Towards operational impact forecasting of building damage from winter windstorms in Switzerland

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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 develop an open-source impact forecasting system for building damage due to winter 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 a 2-day 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. The uncertainty of the impact forecasts is large. For the majority of days with severe winter windstorm damage, the mean 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.

Keywords
building damage, impact forecast, impact modelling, impact-based warning, numerical weather prediction

1 | 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 occurring in the last 50 years (WMO, 2020). With the 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 because 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 weather hazards. Warnings are issued when the predicted hazard intensity, such as temperature extremes, wind gusts, rain, or flood height, reaches a certain pre-defined, user-agreed threshold or has 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 (Aznar-Siguan & Bresch, 2019; IPCC, 2012; WMO, 2015a). Exposure represents the population, or a socio-economic resource, or asset that could be affected by the hazard, whereas vulnerability is 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 varying degrees. The World Meteorological Organisation differentiates between three paradigms (WMO, 2015a). In the first paradigm, the so-called hazard warnings (HbW, example: ‘Tomorrow wind gusts of more than 25 meter per second are expected’), only the hazard information and no impact information is considered as weather warnings described above. In the second paradigm, named impact-based warnings (IbW, example: ‘Tomorrow wind gusts are expected that might result in minor building damages’), 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 (IWs, example: ‘Tomorrow, building damages in the canton of Zurich are expected to reach several million Swiss Francs’). These examples are adapted from WMO (2015a). In this study, we focus on the third, most comprehensive, paradigm.

It is useful to differentiate impact forecasts and warnings in two additional dimensions. First, the formulation of the risk of impact can be qualitative descriptions, quantitative calculations, or a combination thereof. Second, 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 the other 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, which differentiates three warning levels and considers qualitative impact descriptions both in the warning definition and the communication of the warning (Lattimore, 2019; Neal et al., 2014). 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 is 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, 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, which have the knowledge about weather forecasts, and core partners, who decide on preventive measures. Merz et al. (2020) have summarized the current state of the art in impact forecasting for disaster risk management, and concluded that 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 (Aznar-Siguan & Bresch, 2019; IPCC, 2012; Schwierz et al., 2010). The movement to include such a
framework for arriving at 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 selected open sources or free tools are available (among others, see Aznar-Siguan & 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. Slightly 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 perform 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 see the responsibility for informing about impacts resting 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 verification of the warnings (Uccellini & Ten Hoeve, 2019; WMO, 2015a). Additionally, 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). Examples of such a collaboration between all relevant providers of warnings are the Natural Hazard Partnership UK (Hemingway & Gunawan, 2018) and 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 1.1). We study building damages as an example of socio-economic impact (Section 1.2).

1.1 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 & Röösli, 2021), climate change risk (e.g., Donat et al., 2011; Schwierz et al., 2010), and single-event case studies (Stucki et al., 2015).

Merz et al. (2020) have gathered the efforts in impact forecasting of natural hazards in various fields in a review. For meteorological hazards, there have been 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, for example, proprietary models run by insurance companies (Pinto et al., 2019). In the public domain, there have been studies that show the skill of impact forecasting for storm impacts on a theoretical level (Pantillon et al., 2017; Pardowitz et al., 2016), but they 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 the vehicle overturning model in the United Kingdom (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 was found to perform 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 the 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 yet another form of validation of IFc and IW, the reception of IbW in the United Kingdom was studied after Storm Doris by surveys of the general public (Taylor et al., 2019). Taylor et al. (2019) call for 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 (Hemingway & Robbins, 2020; Lazo et al., 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.

1.2 Study focus: ‘Building damage in Switzerland’

In Switzerland, storms are one of the most damaging weather-related disasters, next to floods and hails (Imhof, 2011; WMO, 2020). The storm Burglind/Eleanor that hit Europe on 3 January 2018 was the most damaging winter windstorm hitting Switzerland since Lothar in December 1999. It caused damage to infrastructure estimated at CHF 165 million, interruptions in traffic and the electricity grid, and felled over 1.3 million 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 (Scherrer et al., 2018; WSL & BUWAL, 2001). As a proof of concept for an impact forecast, building damages due to storms is a good choice because of 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 & Röösli, 2021), calculated using GVZ’s proprietary windstorm damage model based on 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. GVZ already 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, increasing several-fold their regular caseload. An impact forecast would enable better logistical planning of the claims-handling, which would reduce 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 client calls and the claim 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 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; nor is there any for 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 the 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 provide a case study of the event Burglind/Eleanor of 3 January 2018. We will answer the following questions: (1) Can an impact model developed for climatological risk assessments be 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.

2 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 (Section 2.1). We replicated the warning decision process of the operational forecaster on duty by constructing a simple automatized algorithm (Section 2.2). For the impact calculations we used a storm
damage model for winter windstorms within the open-source risk assessment platform CLIMADA (Section 2.3). For the verification of the forecasted building damages, we used damage records of the cantonal building insurance of the canton of Zurich GVZ (Section 2.4).

### 2.1 | Weather forecast

MeteoSwiss, the NHMS of Switzerland, operates numerical weather prediction models in different set-ups to produce weather forecasts. The most important set-up for warning decisions is ‘COSMO-2E’, an ensemble set-up 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 (the highest 3-s average of the wind speed; WMO, 2018) in m/s within one day (over 24 h, i.e., 00:00 UTC–24:00 UTC) for each grid point and each of the 21 ensemble members. In the COSMO model, the wind gusts are a derived quantity, which is generated with a gust parameterization (e.g., Stucki et al., 2016). 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 48–72 h). This lead time is relevant for warning decisions.

### 2.2 | Hazard-based warnings

MeteoSwiss issues 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 automated process based on the weather forecasts and the threshold for the warning levels. The thresholds for wind gusts are set differently for low and high elevations above 1600 m 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. First, for each grid point and each ensemble member of the weather forecast, a warning level is assigned based on the elevation-dependent thresholds. Second, every grid point is assigned the median warning level calculated from all ensemble members. Third, each region is assigned the median warning level of all its contained grid points. Note that alternative definitions could be used.

### 2.3 | 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 climatological risk analysis of storms, Welker and Röösli (2021) presented an open-source implementation of such a model for building damages for Switzerland. The exposure and vulnerability from Welker and Röösli (2021) were used in this study, whereas the hazard component was replaced by the weather forecast (Section 2.1).

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 2.1.

Exposure represents the value of buildings in Switzerland (Figure 1). In this study, we use an exposure layer estimated by the LitPop methodology (Eberenz et al., 2020) as a proxy for building values. For spatial verification at the postal code level within the canton of Zurich, the exposure for the canton of Zurich is further downscaled with building footprints from open street maps (details see Welker & Röösli, 2021).

Vulnerability is represented by a function relating wind gust velocity to proportional damage (Figure 2). It was specifically designed for winter windstorms. The shape of this function was first published by Schwierz et al. (2010) and scaled for the current modelling set-up by Welker and Röösli (2021). The use of other parameters such as persistence of wind gust or vertical static stability in impact models has been discussed and rejected because of a risk of over-fitting (Klawa & Ulbrich, 2003). Recent studies using impact models for damage due to winter storms used only gust speed as hazard intensity for their models (Donat et al., 2011; Koks & Haer, 2020; Prahl et al., 2015; Schwierz et al., 2010; Stucki et al., 2015; Welker & Röösli, 2021).

The risk modelling platform CLIMADA combines hazard intensity, the impact function, and for each grid
point, the exposure. The result is a forecasted building damage data set 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 (schematic illustration of the impact forecasting system in Figure 3).

We present two main plots in this study: (1) the average impact for a certain day per grid cell, and (2) the empirical 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 ones 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.

2.4 Building damage records

In Switzerland, building insurance is mandatory, and in the canton of Zurich GVZ insure (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 data set 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 3 January 2018). The third data set 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 the context for the forecasted building damages.

### 2.5 Sensitivity analysis

To understand how the scales of uncertainty in hazard, exposure, and vulnerability relate to each other, we performed a sensitivity analysis. Meteorological uncertainty is represented in the weather forecast with a set of ensemble members that was designed to capture the full range of possible meteorological outcomes. For exposure and vulnerability, the uncertainties are estimated more roughly but with the same goal to capture the full range of possible outcomes. We performed a sensitivity analysis by systematically sampling from the uncertainty of the hazard, exposure, and vulnerability and then checked for the sensitivity of the results (Kropf, Ciullo, et al., 2021a; Kropf, Otth, et al., in preparation; Pianosi et al., 2016; Saltelli et al., 2019; Sobol’, 2001). The approach is based on the Python library SALib (Herman & Usher, 2017) and presented in Kropf, Otth, et al. (in preparation).

We investigate each event individually. Sensitivity analysis creates a distribution of possible total damages in Switzerland, and we look at the sensitivity of the resulting total damages to the parameters that control the uncertainty in hazard, exposure, and vulnerability. To create the distribution, many thousand samples out of the uncertainty representation of hazard, exposure, and vulnerability were drawn and combined in single runs of the impact model.

Meteorological uncertainty was sampled by selecting one of the 21 ensemble members randomly for each run. The parameter hazard_members controls that sampling. Sensitivity analysis was performed with the weather forecasts with a 2-day lead time as described in Section 2.1.

For uncertainty in the exposure, we first perturb the total value of all buildings in Switzerland by a random factor from a uniform distribution between 0.8 and 1.2. Second, we randomly select one of three disaggregation methodologies to bring the total value to the spatial exposure grid: only nightlight, only population count, and LitPop (the combination of nightlight and population count; for more information about the disaggregation methodologies consult Eberenz et al., 2020). The parameters exposure_model and exposure_value control the generation of the exposure.

For vulnerability, we first defined the uncertainty range of the impact functions by repeating the calibration of the impact function, as was done by Welker and Rööslí (2021). Each event was calibrated individually, so the resulting range of impact functions captures the uncertainty of the calibration similar to Eberenz et al. (2021). In the calibration, the mean damage degree and the percentage of assets affected, which generate the mean impact ratio of the impact function, were allowed to be scaled with a factor. The minimum (0.065) and maximum (2.0) values of these calibrations then informed the upper and lower limit of the uniform distribution from which the factor (called vulnerability_scale) is sampled to create a scaled impact function for each run. The possible range is plotted in Figure 4.

### 3 RESULTS

We are able to forecast building damages caused by winter windstorms for Switzerland. We will show the content of our building damages forecast in three ways. First, the result for the Storm Burglind/Eleanor, which hit the Alpine region and Switzerland on 3 January 2018, are shown (Section 3.1). Second, we show results of the spread of the impact forecast caused by meteorological uncertainty (Section 3.2). Third, we compare the aggregated impact forecasts to daily building damage records from the public building insurance company for January 2017–April 2020. We show a temporal and spatial
verification of the impact forecasts and highlight its strengths and shortcomings (Section 3.3).

3.1 | Burglind/Eleanor impact forecast

Burglind/Eleanor hit Switzerland on 3 January 2018 and MeteoSwiss issued a warning level 3 of 5 for most of Switzerland on 1 January (Figure 5a). Our replicated, simple, automatic HbW system (Section 2.2) is based on exceedance probabilities for reaching warning levels (Figure S1). It shows a more patchy distribution of warning levels over Switzerland and generally a lower warning level (Figure 5b). In the definition of the warning levels used by the forecaster, possible impacts are described. With regard to building damage, a warning level 3 cautions that ‘damage to individual roofs’ is possible (Natural Hazards Portal Switzerland, 2021). Neither the MeteoSwiss warning nor our automatic HbW system provides further information on where such an impact might occur.

Our impact forecasting system described in Section 2.3 forecasted mean building damages of close to CHF 90 million for 3 January 2018 based on a weather forecast run initialized on 1 January 2018. The IFc per grid cell shows a concentration of building damages in the northern and western parts of Switzerland (Figure 5c). In the figure, there are also clusters of high forecasted building damages at locations with high exposure values (compare Figure 1). The lower pane in Figure 4 is the main output of the impact forecasting system which has been in semi-operational status since October 2019.

3.2 | Meteorological uncertainty of impact forecast

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 CHF 100,000 and the highest over CHF 600 million. The distribution is skewed, with a fatter tail towards the side of higher damages. This is due to the non-linearity of the impact function (Figure 2) and the inhomogeneity of underlying assets. The spread and empirical distribution are illustrated as a histogram with logarithmic bins in Figure 6. 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 forecasting system. A comparison of scale of this

![Figure 5](image-url)
meteorological uncertainty with other possible uncertainties is provided with a sensitivity analysis, where also the exposure and vulnerability are varied. The results can be found in Section 3.4.

3.3 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 2.4). 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 7a,b). In Figure 7a, the impact forecast of all individual ensemble members with a 2-day leadtime is plotted against the reported damages. The meteorological uncertainty as illustrated in Figure 6 is also quite large for all other 1211 daily impact forecasts between January 2017 and April 2020. The same data is replotted with a linear axis in Figure 7b to provide a focus on severe events relevant for decision making in, for example, the building insurance sector. 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. Besides 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 more than a factor 3 apart; ‘miss’ = impact forecast smaller than a third of reported damage; ‘false alarm’ = impact forecast bigger than 3 times the reported damage). The same plots are given for 1-day and 0-day lead time in Figures S2 and S3.

The events with reported and/or forecasted mean building damages higher than CHF 1 million can be categorized into three types depending on the weather phenomena (Table 1). For the categorization, the catalogue of Sturmarchiv (Schweiz, 2021) was used. The thunderstorms are marked as red markers in Figure 7b, 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 7b (foehn storm, southerly wind events) are all ‘false alarms’ with sometimes very high forecasted impacts. All other days are marked as black markers, and all black markers with forecasted or reported impacts over CHF 1 million are categorized as winter windstorm events. The impact forecast of four out of six winter windstorm events can be rated as ‘success’, while one was ‘false alarm’ and one ‘miss’.

The data of forecasted building damages are available at 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 a low correlation at the level of postal codes (Figure 8b; Spearmen correlation coefficient 0.38 and Pearson correlation coefficient 0.21). The spatial distribution of damages can be better forecasted at the level of cantons (Figure 8a; Spearmen correlation coefficient 0.69 and Pearson correlation coefficient 0.48) than at the level of postal codes (Figure 8b). There is randomness at the small scale and local levels, which contributes to the meteorological uncertainty of the impact forecasts; it is further discussed in Section 4.2.
Sensitivity analysis was performed for each event listed in Table 1, plus 18 other randomly selected events, so for 36 events in total. For each event, the impact model is run many thousands of times with the individual model components (hazard, exposure, and vulnerability) sampled randomly from their uncertainty range (see description of the methodology in Section 2.5). The resulting mean range of the total impact is much larger compared to the distribution shown in Figure 6, which is due to the asymmetrical perturbation of the impact function (shown for Burglind/Eleanor in Figure 9a). The sensitivity of the resulting total damage in Switzerland to the uncertainty of the different model components can then be assessed using sensitivity indices (Sobol’, 2001).

3.4 | Sensitivity

Sensitivity analysis was performed for each event listed in Table 1, plus 18 other randomly selected events, so for 36 events in total. For each event, the impact model is run many thousands of times with the individual model components (hazard, exposure, and vulnerability) sampled randomly from their uncertainty range (see description of the methodology in Section 2.5). The resulting mean range of the total impact is much larger compared to the distribution shown in Figure 6, which is due to the asymmetrical perturbation of the impact function (shown for Burglind/Eleanor in Figure 9a). The sensitivity of the resulting total damage in Switzerland to the uncertainty of the different model components can then be assessed using sensitivity indices (Sobol’, 2001).

The analysis shows that the impact forecasts are most sensitive to the meteorological uncertainty represented in the ensemble members of the weather forecast (shown exemplarily for Burglind/Eleanor in Figure 9b). For all but one of the investigated
The first-order sensitivity index for the hazard component was the highest of all components. The outlier is an event with very small forecasted impacts. For all but four events, first-order sensitivity index for the hazard component was the highest by a large margin (see the results of all 36 events in Figures S4 and S5).

### DISCUSSION

Forecasting socio-economic impacts of winter windstorms in Switzerland based on a regional weather prediction model was technically fully implemented; it shows the uncertainties and allows prioritizing future improvements. 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 by combining the weather information with stakeholder-specific exposure and vulnerability information. We discuss the assessment and uncertainty of the impact forecast in general (Sections 4.1 and 4.2) as well as from the perspective of a building insurer (Section 4.3) in particular. Finally, we will discuss these results with regard to impact warnings (Section 4.4) and suggest some practical implications (Section 4.5).

### 4.1 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: First, winter windstorms are well represented in the weather forecasts. Second, the vulnerability of the impact model was calibrated using data from winter windstorm events (Welker & Röösli, 2021).

False alarms, as in the case of the winter windstorm event Numa on 12 November 2017 (Table 1), are to be expected as part of such a forecasting system. Because of the lead time of 2 days, the storm can still change its course 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 4 February 2020 (Table 1) 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 are not well represented in a weather forecast with a 2-day 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, which are not covered in the impact forecasting system, or 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 have co-occurred. The outlier in Figure 7b 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 1211 days, there have been 8 days in which the impact forecast in the canton of Zurich reached more than CHF 1 million, while 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. The first is that 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 extent of foehn events (Buzzì, 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 extent 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 investigate further, as this might warrant a study of its own.

Two false alarms occurred with forecasted building damages that were more than double the damages of Burglind/Eleanor (see outliers in Figure 7). In the case of the thunderstorm event (10 July 2017; Table 1; red outlier in Figure 7b), 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 of over CHF 1.5 billion in the canton of Zurich, contributing to a major part of the CHF 76 million mean forecasted damage. The median forecasted damage is less than CHF 1000. Thunderstorms were actually occurring on 10 July 2017 over the canton of Zurich, leading to heavy rainfall but not 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, 31 March 2021). Alternatively, a limitation in the numerical representation of the COSMO model could have been reached in that particular member’s run. What can be learned is that impact forecasting systems need to establish a handling method of such outliers. In case of the foehn storm (11 December 2017; Table 1; yellow outlier in Figure 7), several members predicted high impacts in the city of Zurich and the densely populated shore of lake Zurich with a 2-day lead time. Neither the observed damages nor the 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 correcting 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 on which extremes could occur simultaneously at different points and which extremes are possible at different points, but exclusively.

### 4.2 Uncertainty of impact forecasts

Even for successful impact forecasts of winter windstorm events, the meteorological uncertainty represented in the ensemble spread is larger than expected. According to the sensitivity analysis, it is the most important contributor to the uncertainty in impact forecasting (Section 3.4). The meteorological uncertainty is accentuated with the highly non-linear, parameterized impact function that gives a value in Swiss Francs (Figure 6). Two days before the storm event Burglind/Eleanor, the impact forecasts covered a large range because of the meteorological uncertainty represented in the ensemble forecast. The forecasted building damages aggregated over Switzerland range from a small event (around CHF 100,000 CHF) to one of the most damaging events ever recorded (more than CHF 600 million; Eidg. Forschungsanstalt und Bundesamt für Umwelt, 2001). The uncertainty in the impact forecasts remains large also for shorter lead times (Figures S2 and S3). This illustrates that the exact impact cannot be known in advance, which is not surprising.

This represented uncertainty originates from the meteorological forecast, as the other two elements of the impact, namely exposure and the vulnerability, are held constant for producing the main results. There are two main processes governing this meteorological uncertainty. One considers the large-scale weather forecast, and 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 2 days in advance the weather forecast reliably predicts a severe, large-scale weather system over central Europe (Pardowitz et al., 2016). However, large uncertainty remains regarding the exact location and intensity of the gusts. The forecast model represents this uncertainty as well 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 several times the mean forecasted damage. Still, this represented uncertainty does not always capture the full uncertainty: for example, in the case of winter windstorm event Petra on 4 February 2020 (Table 1), the reported damage was more than 10 times 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 detail 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 either in the meteorological forecast or 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 8b). 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 8a).

Using these presented building damage forecasts for societal decisions on preventive actions is decision
making under large uncertainties. Dealing consciously with the 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 the most straightforward way. This is achieved first by transforming the wind gust forecast and its represented uncertainty into building damages, and second by focusing on the mean forecasted building damage, as the range of the represented uncertainty is very large and very volatile.

Representing additional uncertainties, as technically done in the sensitivity analysis, would need additional work to be interpretable as an impact forecast itself and not only as a comparison of scales of the uncertainties. In the meantime, 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 (such as the influence of persistence of high gust speeds on damage), and uncertainty in the economic valuation of past damages in the calibration process.

Finally, it should be noted that one aim of the modeling 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.

### 4.3 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 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—will help facilitate such decisions. The use of exposure and vulnerability allows for a familiar localization of the forecasted impacts. Areas of higher aggregated damages, because of the higher exposure or higher wind speeds, are highlighted (Figure 4c) 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 & Röösli, 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 are 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.

Decisions on preparation before a storm event also depend on the availability of disaster management resources. In looking only at absolute building damages, this additional dimension is not incorporated. The absolute damage is dependent on the density of the exposure values, but it can be assumed that the disaster management resources are also more density available in areas with high values. The relative impact would provide another useful proxy to decide if available disaster management resources might come to its limit. IbW, the second paradigm suggested by the World Meteorological Organisation that incorporates hazard and vulnerability, provides this information on relative impact. It is possible to use the presented forecasting system to also produce such IbW.

### 4.4 Towards impact warnings for general public

The impact forecast shown in Figure 4b is directly usable as impact warning for a building insurer, as discussed, but not for the general public. There are two main shortcomings. First, a member of the general public, for example, 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. Second, as a cautionary remark, a person interested in traffic interruption, forest damages, or any other impact will not see the relevant exposure or vulnerability represented in Figure 4b. This discrepancy is hard to understandably disclaim and could lead to misunderstanding of the warning content. Third, repeated misses or false alarms might lead to the general public
losing their trust in the warning system. Regarding the large uncertainty of the impact forecasts, this issue would need to be handled with extra care.

The presented impact forecast could still be indirectly valuable for NHMS by providing an additional source of information for the decision process led by the meteorologist on duty who issues warnings to the general public. NHMS collaborate with specific partners such as 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.

4.5 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 requires only 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 (APIs) 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 rely on collaboration with specific partners, such as 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 is practiced in the United Kingdom (Lattimore, 2019; Taylor et al., 2019).

5 CONCLUSIONS 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 forecast building damages (in Swiss Francs) with a 2-day lead time. We compared the forecasted impact with reported building damages of the canton of Zurich. Of the investigated 1211 days, there were 6 days with forecasted or recorded building damages from winter windstorms of over CHF 1 million. 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 that is interested in an aggregate impact view for their preventive decisions.

The forecasted building damages contain many uncertainties. A user of that information for societal decisions on preventive actions must be aware of them and find the most suitable interpretation. One of the important limitations of the presented impact forecasting system is that it incorporates the meteorological uncertainty but otherwise uses deterministic components. This set-up highlights the information of the meteorological forecast including its uncertainty. It now requires the user to have a qualitative understanding of the additional unrepresented uncertainty. In future work, the approach used in the sensitivity analysis could be extended with better estimates of the uncertainty of exposure and vulnerability to create impact forecasts representing all dimensions of uncertainty.

From the current state of impact warnings for one or a 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 need aggregated impact information to facilitate their decision-making process, for example, emergency services. Using a software tool such as CLIMADA to create an impact model as proposed in this paper allows the structuring this process (Fischer et al., 2021; Pohl et al., 2017). This opens the use of such specific impact forecasts as additional inputs for the warning decision 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 which in combination would cover most socioeconomic 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, etc.) 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 whether all relevant impacts can be represented with an impact forecast and whether the NHMS have the needed competence to operationally issue and verify such impact forecasts. If NHMS could acquire this competence, for example, through the collaboration with partner organizations, they could extend their role as trusted sources of meteorological information (Taylor et al., 2019) to the broader spectrum of impact warnings.

Goals such as 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 claim 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 as open source and now lends itself to support these next development steps.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

AUTHOR CONTRIBUTIONS

Thomas Rööslı: Conceptualization (equal); investigation (equal); methodology (equal); software (lead); visualization (lead); writing – original draft (lead); writing – review and editing (equal). Christof Appenzeller: Conceptualization (equal); investigation (supporting); methodology (supporting); supervision (supporting); writing – review and editing (equal). David N. Bresch: Conceptualization (equal); funding acquisition (lead); investigation (equal); methodology (equal); supervision (lead); writing – review and editing (equal).

DATA AVAILABILITY STATEMENT

The scripts reproducing the main results of the paper and the main figures are available under http://doi.org/10.5281/zenodo.4696214 (Rööslı, 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 & Bresch, 2019; Bresch & 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.

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