Historical Weather Data for Climate Risk Assessment

Stefan Brönnimann[1,2,*], Olivia Martius[1,2,3], Christian Rohr[1,4], David N. Bresch[5,6] Kuan-Hui Elaine Lin[7]

[1] Oeschger Centre for Climate Change Research, University of Bern, Switzerland

[2] Institute of Geography, University of Bern, Switzerland

[3] Mobiliar Lab for Natural Risks, University of Bern, Switzerland

[4] Institute of History, University of Bern, Switzerland

[5] Institute for Environmental Decisions, ETH Zurich, Universitätstrasse 22, 8092 Zurich, Switzerland

[6] Federal Office of Meteorology and Climatology MeteoSwiss, Operation Center 1, P.O. Box 257, 8058 Zurich-Airport, Switzerland

[7] Research Center for Environmental Changes, Academia Sinica, Taipei, Taiwan

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* corresponding author:
Stefan Brönnimann
Institute of Geography, University of Bern
Hallerstr. 12
CH-3012 Bern
Switzerland
stefan.broennimann@giub.unibe.ch

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Abstract. Weather and climate-related hazards are responsible for large monetary losses, material damages and societal consequences. Quantifying related risks is therefore an important societal task, particularly in view of future climate change. The past record of events plays a key role in this context. Historically, it was the only source of information and was maintained and passed on within cultures of memory. Today, new numerical techniques can again make use of historical weather data to simulate impacts quantitatively. In this paper we outline how historical environmental data can be used today in climate risk assessment by (i) developing and validating numerical model chains, (ii) providing a large statistical sample which can be directly exploited to estimate hazards and to model present risks, and (iii) establishing „worst-case" events which are relevant references in the present or future. Partly because of these developments, weather data rescue has received prominence in recent years. Several data bases with historical documentary information on weather and climate impacts exist. Combining them with the ongoing efforts on weather data rescue and reanalysis will yield a more sound basis for climate risk assessment, now and in future.

Introduction

Weather and climate-related hazards are responsible for losses of lives and capital, damages to infrastructure and effects on ecosystems.[1] Disposing of well-validated risk estimates for the present and future would enable more informed decision making and is therefore societally important. Climate risk assessment – both for the present and future - increasingly uses numerical models and relies on quantitative data. However, suitable data products, e.g., to drive impact models, typically cover only recent decades and other methods (combinations of climate model simulations with semi-empirical or purely stochastic models, or expert judgment) are therefore often used. In this paper we explore the use of weather data prior to that period, *i.e.,* approx. prior to the 1950s, for quantitative risk assessments.

There is a long tradition in analyzing information on historical extreme events for present day risk assessment, for instance, in the areas of flood risk[2-8] or coastal protection,[9-11] and their relation to culture is reflected.[12,13] However, analyzing historical weather events for climate risk assessment was up to now largely separate from the numerical tools used in climate risk assessment as they did not directly feed into quantitative methods and impact model chains. This is now changing. In the past five years, new data assimilation techniques for reconstructing past weather have allowed a considerable backward extension of weather data products.[14-16] Rather than the past 40 years or so, global 3-dimensional weather data products now cover the past 160 years. This considerably extends the period available for estimating weather and climate-related hazards. Statistical analyses profit from larger samples of extreme or unprecedented events and numerical model chains can be established. However, the data products deteriorate in quality when going back in time, requiring profound knowledge of the data and its provenance. Furthermore, the background-climatic conditions in the past were different from the present and future climate, which any approach needs to consider, all the more as planning horizons might be long and climate will change through that time.

In this paper, we outline how historical environmental data can be used in climate risk assessment. Since these are two rather separate fields, we first provide an overview of historical environmental data on the one hand and on the process of risk assessment on the other hand, aiming at readers not familiar with these concepts. Expert readers in the fields may wish to skip this part.

In the third part we use three examples from Switzerland to show how numerical model chains can be developed and evaluated using historical instrumental and documentary data. The first two examples provide „worst-case“ climate and weather events, respectively, that are still relevant today and for which statistical and dynamical downscaling techniques can be applied. Future climate change can be incorporated into the model chain, either in the form of downscaled scenario simulations, or by performing climate change surrogate scenarios. In the last example, we demonstrate how the larger sample accessible with historical data can be exploited statistically to produce a hazard map. These examples are then discussed. We conclude with recommendations on how to combine historical and weather data.

Historical Weather Data

Documentary data

The most direct information on climate risks prior to age of digital data acquisition are historical documents. Rich documentary sources are available from Europe (see review by Brázdil et al.[17]) and the Mediterranean[18] since the Early Middle Ages (or even earlier: see Manning et al.[19]). The historical weather records of China[20,21] are especially abundant due to its long and continuous dynastic history. In the following, characteristics of documentary data are outlined for the cases of China and Europe, but documentary data are also available from South America,[22] North America,[23] Japan,[24,25] the Tropics, [26] and Africa.[27]

The Chinese possess a rich legacy of documents describing weather events and their impacts on agriculture and other human activities in historical times.[24,28] The earliest written records were the inscriptions on the oracle bones of the Shang Dynasty (circa 18th to 12th century BCE) describing weather forecasts for the kings or actual weather conditions but the records were not systematic and many were lost or fired. In the following Zhou and Qin dynasties, some important historical books such as *Chun Qiu* by Confucius (551-479 BCE) and *Shi Ji* by Sima Qian (145-86 BCE) also documented unusual weather and climate such as severe flood, drought, famine, hail, and summer snow. Nonetheless, ever since the writing of *Han Shu* (The Book of Han Dynasty, 206 BCE-23 CE), the standard of writing official histories was followed in the succeeding dynasties for more than a thousand years.[29] In the official form of the histories, the entries of weather and climate conditions were contained in the volumes of *Wu-Xing-Zh*i (Records of Five Elements) or *Zai-Yi-Zhi* (Records of Disasters and Portents). Beginning in Ming dynasty (1368-1643 CE) until the end of Qing dynasty (1644-1911 CE), the writing of local chronicles, *Fang Zhi*, greatly expanded the availability of the documentary sources spreading across mainly eastern China from which a wealth of weather and climate information can be retrieved for reconstruction.[30] Totally, there exist over 8,000 volumes of such historical documents and fortunately a team led by Zhang De'er has compiled almost all weather related records into *A Compendium of Chinese Meteorological Records in the Last*

3,000 Years,[31] and recently another team has digitized the records into a REACHES data base that covers more than 1,400 geographical sites in China with observational records.[32]

The aforementioned Chinese records mostly refer to anomalous weather and climate conditions (e.g. flood, drought, unusual cold and hot weather, thunderstorms, dust rains, and hailstorm) presenting climate extremes of the times. The temporal resolution varied according to the frequency and characteristics of the events. Many of the records were documented with governmental responses (e.g. distribution of relief crops, relief of tax, and repair of dikes) and societal consequences (e.g. reclamation, crop price, famine, disease, migration and revolt) from which the severity of the events and risk assessment can be indexed and reconstructed.[12] By combining and evaluating the information on the unusual weather events and the consequences, Chinese scholars are able to develop several matured indexes and datasets for dryness/wetness indexes (normally indexed as five or seven grades ranging from 1-very wet to 5-very dry) such as CMA[33] yearly charts of dryness/wetness in China for 1470-1979, and an improved dataset extending the time span from 137 BCE to 1469 BC.[34] The cold/warm index ranging from -2 (cold) to +1 (warm) is also well developed and widely applied.[35,36] Through those endeavors a number of precipitation and temperature reconstructions could be derived for different parts of China in the last two millennia.[37]

In Europe, reports on extreme weather situations have been an essential part of annals and chronicles from the Early Middle Ages, i.e. from the 6th century C.E. onwards.[38,39] Those annals were mostly compiled in the Christian monasteries and churches (and later on also in medieval towns), and consisted of simple lists of annual entries mentioning the most important events, such as the death of a king, wars, but also including floods, hail, storm surges and other weather related issues.[40] In some cases, they also tell about pre-instrumental risk management and risk assessment, e.g. about the protection of forests to detain avalanches or where to choose flood-secure places for settlement. However, historical source criticism is essential when using this information for historical climatology.[39]

Annals and chronicles often started by copying older annals and chronicles from other monasteries, thus often referring to a different area. The contemporary part of the chronicle based on eye-witnesses, however, can be trusted in most of the cases. Chronicles from the Late Middle Ages onwards (1250-1500 C.E.) also contain quite detailed weather reports.

In Early Modern Times (1500-1800 C.E.), chronicles composed by single authors on behalf of cities became more frequent and detailed[41] such that they can be used to study past extremes. Furthermore, administrative records became more and more important for historical climatology during the last 20 years, because they will allow the reconstruction of extreme events and what had been “normal” to the people over a long time span based on homogenous datasets. An example of a long record of manorial accounts are the accounts of the Bishopric of Winchester, which run from 1209 until 1450.[42-44]

On the European continent, municipal records can be used for flood reconstruction at monthly or even weekly resolution. Rohr[38,45,46] has examined the bridgemaster’s accounts (“Bruckamtsrechnungen”) of the city of Wels (Austria), starting from the mid-14th century. Wetter et al.[47] based their flood reconstruction for the Rhine River in Basel on weekly expenditure books (“Wochenausgabebücher”) as well. Similar accounts have survived from Bratislava (Slovakia), but they still are under examination. They report on the maintenance and repairs of bridges of infrastructure after heavy floods (and thus flood impact), but also about prevention systems. In this way, they complement the evidence of flood marks, which are reliable only to some extent (because they have been partly re-painted, re-affixed or transferred to other buildings). In a similar way, records in municipal accounts concerning damaged roofs can be used for the reconstruction of storminess in coastal areas.[10]

Looking not only at the weather-related information, but also at grain prices, these sources can tell us much about the resilience and vulnerability of past societies, and about the risk management to cope with shortages in grain supply. Grain and grape harvest dates based on accounts kept by medieval and early modern landowners, both communities (urban hospitals, monasteries etc.) and single aristocratic owners,[48-51] have been used to reconstruct climate.

The most direct information on weather extremes comes from weather diaries. The oldest preserved are from 14th century England, e.g. by William Merle from Oxford (1337–1344). From the 16th century onwards they became much more frequent. Some of them just cover several months, others more than one decade. The most excelling one has been composed by the physician Louis Morin from Paris, who observed temperature, precipitation and winds three times a day for about 40 years. Some of the weather diaries concentrate on phenological data, such as the one by the Bernese “weather parson” Johann Jakob Sprüngli (1717–1803).[52]

Similar as for China, European documentary data were used to generate temperature and precipitation indices such as the so-called Pfister indices.[41] Those Pfister indices can be used both for temperature and precipitation, reaching from -3 (extremely cold) to +3 (extremely hot), and from -3 (extremely dry) to +3 (extremely wet) respectively. They have been used e.g. for studies on Switzerland[52] and the Burgundian Low Countries (Netherlands, Belgium, Luxemburg, eastern France).[53] Comparable classifications are used for Central Europe,[4] the Czech lands,[54] southern Spain,[55] and Poland.[56]

Documentary climate information for Europe such as weather diaries is compiled various databases such as EURO-CLIMHIST (www.euroclimhist.unibe.ch),[57] TAMBORA (https://www.tambora.org/),[58] or TEMPEST (http://dx.doi.org/10.5285/d2cfd2af036b4d788d8eddf8ddf86707).[59]

Based on compilations of documentary data, “worst case scenarios” can be constructed for climate risk assessment. For instance, documentary evidence showed that 1540 has obviously been the driest and hottest year of the last 1000 years in Western and Central Europe.[60] Hundreds of written records testify that the water levels became extremely low.[61] The harvest was extremely poor, ships on rivers (in those time the most important routes for transport) could not navigate. Today, such a drought and low water level would, for instance, bring about the collapse of the cooling system of the Swiss nuclear power plants. Likewise, the floods of 1480, 1651, and 1852 serve as benchmarks in a recent Swiss assessment of extremes flood risk in the Aare and Rhine catchments (https://www.wsl.ch/en/projects/exar.html). Further back in time, the St. Mary Magdalene’s flood in 1342 (or better: a series of floods in 1342 and 1343, as we know today), which is well documented in historical sources[62] is sometimes used as worst possible flood.

Historical Instrumental Data

Instrumental data were collected starting in the late 17th and early 18th century (for a review see Edwards[63]). Besides enlightenment science, they were also collected for practical applications such as agriculture or medicine and they were measured in colonial or missionary contexts.[25,29] A huge amount of early instrumental weather reports stem from ship logbooks including temperature, precipitation, air pressure and winds.

In the early years of instrumental observations, serial records were too short for any sort of risk assessment. However, weather extremes were one of the driving factors behind organized observation networks (particularly at sea) and eventually state weather offices and forecasts, as shown by Moore[64] on behalf of the Great Storm of 1703 and the Royal Charter storm of 1859.[65]

The question of insurance became an important topic in the early 19th century.[66,67] Winkler,[68] for the case of Bavaria, reports on a hail hazard map that was created in 1816 (though the map itself is lost) that was intended for use in the context of insurance claims. Only with a sufficiently large data base, could first “climatologies” – or „hazards maps“ as we would say today – be drawn. An example for an early quantitative approach are several maps in the

Berghaus physical atlas[69] (published 1838-1848, re-edited 2004), that accompanied Humboldt's „Kosmos". One map includes a climatology of North Atlantic hurricane tracks (by displaying reconstructions of ca. 20 tracks, Fig. 2 top left), another one shows the frequency of thunderstorms over Europe (Fig. 2, bottom left). These maps, particularly the hurricane map, depict the main features remarkably well when compared to present day maps.

With Humboldt and many others began the monumental work - still not finished today – of measuring, compiling and making available the huge amount of weather information worldwide. In the mid-19th century, Heinrich Dove and James Pollard Espy collected global weather data and Matthew Maury collected the marine observations.[63] Köppen[70] compiled a climatology of cyclones over the North Atlantic. From the mid-19th century onward, compiling weather data occurs increasingly in the framework of national institutions rather than by private initiative.[71-73] It is important to note that historical observations always contain societal imprints as they were measured and compiled for specific purposes.[74]

Today, data bases such as the International Comprehensive Atmospheric Data sets (ICOADS),[75] Global Historical Climate Network (GHCN),[76] the International Surface Temperature Initiative (ISTI),[77] or the International Surface Pressure Databank (ISPD)[78] provide some of these data. Ship logs were collected in the CLIWOC project (http://webs.ucm.es/info/cliwoc/)[79,80] with a focus on British, Dutch, and Spanish logbooks)

For climate risk assessment, extremes in some of the measurement time series (e.g., wind maxima, hurricane tracks), can be used directly to obtain local hazard estimates as outlined in the next section and similar as in hydrological risk assessment.[6,81,82] Furthermore, historical instrumental data can be used for quantitative weather reconstructions using statistical or dynamical approaches such as reanalyses, as detailed later in the paper.

Climate Risk Assessment

Main concepts

Risks emerge through the interplay of climate and weather-related hazards, the exposure of goods or people to this hazard, and the vulnerability of exposed people, infrastructure and environment to climate and weather-related hazards. Note that this definition of vulnerability is narrower than other definitions that include broader socio-economic aspects of vulnerability such as cultural dimensions.[83] Risk can actively be managed[84] and adaptation allows reducing risk,[85] as society shapes exposure and vulnerability.

Risk is the “effect of uncertainty on objectives”. It can thus be defined as the combination of the probability of a consequence and its magnitude, i.e. risk = probability x severity, where severity is often named impact in the weather and climate context. In the simplest case, ‘x’ stands for a multiplication, but more generally, it represent a convolution of the respective distributions of probability and severity. According to the Intergovernmental Panel on Climate Change,[86] natural hazard risk is the combination and hence a function of hazard, exposure and vulnerability:

risk = f(hazard, exposure, vulnerability)
= probability of hazard x f(intensity of hazard, exposure, vulnerability)

where the latter three elements constitute severity. Hazard describes weather events such as storms, floods, drought, or heatwaves both in terms of probability of occurrence as well as physical intensity. Exposure describes the geographical distribution of people, livelihoods and assets or infrastructure, generally speaking of all items potentially exposed to hazards, including ecosystems and their services. Vulnerability here describes how specific exposure will be affected by a specific hazard, i.e. relates the intensity of a given hazard with its impact, such as wind damage to buildings as a function of wind speed or the effect of a flood on a local community and its livelihoods.

Risk is best measured in the metrics relevant for decision making, i.e. can be the number of affected people in the context of evacuation or the replacement value of buildings in the context of property insurance. Any risk model hence attempts to quantify the mentioned elements in a way most appropriate for the specific purpose. Depending on purpose, the level of detail in quantification of any element will thus vary.

Weather (Hazard) Data for Climate Risk Assessment

To characterize and quantify meteorological and climatological hazards (for insurance applications) several different data sets are typically used. These data sets vary in their temporal and spatial resolution, the covered time period and the atmospheric hazards that they represent. We briefly introduce the most prevalent data sources and discuss their potential and limitations for applications in climate risk assessment.

Direct observational data sets include measurements from ground weather stations, weather balloon soundings, manual observations and many more. Indirect observations include remotely sensed information from satellites[87] and weather radars.[88] Observational data sets can directly be used for the analysis of weather extremes and hazards for climate risk modeling.[89-91] For some applications information on a regular spatial grid is necessary, this can be achieved by statistical interpolation of the data points.[92] Note that these gridded data sets based obtained through statistical interpolation have limitations regarding the representation of extremes.[93]

The issue of irregular data points is also ameliorated in reanalysis data sets. These blended data sets combine observations with numerical weather prediction (NWP) model output using data assimilation techniques developed for numerical weather forecasting. They offer information on the four-dimensional state of the atmosphere on regular longitude / latitude grids that extend back to the late 1950s for full reanalysis data sets.[94-96] Reanalysis data sets are considered to be our best estimate of the state of the atmosphere in the past and therefore they are a very important basis for the characterization of atmospheric hazards for impact modeling.[97] Reanalysis are physically consistent in space and time. They are homogeneous in time in the sense that they are produced using a constant configuration of the underlying NWP model, however, the number and type of assimilated observations changes over time and affects trend analyses,[98] and model biases may lead to artificial changes in weather features.[99]

A limitation of the reanalysis data sets is their still comparatively coarse spatial resolution, which requires further statistical or dynamical downscaling for many impact modeling applications. Statistical downscaling uses methods such as quantile mapping or analogue methods to optimally combine coarse resolution (reanalysis) data with local observations.[100-102] For dynamical downscaling numerical weather prediction models are run at high spatial resolution with the coarse resolution (reanalysis) data as boundary and initial condition.[102-104]

None of the data sets discussed so far allow analyzing climate risk evolution in a future warmer climate. For this, projections from global and regional climate models (GCMs, RCMs) are needed. These projections are based on pre-defined future CO_2 emission scenarios.[105] GCMs provide model output for the entire globe at a relatively coarse resolution, indeed the resolution is comparable to the resolution of the surface input reanalysis data sets. RCMs use the GCM model output as initial and boundary conditions to dynamically downscale the information to higher spatial scales. These GCM-RCM model chains (e.g. the CORDEX data set[106]) are the main source of information about the future evolution of atmospheric hazards.[107,108]

Impact (Damage) Data for Climate Risk Assessment

Risk modeling requires impact (damage) data for model development and model validation purposes. Impact (damage) data is very diverse including, e.g., insurance damage (sometimes labeled "loss") data, yield data, energy consumption data, human and animal health indicators, mobility data, migration data, and economic indicators. Currently, it is often very difficult to get access to impact data as the data is either owned by private companies, protected by privacy regulations, or the data is not gathered and stored by a central institution at all.[109,110] Even if access to the commercial (damage) data is possible, these data sets rarely extend very far back in time. On the positive side many long historical time series and data sets often contain impact information. For example, the abundant and detailed data in the Chinese records have assisted social responses and risk assessment analysis for flood and drought hazards in the last Qing dynasty (1644-1911).[12] Impact time series are some of the longest time series on natural hazards that are available.[47]

Risk modeling

To relate physical intensity of a phenomenon (hazard) with impact data, such as (excess) temperature during a heat wave with resulting (excess) casualties, statistical (e.g. regression) models are often used.[111] Such models depend on statistical inference and hence lack projective or even prognostic capabilities, as they do not establish neither causality nor mimic underlying processes. The next best way to model impacts is by simulating a few selected cases or scenarios. In the simplest case, imagine a single storm event (as a single wind field) affecting a spatially explicit set of exposures using a calibrated set of impact functions. Such an approach allows assessing the sensitivity of the consequence (*e.g.* a measure of risk, like storm damage) to key drivers (hazard, exposure and vulnerability) and various assumptions therein. Instead of simulating one single event, one can expand on this and consider *e.g.,* all historic weather events, which allows establishing a historic view on risk. Still, given the low frequency and hence small number of past extreme events, this is still not good enough to assess risk in a comprehensive fashion. Therefore, probabilistic approaches have been developed, simulating thousands of events and employing Monto Carlo techniques to sample the underlying distributions.[112] While such probabilistic models have initially been developed to better assess building damages, especially since hurricane Andrew in the US (1992), similar approaches are by now applied in other sectors, such as agriculture or the energy sector.[113,114]

While these probabilistic approaches are a powerful tool to establish comprehensive measures of risk, data scarcity and heterogeneity do pose limits. Nevertheless, since risk-based decisions are taken daily and practitioners cannot afford the luxury to wait another century before dealing with tropical cyclone risks, the combination of best available (historic) data and (probabilistic) methods is in most cases the most suitable approach. Besides the urgency to model risks now, such sophisticated models allow for fast learning after each event, as new data becomes available and hence their fitness for purpose will further improve over time. In addition, since the dependency of risk to changes in hazard is treated explicitly, probabilistic models are well suited to tackle questions about impacts under changed climatic conditions – and essential to assess options to best manage risks, now and in future.[85,115]

Using Historical Weather Data in Model chains

Historical weather data can be used in climate risk assessment in various ways. The arguably most powerful way is the backward extension of reanalyses. In 2006, Compo and Whitaker (2006) demonstrated that it is possible to produce global reanalyses from only surface and sea-level pressure. This information extends back to the mid-19th century, when national weather services started. In the meantime several products have been generated and are highly used.[14-16] For applications related to climate risks, the resolution of these products is often insufficient, and statistical or dynamical downscaling is required. However, once a reanalysis is available, the same methods as outlined in the previous section can in principle be used. Gridded weather products can also be generated from statistical methods such as analog approaches.

While these numerical techniques open-up new options, the application to historical data is not straight forward. In the following we present several examples of how historical weather and climate data can be used in a quantitative way to study today's climate risks – and even allow for future projections of risk. A discussion follows in the next section.

A worst case climate event: The „Year Without a Summer“ of 1816

Adverse weather that persists for an extended period of time, e.g., an entire season, can be addressed as an extreme climate event. Such events in the past provide analogs for possible events in the present and future. For instance, the drought of 1876-1878, arguably the deadliest climate event in human history, has been studied to test the vulnerability of the global food system.[116] In the USA, the 1930s "Dust Bowl" droughts are used as an analog for possible future droughts, and potential yield losses were modeled.[117] In the following we use another well-known example, the „Year Without a Summer“ of 1816 in Central Europe which was related to the eruption of Tambora in Indonesia in 1815.[118,119]

Endless rainfall and low temperatures led to poor harvests and in some regions to famine. To a society that was already vulnerable due to preceding wars, economic difficulties, and political transition, the consequences were disastrous. Furthermore, a massive snow pack accumulated – at high altitudes consisting of the winter snow of 1816 that had not molten, the summer snow of 1816, and the winter snow of 1817. It has been argued that subsequent snow melt led to the highest level ever recorded of Lake Constance.[47]

For climate risk assessment, the „Year Without a Summer“ of 1816 can be considered as "worst case" climate. Of the extreme anomalies (in Geneva amounting to -3.5 °C and +80% for seasonal mean temperature and precipitation[120]) only part can be attributed directly to the eruption, while another part was due internal variability.[118] However, "worst case" entails that different factors act in the same direction. It is therefore an interesting case for testing the resilience of our society under large stress. The case has also been studied to address the stability of the global food system.[116]

In the following we summarize two recent studies. The goal of these studies was to simulate crop yields[121] as well as discharge and lake levels[122] in Switzerland in 1816 and 1817 using state-of-the-art models. The following model chain was used (see Fig. 2): Historical weather data were digitized and compiled, resulting in a number of daily time series for Switzerland and adjacent countries.[123] Daily gridded fields for the period 1961-2010 served as a pool of analog, from which a sequence of daily "best analogs" was sampled to obtain a 2 km-resolved daily weather reconstruction for 1815-1817.[121] These data were then used to drive impact models, namely a crop model[121] and a hydrological model.[122] Historical data were also used for the validation. For instance, the crop model simulations could be evaluated by making use of historical phenological data. The hydrological model was evaluated using historical discharge and lake level data.

Once the model chain is established, different scenarios can be run with respect to vulnerability and exposure. For instance, Flückiger et al.[121] analyzed the consequence under present-day climate conditions and present-day crops (likewise, a "delta change" approach could be used to run future climate scenarios). One of the findings was that maize, which was rarely planted in 1816 but is an important crop today, would suffer even stronger from the adverse weather. The hydrological simulations can be used in a present-day context to assess the role of snow melt and the risk of flooding due to the combination of the melting of a very large snow pack (e.g., due to one or several very strong volcanic eruptions) and an extreme precipitation event. One surprising finding of the study was that the snow melt contribution in the 1817 flooding (evaluated for the Rhine in Basel) was not very large and an unusual heavy precipitation event (for which there is documentary evidence) is required. In addition to process knowledge gained from these studies, the established model chains can be used to simulate scenarios of vulnerability and exposure.

A worst case weather event: Snow-fall and avalanches in the southern Alps 1916

While the "Year Without a Summer" was a worst-case climate event, risk assessment is often more interested in extreme weather events, i.e., more local events on a shorter time scale. The Galveston hurricane 1900, the Long Island Hurricane 1938 and the Tri-State Tornado 1925 are well known examples. Here we present the example of the avalanches in the southern Alps in December 1916.

Within about one week in December 1916, in midst of the first World War, large amounts of snow accumulated in the Southern Alps on a snow pack that was already above the 90th percentile of climatology of 1931-1960.[124] On 13 December 1916 massive precipitation event deposited a large amount of wet snow or even rain on top of the snow pack. The avalanches triggered by this event killed hundreds, if not thousands of soldiers.

This event was studied using a different model chain. In this case, a global dynamical reanalysis (ERA-20C)[15] was used as a starting point, but this reanalysis obviously builds on historical weather data. The Weather Research and Forecasting Model (WRF) was used to dynamically downscale the weather during this period. In addition, snow data were digitized to evaluate the model.[124]

The case allows identifying the ingredients of a worst-case event. They consist of a blocked atmospheric circulation, persistent southwesterly flow of moist air towards the Alps, and a warm Mediterranean Sea as a general setting and then a sudden temperature increase with a rain-on-snow event. The same features could cause avalanches today.

In this case, no quantitative impact model was used. However, with the model chain established one could use the WRF for further applications regarding the risk of avalanches or the effect of the massive snow pack. On the climate side, so-called "climate change surrogate scenarios"[125] could be used to address the effect of climate change. In these simulations, temperature is increased while keeping relative humidity fixed (i.e., increasing absolute humidity), a recent study has done that for Vb cyclones.[126]

Using historical events in a statistical way: Winter wind storms in Switzerland

The third example relates to wind storms. This is an area where historical observations are often used to study extreme events and their impacts (in Europe,[127-129] building on the pioneering work of Lamb and Frydendahl[130], as well as in East Asia[20]) and particularly to address phenomena such as temporal clustering or changes on decadal time scales.[11,131] A recent SwissRe brochure on historical storms testifies to the usefulness of historical extremes for climate risk assessments.[132]

For Switzerland (as for other regions) only few large events such as storms Lothar (1999) and Vivian (1990) are well observed and were hitherto used to base storm risk maps on. Reanalyses now offer a much wider time window.[133]. Stucki et al.[134] compiled a storm catalog from measurements[135] and reanalysis data[14] as well as from historical damage data. Comparisons of the damage-based catalog with measurements and reanalyses allow a first assessment of the robustness of storm frequency estimations. Then, from 140 years of historical reanalysis data, ca. 100 storms were dynamically downscaled. From this large sample of storms, a risk map could be constructed using methods of extreme value statistics.[136] At the same time, these ca. 100 storms were used to drive a storm damage model,[104] from which statistical winter storm loss maps could be generated.

These loss maps could be validated for present cases with electronically available data, but also for one historical case, a Föhn storm in 1925 (Fig. 4).[137] Newspaper reports and other historical sources were used to map the damage, which then could be compared to modeled losses. Results show a good correspondence (Fig. 4).

This large sample of storms provides interesting insights. For instance, the Swiss Plateau is far more affected by winter storm losses than south-eastern Switzerland.[104] In general, the densely populated areas stand out. This model chain can now be used to assess different exposure and vulnerability scenarios (note that wind storm trends derived from 20CR reanalyses may not be reliable prior to ca. 1950, but multidecadal variability fits well with observations[133]).

Discussion

The examples presented use different methods and model chains. The first case uses analog re-sampling, which is a simple, yet powerful method. Circulation analogs have been used to reconstruct past weather,[138] for precipitation forecasting[139] and for downscaling future weather extremes from climate model simulations.[140] In our case we used impact models on top of the analog approach.

The example shows that analog methods may be particularly suitable for "climate extremes", where the individual day is less important than the seasonal extreme. However, all analog approaches require a large pool of analogs. Analogs might be further improved using post-processing (quantile mapping, data assimilation), but more fundamental limitations remain, as our example shows. The background climate in 1816 was different than today and in the future, which needs to be accounted for. Further, the triggering event of the flood in 1817 was not captured with the analog and required combining the analog reconstruction with a scenario, which was evaluated using documentary data. Recourse to documentary sources is of utmost importance for the use of historical weather data for climate risk assessment.

The second example used dynamical downscaling, which also is a widely used method. It has been applied for a number of historical weather extremes including blizzards, flash floods or storms.[141-143] Fortunato et al.[144] used a suite of models to downscale a strong storm that hit the Iberian Peninsula in 1941 and to simulate water levels and inundated area in the Tagus estuary. Bresson et al.[145] studied the 1952 North Sea storm surge using downscaling coupled with a wave model.

These examples show that downscaled historical extremes can contribute to better understand processes or to derive quantitative information, which then can feed into well established impact model chains. However, it may not always work (we need documentary environmental data to evaluate the results), or it may not always provide added value. Dynamical downscaling implies that a driving data set (mostly a global reanalysis) of sufficient quality is available. Another question relates to the fact that several of the reanalyses are ensemble products. There are no simple diagnostics to learn beforehand which member will give the best results or it the ensemble mean is sufficient.[103] Finally, downscaling arguably will provide most benefit in those regions where the land surface or topography matters, such as in an Alpine setting or near coasts.

The third example presented uses a large pool of past extreme events, processed in a quantitative way. Documentary data and long instrumental records have been widely used to compile detailed catalogs of extreme weather events.[134,146-149] For China, Xiao et al.[12] applied multiple data sets integrating flood/drought index (hazard data), population (exposure data), cropland area, crop yield per unit area, governmental grain relief, gruel charity in Beijing, migration of refugees, and revolting events (loss and vulnerability data) to study climate extremes and political and societal responses. What is new in the example shown is the model chain, which however is computationally expensive. Furthermore, the selection of events is a critical step as events may be missing from the catalog. Also here, recourse to documentary data is important.

This shows that although model chains may be built to perform quantitative risk assessment based on historical weather data, there are important differences to doing the same work in the past 50 years. In all cases we need additional information, often in the form of documentary data.

Conclusions

Weather and climate-related hazards cause tremendous losses each year. Estimating related risks in the present as well as in the future - in the view of climate change, but also socio-economic changes – is considered an important task. Historical environmental data can help in this task, particularly as numerical model chains are now available that bridge all steps from weather observations to weather impacts.

Efforts towards rescuing, compiling and preserving historical weather data are underway, undertaken by many individual projects,[32,150-153] coordinated within the Atmospheric Circulation Reconstructions over the Earth initiative (ACRE)[154] and facilitated by climate services.[155,156]

However, using historical weather data for climate risk assessment is not an off-the-shelf approach. It requires various expertises in risk assessment, in weather data generation and modeling, and in interpreting documentary data. This requires a new collaboration between climate scientists and historians.

For a long time, the past record of events was the only available information to assess risks. As extreme events are too rare to be individually remembered, there is a need for societal memory and its culturally embedded maintenance. Today, reanalyses reach the length of societal memory, but complement the documentary data by continuous, global, quantitative weather analyses.

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Figures

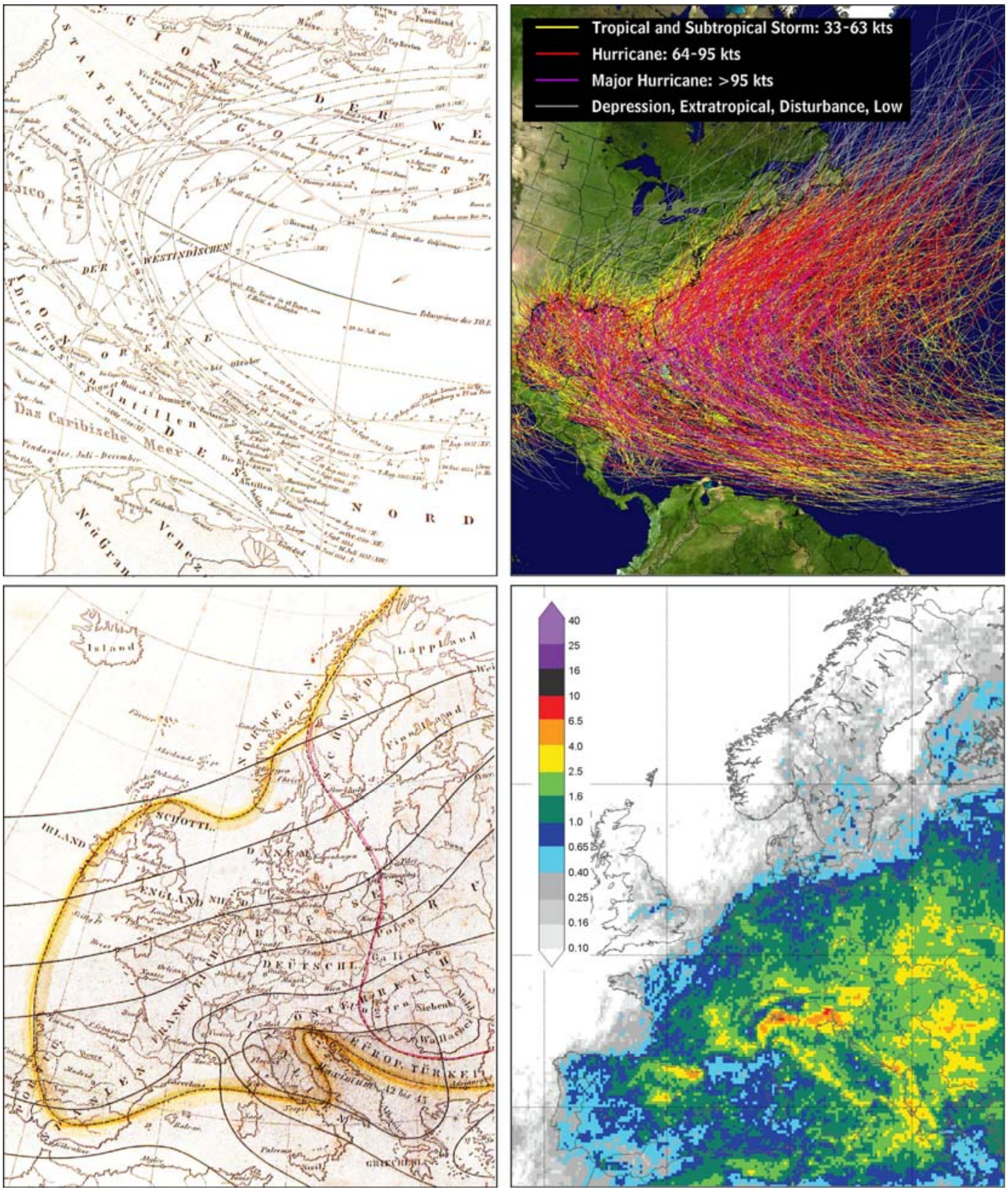

Figure 1: (left) Maps from the Berghaus physical atlas showing (top) tracks of Atlantic hurricanes reconstructed from the logs of Prussian merchant ships and (bottom) the annual frequency of thunderstorms over Europe (green area: summer thunderstorms, yellow area: thunderstorms in autumn and winter, red line: no winter thunderstorms occur east of this line). **(right)** Contemporary maps of (top) Atlantic hurricane tracks (1851-2017, from National Hurricane Centre, NOAA), and (bottom) annual mean lightning flash density (flashes per km^2 per year).[157]

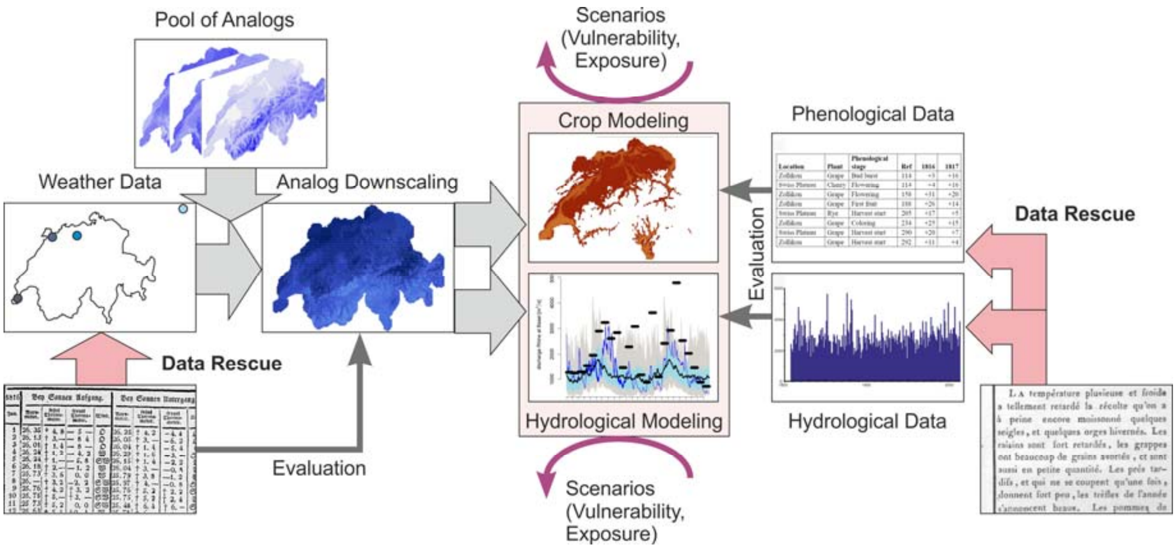

Figure 2: Using historical weather data to study the consequences of the "Year Without a Summer" of 1816 in Switzerland. Daily 2 km weather reconstructions were generated from weather data using an analog approach, which then was used to drive impact models (a crop model and a hydrological model). These models were validated using historical impact data (phenological and hydrological data). With the model chains established, scenario simulations can be run (e.g., for estimating the effect of a "Year Without a Summer" in the present climate).

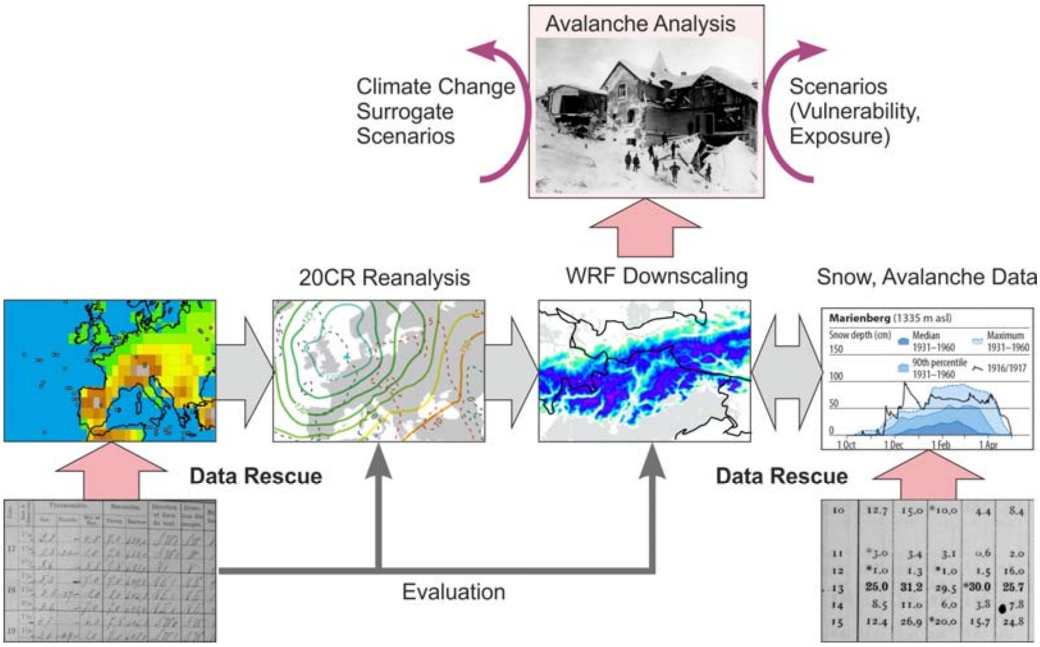

Figure 3: Historical weather data, reanalyses, and dynamical downscaling were used to study the 1916 avalanche event in the Southern Alps. The downscaling provided hourly 2 km-resolved weather reconstructions for this event, which were evaluated using historical snow depth data. Scenario simulations could now be run by on the on hand changing climate, and on the other hand by incorporating – and varying – vulnerability and exposure.

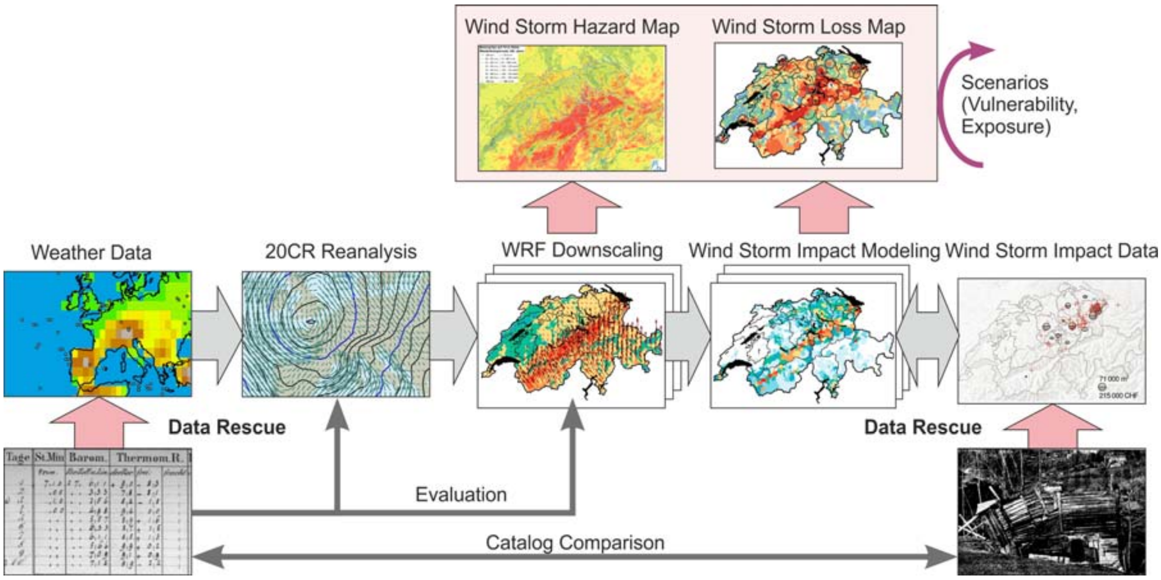

Figure 4: Historical weather data, reanalyses, and dynamical downscaling were used to study approx. 100 storm events in Switzerland. The downscaling provided hourly 2 km-resolved weather reconstructions for all events, which were used for damage modeling. The result was then evaluated using historical damage data (in detail for one case). From this, a wind store hazard map and a wind storm loss map was generated for Switzerland. Scenario simulations can be run by changing vulnerability and exposure.