidg. Forschungsanstalt WSL und Bundesamt für Umwelt, Wald und Landschaft BUWAL.

Zimmerli P., Renggli D. 2015. Winter storms in Europe: messages from forgotten catastrophes. *SwissRe*. *Available at http://media.swissre.com/documents/Swiss_Re_Winter_storms.pdf*.

Zscheischler J., Martius O., Westra S., Bevacqua E., Raymond C., Horton RM., van den Hurk B., AghaKouchak A., Jézéquel A., Mahecha MD., Maraun D., Ramos AM., Ridder NN., Thiery W., Vignotto E. 2020. A typology of compound weather and climate events. *Nature Reviews Earth & Environment*.

Zscheischler J., Westra S., van den Hurk BJJM., Seneviratne SI., Ward PJ., Pitman A., AghaKouchak A., Bresch DN., Leonard M., Wahl T., Zhang X. 2018. Future climate risk from compound events. *Nature Climate Change* **8**:469–477. *Available at https://doi.org/10.1038/s41558-018-0156-3*.

Zumwald M., Knüsel B., Baumberger C., Hirsch Hadorn G., Bresch DN., Knutti R. 2020. Understanding and assessing uncertainty of observational climate datasets for model evaluation using ensembles. *WIREs Climate Change* **11**:e654. *Available at https://doi.org/10.1002/wcc.654*.

9 Appendix

9.1 Funding statement

This thesis was financed by the starting grant of the Chair Weather and Climate Risks of Prof. Dr. David N. Bresch located at the Swiss Federal Institute of Technology ETH Zurich and the Federal Office of Meteorology and Climatology MeteoSwiss.

9.2 Appendix to chapter 2

9.2.1 Danksagung

Wir danken folgenden Personen und Organisationen für Daten zu den Schäden und Auswirkungen von Burglind/Eleanor: **Christoph Welker** und **Mirco Heidemann** (beide Gebäudeversicherung Zürich), **Markus Imhof** (Interkantonaler Rückversicherungsverband), **Gunthard Niederbäumer** (Schweizerischer Versicherungsverband), **Gabriela Vrecko** (SBB), **Joshu Jullier** (Swissgrid AG), **Rolf Manser**, **Erica Zimmermann** und **Gerda Jimmy** (alle Bundesamt für Umwelt), **Jessica Ladanie** (viasuisse), **Dominique Thiévent** (Beratungsstelle für Unfallverhütung in der Landwirtschaft).

Wir danken folgenden Personen von MeteoSchweiz für die Begutachtung des Berichts: **Christof Appenzeller**, **Marco Arpagaus**, **Heike Kunz**, **Mischa Croci-Maspoli**, **Marco Gaia**, **Roland Mühlebach**, **Christoph Schmutz**, **Cornelia Schwierz** und **Marco Stoll**.

9.2.2 Auszug aus dem Literaturverzeichnis

Bundesamt für Umwelt BAFU, 2018: Winterstürme Anfang 2018: Rund 1.3 Mio m3 Holz liegen am Boden, Medienmitteilung vom 18.01.2018.

Bundesamt für Umwelt BAFU (Hrsg.) 2017: Jahrbuch Wald und Holz 2017. Bundesamt für Umwelt, Bern. Umwelt-Zustand Nr. 1718: 110 S.

Eidg. Forschungsanstalt WSL und Bundesamt für Umwelt, Wald und Landschaft BUWAL (Hrsg.) 2001: Lothar. Der Orkan 1999. Ereignisanalyse. Birmensdorf, Bern; Eidg. Forschungsanstalt WSL, Bundesamt für Umwelt, Wald und Landschaft BUWAL, 365 S.

Gebäudeversicherung Bern: Sturmtief „Burglind“ Schäden in der Höhe von 30 Millionen Franken, Medienmitteilung 11.01.2018.

9.3 Appendix to chapter 3

9.3.1 Contributors

Thomas Röösli / ETH Zurich, Switzerland

Prof. Dr. David N. Bresch / ETH Zurich, Switzerland (lead)

in collaboration with

Dr. Marc Wüest / Swiss Re, Switzerland

Dr. Dominik Renggli / Swiss Re, Switzerland

Dr. Angelika Werner / Swiss Re, Switzerland

Peter Zimmerli / Swiss Re, Switzerland

With support from

Pieter Huisman / Swiss Re, The Netherlands

Editor: Alan Whitelaw / CGI IT UK Limited, United Kingdom

9.4 Appendix to chapter 4

9.4.1 Code and data availability

The scripts reproducing the main results of the paper and the figures are available under https://doi.org/10.5281/zenodo.4442602 (Röösli *et al.*, 2021b). 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 (Röösli & Bresch, 2020).

CLIMADA is openly available at GitHub (https://github.com/CLIMADA-project/climada_python, last access: 17 July 2019; Bresch & Aznar-Siguan, 2019) under the GNU GPL license (GNU operating system, 2007). The documentation is hosted on Read the Docs (https://climada-python.readthedocs.io/en/stable/, last access: 17 July 2019) 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: https://doi.org/10.5905/ethz-1007-252 (Bresch *et al.*, 2020).

9.4.2 Author contributions

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, conceptualized CLIMADA, and oversaw its implementation in Python, based on his own previous MATLAB implementation.

9.4.3 Competing interests

The authors declare that they have no conflict of interest.

9.4.4 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 (last access: 13 January 2021). 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, and Samuel Eberenz and Maurice Skelton for providing valuable input on the manuscript. Additionally, we would like to thank Alexandros Georgiadis and the anonymous referee for providing valuable input during the review process, which helped to improve the manuscript a lot.

9.4.5 Review statement

This paper was edited by Joaquim G. Pinto and reviewed by Alexandros Georgiadis and one anonymous referee.

9.4.6 Appended tables and figures

Table 5 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	-

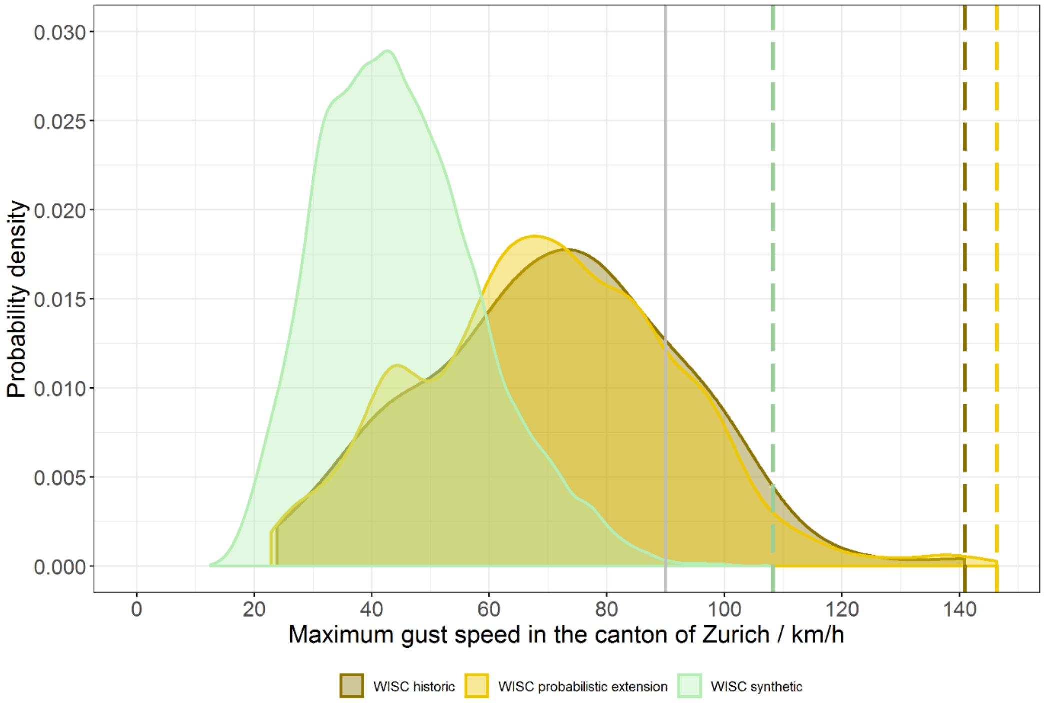


Figure 25 Probability density functions of the maximum gust speeds at building level in the canton of Zurich for the three hazard event sets "WISC historic" (brown), "WISC probabilistic extension" excluding the parent windstorms (yellow), and "WISC synthetic" (green). The maxima of the individual distributions are shown as dashed vertical lines. In the GVZ damage model, damage is possible from a wind gust speed of more than 90 km/h, which is here indicated by a grey solid vertical line.

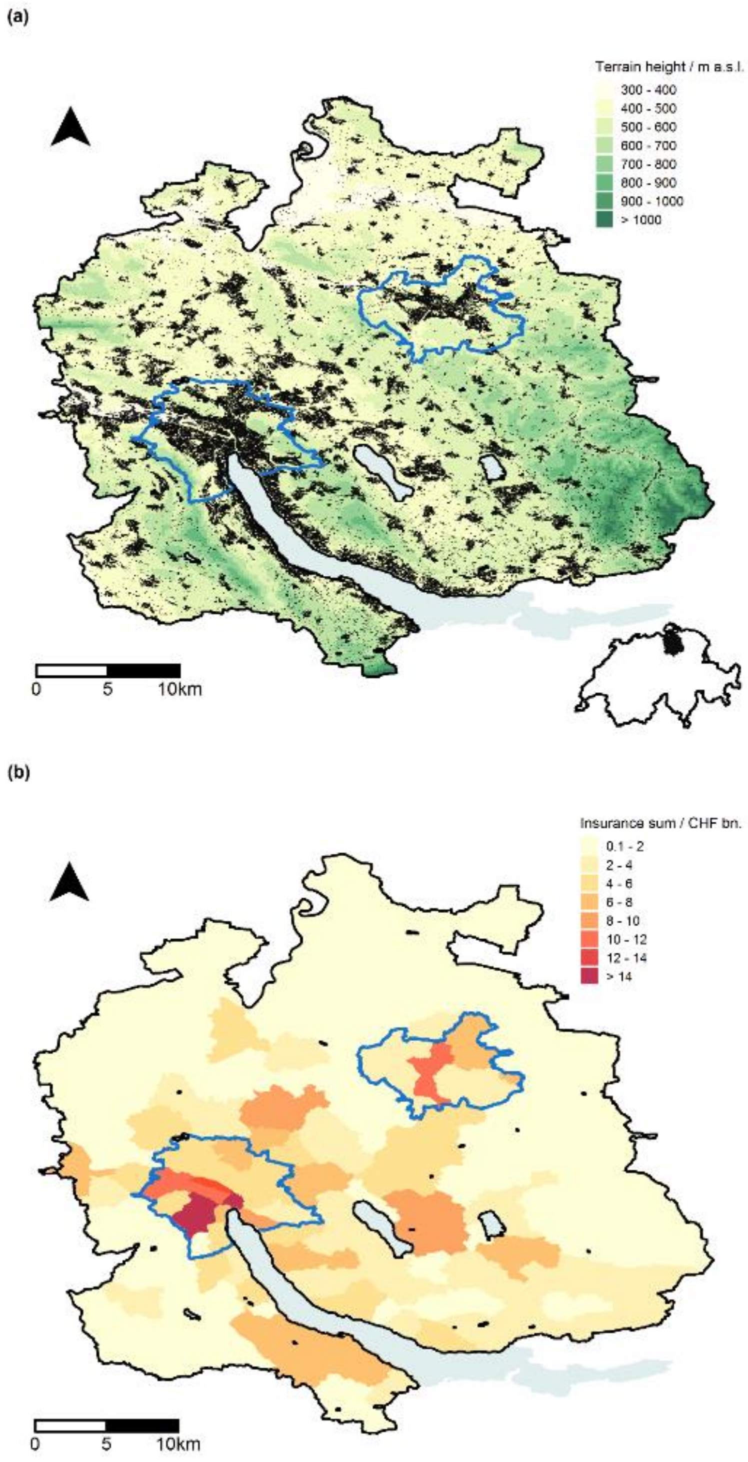
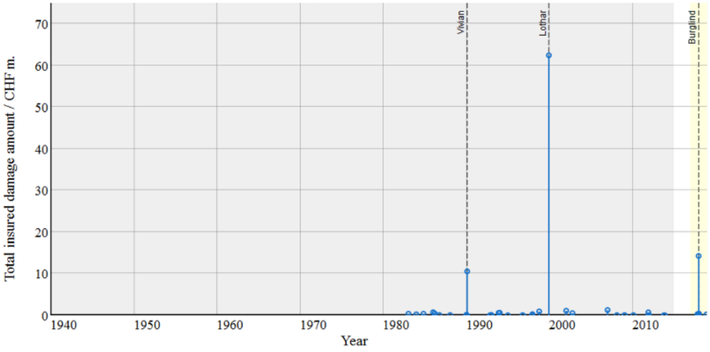
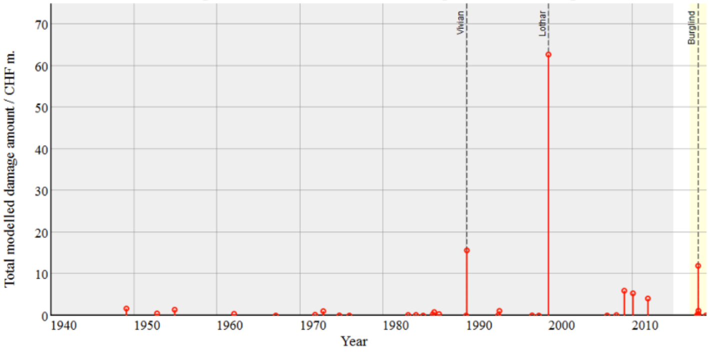


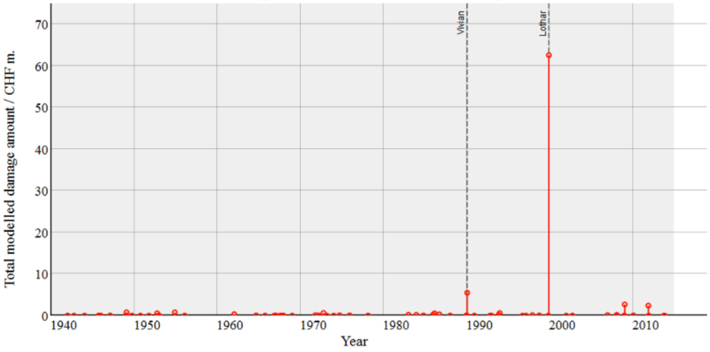
Figure 26 (a) Terrain height for the canton of Zurich (colour scheme) according to a digital elevation model with a horizontal grid size of 200 m (source: Swiss Federal Office of Topography; Swisstopo, 2019). In addition, the spatial distribution of all buildings insured by GVZ is indicated and the urban 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).



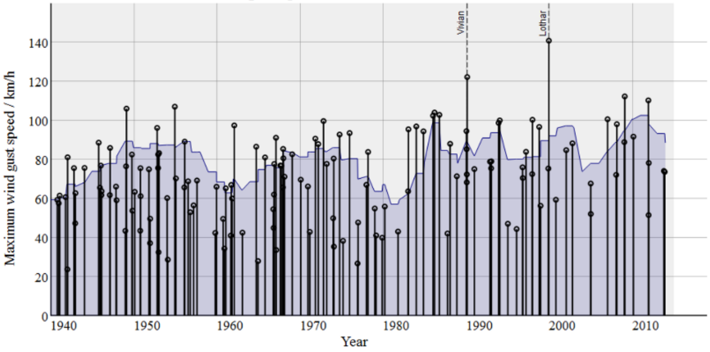
(a) Normalised insured damage (WISC historic & observed footprints)



(b) Modelled damage (WISC historic & observed footprints; GVZ damage model)



(c) Modelled damage (WISC historic; CLIMADA impact model)



(d) Maximum wind gust speed in the canton of Zurich (WISC historic)

Figure 27 Variability of windstorms and associated damages in the canton of Zurich: (a) normalised insured damage, (b) modelled windstorm damage based on the GVZ damage model and the hazard event sets "WISC historic" and "observed footprints", (c) modelled windstorm damage based on the CLIMADA impact model and "WISC historic", and (d) maximum gust speeds at building level in the canton of Zurich according to "WISC historic" (black stem plot). The filled time series in (d) additionally shows the 5-year moving average *of the yearly maximum gust speeds in the canton of Zurich. The period for which "WISC historic" hazard data ("observed footprints") is available is shaded grey (yellow) in (a) and (b). The windstorm events Vivian/Wiebke, Lothar/Martin, and Burglind are marked.*

9.5 Appendix to chapter 5

9.5.1 Data and Code Availability

The scripts reproducing the main results of the paper and the main figures are available under http://doi.org/10.5281/zenodo.4696214 (Röösli, 2021). Using the openly shared methodology and software code, the presented impact forecast can be calculated for any European country based on open forecast data of the German weather service (https://opendata.dwd.de/).

CLIMADA is openly available at GitHub (https://github.com/CLIMADA-project/climada_python, Aznar-Siguan and Bresch, 2019; Bresch and Aznar-Siguan, 2021) under the GNU GPL license. The documentation is hosted on Read the Docs (https://climada-python.readthedocs.io/en/stable/) and includes a link to the interactive tutorial of CLIMADA. CLIMADA v2.1.0 was used for this publication, which is permanently available at: http://doi.org/10.5281/zenodo.4659173.

The COSMO weather forecast data can be ordered through MeteoSwiss: https://www.meteoschweiz.admin.ch/.

The reported building damages of the claims database are proprietary data of the cantonal building insurance of the canton of Zurich GVZ. For future academic studies, inquiries can be directed at the natural hazards team of GVZ.

9.5.2 Funding statement

This study has been entirely funded by core funding of the chair for weather and climate risks at ETH Zurich, Switzerland, a joint professorship between ETH Zurich and the Swiss federal office for meteorology and climatology, MeteoSwiss.

9.5.3 Conflict of interest disclosure

The authors declare that they have no conflict of interest.

9.5.4 Acknowledgments

We would like to thank: the cantonal building insurance of the canton of Zurich GVZ, especially Christoph Welker, for the collaboration and access to their claims data. MeteoSwiss for the forecasting data, especially Marco Arpagaus, Guy deMorsier, Pirmin Kaufmann for support regarding wind gust parameterization and NWP forecast. The osm team for providing the data for the operationalization of the prototype. Saskia Willemse and Irina Mahlstein for discussions about impact warnings. Daniele Nerini for discussions about post processing. The WCR Group, especially Samuel Eberenz, Zélie Stahlhandske, Chahan Kropf and Jamie McCaughey, for reviewing the text and code of this study.