~~Decadal variations~~A long record of European ~~windstorms: linking research~~windstorm losses, and its comparison to ~~insurance applications~~standard climate indices

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Abstract.

~~The insurance sector is affected by decadal-scale variations in annual European windstorm losses amounting to a few billion euros, yet has not applied recent advances in understanding and predicting this variability to their pricing of windstorm risk. This is mainly due to an unknown relation between insured wind losses and meteorological definitions of storminess used in research. This study aimed to reduce this uncertainty.~~

~~A history of windstorm insurance losses over the past 72 years was developed from winds in weather reanalyses. Then, typical storm proxies used by researchers, such as the North Atlantic Oscillation (NAO) and the Arctic Oscillation, were compared to the new windstorm loss record. The relationship between the proxies and losses has two distinct regimes: highly consistent from 1950 up to the 2000s, then a divergence in the past 10 to 15 years. The recent separation is large and robust, with high confidence that modern values of researchers' proxies approach levels last seen 30 years ago, whereas decadal-mean losses are far lower today than in the 1980s and '90s.~~

~~The cause of this divergence was explored. Storm damages are most closely associated with peak gusts deriving their momentum from winds in the free troposphere, and pressure gradients at the surface used in typical climate indices can only partially describe higher level winds. Based on this reasoning, a new Hemispheric Geostrophy Index (HGI) was defined as the difference in 700 hPa heights between the tropics and the Arctic. It was found to vary coherently with decadal losses in the past, and crucially retains this consistency in the past 15 years too. Breaking down the HGI into component parts revealed that lower storminess in recent times is linked to ongoing reductions in poleward baroclinicity. Further development of loss history and climate indices would help bridge decadal research to insurance applications.~~

Skilful predictions of European winter climate variations at interannual and longer timescales are not used by the insurance industry despite their great exposure to windstorm damage. The main reason is the lack of a long, reliable record of losses to understand how forecasted time-mean circulation anomalies relate to insurance risk. This study fills that gap with a European windstorm loss record from 1950 to 2022, based on ERA5 peak near-surface winds per event which were converted to losses using an established damage function. The resulting dataset successfully identifies major storms over the past 70 years, and simulates the multidecadal variations from low values in the 1960s up to high levels in the 1980s and '90s then down to the

2010s. However, it underestimated the steepness of the observed loss decline from the stormy end of the 20th century to the lull in the past 20 years. This was caused by a quite flat trend in ERA5 winds over the period. By contrast, observed peak gusts contained a significant decline, and imposing their trends on ERA5 winds reconciled modelled losses with industry experience over the past few decades.

Indices of European winter climate used in long-range forecasting were compared to the new modelled loss dataset. They had correlations of around 0.4 at interannual timescales, rising to about 0.7 for decadal and longer variations. The correlations at decadal scales were above 0.8 over the 60 years up to 2010, before a decoupling between climate indices and losses in more modern times. The climate indices have a similar multidecadal trend as ERA5 extreme winds, and much flatter than found in observed gusts and losses. Resolving the modern-day divergence between climate indices and losses may help connect decadal forecasting to insurance.

1 Introduction

Extreme wind gusts from winter storms cause much damage to Europe. For example, Barredo (2010) examined Europe-wide economic losses in the Munich Re NATHAN catastrophe database for the period 1970-2008 and, when trended to 2022 using ~~a typical ~~5% p.a. growth (e.g. Klawa and Ulbrich, 2003), there are ~~several~~four storms with losses exceeding 20 billion USD~~,~~ (Capella in 1976, 87J in 1987, Daria in 1990, and Lothar in 1999), and the annual average from the top 25 events is around 7 billion USD. Such large impacts ~~motivate~~stimulate research into Europe's climate of extreme windstorms.

The property insurance sector covers around one half of these losses (e.g. Guha-Sapir et al., 2022), and therefore has keen interest in this risk. The majority of the market is classed as traditional insurance, while ~~forestry suffers a significant part too (e.g. Gardiner et al., 2010).~~the more modern insurance-linked securities (ILS) segment provides additional capacity from outside investors. Traditional insurance manages their exposure according to a view of the windstorm risk typically over the next five or so years, corresponding to their ~~global ~~review cycle of weather perils, ~~and are able to tailor their risk management to suit~~whereas ILS is more active at annual timescales with a significant fraction tradeable much more frequently. This study will focus more on storm climate variations at ~~these, or longer timescales~~decadal scales due to the dominance of the traditional insurance market, though some results will be presented at the annual timescales of more relevance to ILS.

~~Several studies document significant variability~~Most participants are very familiar with huge interannual variations of windstorm losses, readily apparent in published research (e.g. Figure 4 of Barredo, 2010). The large variations of the European wind climate at decadal and longer timescales ~~(e.g.~~are perhaps less well known, though there has been a significant amount of published research (e.g. WASA Group, 1998, Dawson et al., 2002, Brázdil et al., 2004; Cusack, 2013; Stucki et al., 2014; Feser et al., 2015; Dawkins et al., 2016; Laurila et al., 2021). Cusack (2013) focused on a measure reflecting insured losses and found the decadal-mean windstorm damage in the Netherlands contained variations with amplitudes exceeding a factor two. ~~At the same time~~In parallel, there has been much progress in identifying and understanding drivers of these decadal storm variations, as recently reviewed by Cassou et al. (2018). Researchers ~~find~~have found decadal and longer timescale anomalies

~~are~~being driven by North Atlantic Ocean heat contents (Omrani et al., 2014; Peings and Magnusdottir, 2014; Hu et al., 2019), Arctic sea ice extent (e.g. Smith et al., 2022) and thickness (e.g. Lang et al., 2017) or more generally Arctic change (e.g. Cohen et al., 2018), and their interaction via ocean heat transport through the Norwegian Sea into the Arctic Seas (Zhang, 2015; Årthun et al., 2017). Other parts of the climate system ~~parts~~ have also been associated with decadal and longer changes in mid-latitude storm activity, such as the tropics (Greatbatch et al., 2012), the stratosphere (Scaife et al., 2005), anthropogenic gases (e.g. Shaw et al., 2016), and major volcanoes (Swingedouw et al., 2015).

The documented decadal variability and process-based research are now complemented by skilful forecasting of ~~wintertime climate~~the dominant mode of winter-mean variability in the North Atlantic sector~~.~~, the North Atlantic Oscillation (NAO). Decadal prediction systems integrate the set of diverse drivers into a ~~unified~~ view of the future climate, and skilful North Atlantic decadal forecasts were first reported in Keenleyside et al. (2008~~) helped focus research onto this area.~~). A study by Eade et al. (2014) found prediction systems contained more skill than implied by rather low signal-to-noise ratios, and ~~it~~suggested large ensembles of forecasts could ~~be extracted by using larger numbers of forecast ensemble members.~~realise this potential. Recently, hindcast tests conducted by Athanasiadis et al. (2020) ~~find~~found correlations ~~of~~up to 0.63 between forecasted and observed decadal NAO anomalies for a 40-member ensemble, ~~together with the promise~~and promising signs of higher correlations from larger ensembles. Indeed, Smith et al. (2020) found correlations of 0.79 based on an ensemble with 676 members.

Despite these advances in characterising and understanding decadal ~~wind~~climate variability in Europe and the wider North Atlantic sector, and skilful decadal forecasting, there has been no known application ~~of it to~~in European windstorm insurance. The main reason is the uncertain relation between ~~the metrics of wind risk~~predicted climate indices – essentially large scale, winter-mean circulation anomalies – used in ~~published research~~forecasting, and the windstorm losses of ~~most relevance~~concern to insurance~~. It is not clear what fraction of the decadal variations of storm losses are captured by the storm proxies, and in the context of severe consequences for mis-priced risk, quantitative estimates of their connections are needed to inform risk management~~.

Published research relating to storminess use a much broader array of metrics, in addition to the NAO mentioned above. For example, the basic observed quantity may range from meteorological variables such as wind speeds at the near-surface (Smits et al. 2005, Chang, 2018) or upper troposphere (Harvey et al. 2020), vorticity at 850 hPa (Deroche et al. 2014) and geostrophic winds derived from surface pressure gradients (WASA Group 1998), or they may be based on economic losses (Barredo, 2010), or forestry damage (Gregow et al. 2017). ~~A~~These quantities are processed in a variety of ways to produce a measure of windiness. While all metrics have a reasonable relation to storminess, their precise relations to losses are unknown. Insurance companies are cautious about using results with unknown relation to loss because they can suffer severe penalties for mis-priced risk.

This barrier to applications would be removed with a long windstorm loss history ~~in Europe is needed, to quantify the relation between published climate indices and insured windstorm damages at multidecadal scales~~to assess the storm metrics. However, publicly available information on losses is limited. For example, the EM-DAT database (Guha-Sapir et al., 2022) contains reliable information for some major storms, but misses national losses for many significant events in the past 50 years. PERILS (available from https://www.perils.org/losses) provides reliable estimates of insured losses ~~at~~covering the countries contributing the vast majority of Europe-wide ~~scale~~insured losses, for significant storms since 2009, and five earlier storms in the previous ten years. ~~The commercially confidential nature of insured losses may have contributed towards this incomplete picture~~It is encouraging for the future, but too short at present for robust assessment of ~~loss in the public domain.~~ storm metrics. The ~~first part~~main aim of this study ~~creates~~is to develop a comprehensive windstorm loss history for Europe in the period 1950-2022, using near-surface winds from reanalyses in combination with a standard method to convert windspeeds to losses. ~~The second part of this study quantifies the connection between some of the most commonly used climate indices in published work to the new loss history. These two parts establish the relevance of existing research results to insurance applications. It is found that typical indices do not reflect decadal storminess in recent times, and a new climate index will also be introduced, partly to help provide some insight into this breakdown, and also to identify promising directions for future work seeking to connect research insights to storm applications.~~ Section 2 provides details on the data used in this study, while Section 3 describes how storm losses are computed. Section 4 contains an initial evaluation of its losses with insurance industry knowledge, together with further development to reproduce multidecadal trends in observed losses. A comparison of commonly used climate indices to these calibrated losses is given in Section 5, then the main conclusions are presented in Section 6.

2 ~~Data~~Datasets and processing

~~2.1 Datasets~~

~~The atmosphere and ocean data cover the January 1950 to April 2022 time period.~~

~~The preliminary extension of ERA5 global reanalysis back to 1950 (Bell et al., 2021) is a primary source of atmosphere data. The instantaneous values of winds at 10m above short grass for each hour are used as the main input into the metric of Europe an storminess presented in the next section. Monthly means of geopotential heights at fixed pressure levels, and the pressure at mean sea level are extracted from ERA5. The monthly mean geopotential heights were also downloaded from NCEP-NCAR Reanalysis 1 (Kalnay et al., 1996) and the average of these two reanalyses are used.~~

~~The population data used in the storm loss metric is from Gridded Population of the World, version 4, at 2.5 minutes of arc resolution (CIESIN, 2018).~~

~~PERILS insurance industry losses were obtained from https://www.perils.org/losses.~~

~~2.2~~Windstorm damages are computed over the domain of 12 countries shown in Figure 1, including those that are key to European windstorm insurance, such as Germany, France, United Kingdom and Netherlands. Other countries will experience smaller insured losses due to either their weaker wind climate, or smaller population, or reduced insurance penetration. The industry considers the highlighted region in Figure 1 to incur the vast majority of European windstorm *insured* losses.

2.1 Loss data

Observed winterstorm losses are developed from a published loss in a given year, which is indexed to the common year of 2022 to remove the effects of societal changes on loss estimates. All loss data in this study are indexed from 1999 onwards, therefore trends from that year to 2022 need defined. Klawa and Ulbrich (2003) chose 5% p.a. trend for the period 1970-1999, a value that was positioned between inflation rates for buildings in Germany, and sharper increases of 7% p.a. through the 1990s reported by Munich Re (2002). Trends in the 21st century are expected to be lower for two main reasons: (i) inflation was generally higher in the 1970s through to the early 1990s than from 2000 to 2022, (ii) Munich Re trends include growth in exposure from increased uptake of insurance, and re-unification of Germany, both of which do not contribute to growth over the past two decades.

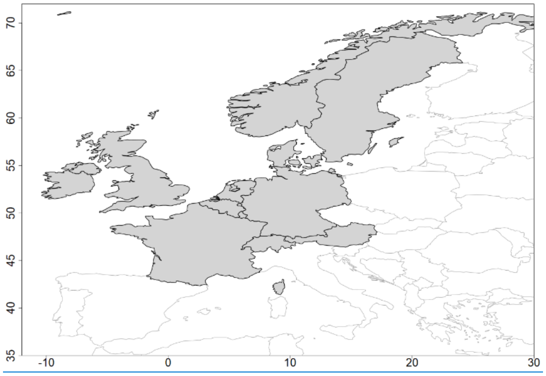


Figure 1: a map of Europe, with the shaded area showing the 12 countries studied here.

An appropriate trend for the 21st century is developed by decomposing total losses into trends in frequency and severity of claims. Both general measures of inflation and slightly more relevant construction cost indices suggest increases in claim severity of 2 to 3% p.a. from 2000 to 2022. The growth in claim frequency is expected to be more muted than in the 20th century due to slower population growth and near-saturation of windstorm insurance uptake in these markets. Instead, the growth in number of claims in the 21st century is more driven by the growth in the number of properties. Data on the total number of dwellings in Germany (from https://www.destatis.de/EN/Themes/Society-Environment/Housing/_node.html) and the U.K. (e.g. https://www.gov.uk/government/statistical-data-sets/live-tables-on-dwelling-stock-including-vacants) indicate 0.5 to 1% p.a. growth over the past 20 or more years. In this study, the claims frequency and severity components are combined into a uniform trend of 3.5% p.a. from 1999 to 2022.

For comparison, the work by Pielke and Landsea (1998) considered three factors, namely inflation, population, and wealth. The combination of the three factors produces a quantity akin to the nominal Gross Domestic Product (GDP), and their explicit partitioning in Pielke and Landsea (1998) served to distinguish their analysis from previous published work which largely relied on inflation alone. An analysis of GDP figures from the OECD (available from https://data.oecd.org/gdp/gross-domestic-product-gdp.htm) for the three biggest countries (France, Germany, U.K.) reveals a range of 4.1 to 4.3% p.a. growth in GDP over the period 2000 to 2022. However, the GDP includes a measure of growth in wealth/possessions (aka real GDP per capita) which is of little relevance to most windstorm claims mainly consisting of tile damage. Data from Eurostat (https://ec.europa.eu/eurostat/databrowser/view/sdg_08_10/default/table?lang=en) indicate the real GDP per capita has been growing at an average rate of just under 1% p.a. in the 21st century, hence the lower growth rate of 3.5% p.a. used in this study is more consistent with the factors driving trends in windstorm damages. Other types of catastrophes causing more severe damage to properties, such as flood or tropical cyclones, would be more appropriately trended using nominal GDP.

The set of reported losses can be split into two groups: more modern storms in 2009-2022 taken from PERILS (available from https://www.perils.org/losses) and older storms which have been intensively studied due to their severe impacts. Losses for both groups are based on market surveys following the event, and due to strict financial standards, these *reported* losses are likely to be thoroughly reviewed internally, and accurate. However, the trending of the losses to a common year is a significant source of uncertainty, more so for older storms. For example, the true average 21st century trend in total losses could be as low as 2.5% or as high as 4.5% p.a. based on claims frequency and severity data discussed above, and there is additional uncertainty since most damage concerns roof tile replacement and much narrower than broader inflation or construction cost measures. These considerations suggest the potential bias in indexed losses is reasonably approximated as growing by 1% per year. Therefore, the more modern PERILS loss estimates could be biased by around 10%, while damage estimates of older storms are expected to be more uncertain.

Table 1 summarises the loss data used to evaluate the new dataset. PERILS losses represent the same domain highlighted in Figure 1, and include those events causing more than €200 million insured loss. The same loss threshold of €200 million will be applied to events in the new dataset for the loss validation performed in Section 4. All other sources of loss estimates may potentially include losses outside of the 12 countries, though such an additional contribution is expected to be minor and within uncertainty, especially for older storms. Multiple sources are available from Swiss Re over the years, and the earliest values are chosen so as to minimise the use of their trending based on the United States consumer price index (Swiss Re, 2002).

Table 1: historical loss data used for validation.

Storms	**Loss estimate in € billions, and source**	**Final estimate in € billions, and range**

2009-2022	PERILS reported, + 3.5% p.a. to 2022	PERILS (± 10%)
Kyrill, Jan 2007	6.12 (PERILS) 6.95 (Swiss Re, 2008)	6.5 (± 15%)
Dec 1999	22.2 (PERILS) 23.5 (Munich Re, 2002) 22.7 (Swiss Re, 2002) 22.2 (RMS[a])	22 (± 20%)
Jan-Mar 1990	35.3 (Munich Re, 2002) 27.3 (Roberts et al., 2014; extracted from Swiss Re) 34.7 (RMS, 2007[b])	30 (± 20%)
87J	9.0 (Munich Re, 2002) 8.25 (Swiss Re, 2002) 9.6 (RMS, 2007)	9 (± 20%)
Capella	9.0 (Munich Re, 2002)	9 (± 30%)

[a] https://www.rms.com/blog/2019/12/18/twenty-years-after-storms-anatol-lothar-and-martin-memories-from-the-end-of-the-millennium

[b] RMS estimate of storm Daria inflated to total 1990 loss using its fractional contribution to the total from Munich Re (2002)

2.2 Wind data

The windstorm losses from 1950 to 2022 are based on instantaneous (12-minute timestep) winds at 10m above short grass, available from ERA5 (Bell et al., 2021) at hourly frequency. Peak gusts are more commonly associated with damage (e.g. Prahl et al., 2015) however, it was found that storms based on ERA5 peak gusts (ECMWF, 2016) validated poorly. For example, footprints based on ERA5 peak gusts indicate storm Kyrill produced the biggest loss in the past 70 years, and 72% higher than those of Daria (1990), while storm 87J (1987) was a lowly rank 42 and just 12% of Kyrill's loss. In sharp contrast, Table 1 indicates storm 87J and Capella had greater losses than Kyrill, and breakdowns by event for the 1990 and 1999 seasons from both Munich Re and Swiss Re indicate Daria and Lothar losses are higher again. As a result of intensive research into these extreme storms, there is a high level of confidence that the true storm loss relativities are very different from those based on ERA5 gusts. Losses based on ERA5 near-surface winds will be shown later to be more consistent with experience than those based on ERA5 gusts.

Observations in the Integrated Surface Database (ISD, Smith et al., 2011) from the National Oceanic and Atmospheric Administration (NOAA) National Centre for Environmental Information (NCEI) are also analysed. The ISD is a global collection of surface-based observations built from many national sources, with its specific purpose to homogenise the mixture of data formats used worldwide, and thereby ease access for researchers. It contains observations at hourly to 6-hourly frequency from over 20,000 weather stations which have been active for some time within the period from 1900 to the present day. ISD offer additional products in line with their aim to make global surface weather observations more accessible. The Global Summary of the Day (GSOD) is a more concise version of ISD with fewer variables at daily resolution, and the daily maximum values of peak gusts in this dataset are used later in this study.

2.3 Climate index data

The three most commonly used indices of mean circulation anomalies over Europe, and often linked to regional storminess, are the NAO, Scandinavian Pattern (SCA) and the Arctic Oscillation (AO). NAO data (Hurrell et al., 2003) are provided by NCAR (available at https://climatedataguide.ucar.edu/climate-data/) and both the principal component (PC) and station-based (Lisbon and Iceland) versions are assessed. Monthly mean pressures at sea level have been extracted from ERA5 archives to define the two other indices. The SCA values (Barnston and Livezey, 1987) are computed as the difference between a southern (35° N to 50° N, 10° E to 30° E) and northern box (60° N to 75° N, 10° E to 30° E), while AO values are computed as the average value over the North Pole (north of 60°N) of mean sea level pressure from ERA5.

2.4 Data processing

~~Monthly~~All monthly data are processed into storm seasons by averaging monthly values from October to March, except for the storm index which includes ~~events in April too. The analysis of storminess will be based on running means over 11 years, and using centred plotting (e.g. the value plotted at 1989/90 is a linear average of the 11 values from 1984/85 to 1994/95). Some of the later analysis will convert values to standardized anomalies (mean of zero, standard deviation of one) to facilitate comparison of quantities with different units. The standardization is based upon the distribution of the running mean values.~~those few extreme events occurring in April.

~~3 A European windstorm loss history~~

~~3.1 Basic Method~~

~~Studies of European wind climate use very diverse measures. For example, the basic observed quantity may range from meteorological variables such as wind speeds from the near-surface (Smits et al. 2005) to the upper troposphere (Harvey et al. 2020), vorticity at 850 hPa (Deroche et al. 2014) and surface pressures (WASA Group 1998), or they may be based on economic losses (Barredo, 2010), or forestry damage (Gregow et al. 2017). Further, the storm metric function may be based on higher percentiles of wind speeds or vorticity or surface pressures, or the rate of change of surface pressure, or gale-days, or they may be inferred from winter-mean changes in winds or pressure gradients over Europe. The varied set of storm climate definitions inevitably leads to a spread in results. A timeseries of insured property losses is developed in this study, and the large amounts of wind damage in Europe is of benefit to statistical analysis.~~

~~ERA5 instantaneous winds at 10m above short grass, at hourly frequency,~~ The main focus of this study are those variations at decadal and longer timescales which can be assimilated into the ca. 5-year pricing review cycle of most insurance business.

These variations are examined using low-pass filtered versions of annual timeseries, produced by applying a fourth-order Butterworth filter with a 10-year cutoff frequency.

Some of the later analysis converts timeseries to standardised anomalies (mean of zero, standard deviation of one) using their sample statistics, to enable comparison of quantities with different units, such as storm losses and climate indices.

3 Defining storm event losses

The maximum values of ERA5 near-surface winds were ~~used to construct a record of storm damage from 1950 to the present day. In brief, the maximum~~ computed at daily ~~winds were found, then merged into the maximum per storm event defined as up to a 3-day window,~~resolution for every grid cell in ~~Europe. These maximum~~the domain, and a proxy of damage (D) for the entire domain was defined for every day from 1950 to 2022 as follows:

$$D = \sum_{i=1}^{N} \left[max\left(\frac{v_{i,d}}{v_{i,98}} - 1, 0 \right) \right]^3$$

where there are N grid cells in the domain, $v_{i,d}$ is the daily maximum wind, and $v_{i,98}$ is the climatological 98th percentile of wind. This daily damage quantity is based on the loss proxy discussed below.

The next step is to form storm events as a series of up to three days centred on the days with peak values of D, then compute the event maximum wind ($v_{i,s}$) over the days of the storm, for each grid cell. The outcome is a matrix of peak windspeeds stored for each grid cell, and every storm.

The grid cell peak storm winds were converted to ~~grid cell~~domain-wide event losses using the model from Klawa and Ulbrich (2003):

~~$$event\ loss = c. \sum_{i=1}^{N} P_i \left[max\left(\frac{v_i}{v_{i,98}} - 1, 0 \right) \right]^3$$~~

$$L_s = c. \sum_{i=1}^{N} P_i \left[max\left(\frac{v_{i,s}}{v_{i,98}} - 1, 0 \right) \right]^3$$

where ~~there are N grid cells in~~L_s is the ~~domain, and~~loss for storm s, P_i is the population count for the i'th cell, ~~P_i is its population count, v_i is its event maximum wind, and $v_{i,98}$ is the climatological 98th percentile of wind.~~ and c is a constant of proportionality intended to re-scale values to represent losses. The population data is from Gridded Population of the World, version 4, at 2.5

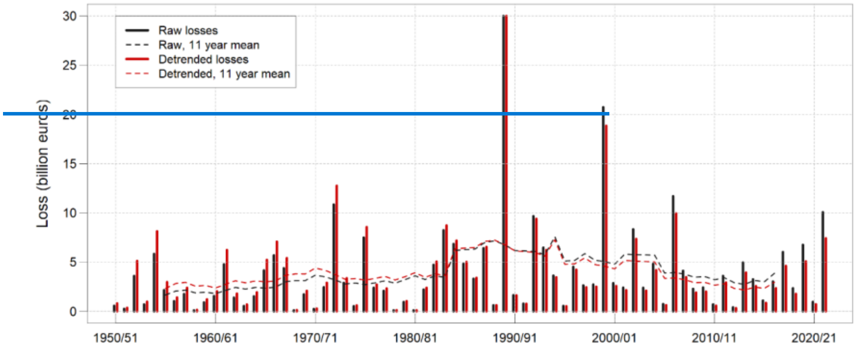
minutes of arc resolution (CIESIN, 2018). The constant of proportionality c in this model ~~has been~~is used to scale values to losses, and in this study was defined to ~~produce~~reproduce a €30 billion aggregate ~~loss for~~ wind loss in the 1989/90 season, ~~a value in line with industry expectations (e.g. Munich Re (2002) estimate €16 billion when trended to 1999, and this figure is expected to more than double if trended to 2022). The essence of the above loss definition is that damage amounts are proportional to (a)~~from Table 1. Finally, event losses in the October to April period were summed together to form total damage per windstorm season.

The above equation defines losses to vary with the cube of the wind excess above the local 98th percentile, and ~~(b) the exposure, represented by population density~~population density. Klawa and Ulbrich (2003) discussed the basis of this formulation, together with a validation based on 20 years of industry-wide insured losses in Germany, and other selected events. Another feature of this loss equation, of more relevance later, is the assumption that the size of loss for a given wind speed is independent of time. Whether this assumption holds over the 1950 to 2022 period is unclear, and discussed in greater depth in the next section.

4 A European windstorm loss history

4.1 Initial evaluation of historical losses

Figure ~~1~~2 shows losses per windstorm season from 1950/51 to 2021/22 using the ~~methodology above (black bars), and including those storms with losses above €200 million for validation with PERILS observed losses, performed later~~ERA5 winds. At a high level, the model compares well to observed losses for key storms: the historic years of 1990 and 1999 are ~~captured~~prominent, as are other large loss years containing ~~benchmark~~landmark storms (most notably ~~Kyrill in January 2007;~~the Lower Saxony storm in November 1972; Capella in January 1976, and the stormy period in the early 1980s following the El Chichón eruption; and Kyrill in January 2007).



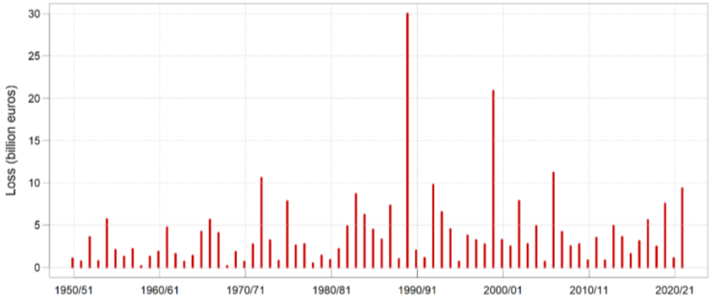


Figure ~~1: timeseries~~2: barplot of Europe-wide annual windstorm losses, ~~and their running means over 11 years~~from 1950/51 to 2021/22.

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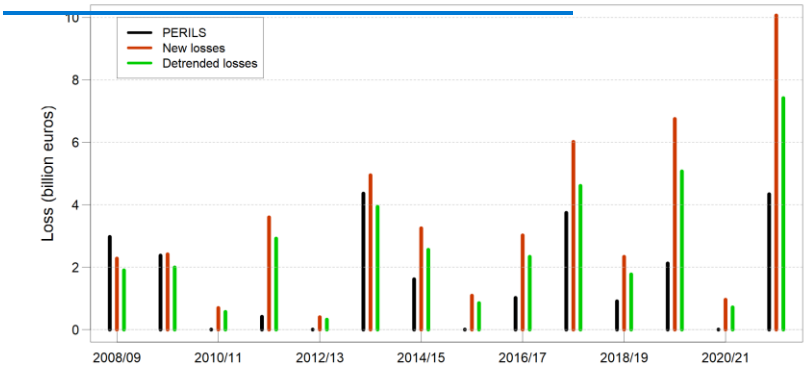
~~3.2 Evaluation~~

~~More quantitative loss validation was performed using PERILS reported losses at the time of event. PERILS produce benchmark quality loss estimates for storms since 2009, and have extended their record to include some older, key events too. They survey the market's losses to produce quantitative estimates for those storms with losses exceeding €200 million, and these have been trended to 2022 values using a typical long-term growth of 5% pa. Figure 2 shows the new timeseries alongside PERILS losses trended to 2022 values, and a high bias of 100.5% is found over the past 14 seasons.~~

~~There are several loss sources which indicate the current high bias is absent for well documented, severe events in earlier times. (i) RMS (2007) estimates for the historic storm named 87J (the dominant loss event in 1987/88 season) would trend to around~~

~~€10 billion in 2022, above the €7.15 billion in the new dataset. (ii) Figure A2 in Barredo (2010) indicates losses in 1976 were double those in 2007, and losses in 1987 exceeded those in 2007, whereas the new dataset places 2007 losses above those two earlier years. (iii) The new dataset has larger losses in 2022 than 1976 and 1987, running against best estimates which places 2022 as the weakest of these three years. (iv) PERILS and Munich Re estimate the total losses from the three major events of December 1999 to have caused approx. €10 billion and €10.6 billion respectively, at the time of occurrence, and applying a typical 5% p.a. trend suggests losses of around €30 billion if they occurred today, or around six times higher than PERILS losses in 2021/22 season, whereas the new loss timeseries indicates losses in the 1999/00 season were just double those of 2021/22. (v) Figure 2 in Cusack (2013) indicates the decadal losses in the 2000s in the Netherlands were similar or slightly lower than in the 1960s, whereas the new dataset has more than double the losses in the 2000s, versus the 1960s. In summary, independent loss estimates from a variety of sources all indicate the new damage timeseries based on ERA5 winds have a positive trend versus observed values, towards significant overestimates in recent years.~~



More detailed loss validation was performed by comparing with PERILS insured losses in Figure 3. The new dataset of losses exceeds those of PERILS in all but one year, and the probability of 13 or more years being higher out of 14 years, when both are drawn from the same parent distribution, is 0.00092 from the binomial distribution. There is a corresponding high bias of 107% over the 14-year period, and their means are significantly different at the 5% level. The evidence that modelled losses exceed observed in 2009-2022 is compelling. On the other hand, the modelled losses for older storms do not have such a high bias versus observed values: both the €30 billion for 1990 and a little over €20 billion for 1999 are consistent with observed (the former by design), while modelled losses for Capella in 1976 and 87J in 1987 are more than 20% **lower** than the observed values in Table 1.

Additional evidence on this contrast between older and newer storms can be gained from Figure A2 of Barredo (2010). While Barredo's absolute values are not suitable because they concern economic rather than insured losses, they can inform on the relativity between storms, and suggests losses in 1976 were double those in 2007, and losses in 1987 exceeded those in 2007. The values in Figure 2 place 2006/07 losses around 30% above those two earlier seasons, and not consistent with values in Barredo (2010), as well as Table 1.

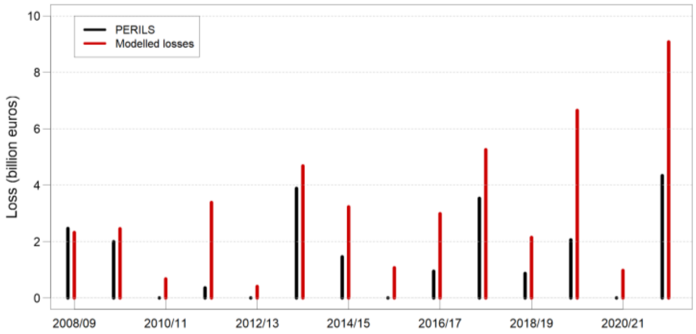


Figure ~~2~~3: a barplot of Europe-wide windstorm losses for the past 14 seasons, from PERILS and the new dataset.

The evidence clearly indicates modelled losses based on ERA5 winds tend to be low for earlier landmark storms, then evolve into more than double those observed in the most recent period. The growing positive bias in modelled losses in recent times is substantial, and is investigated further in the next subsection.

4.2 Multidecadal trends in losses

The mis-matched values of the loss decline from the 1980s and '90s to the 2010s could be caused by one or more contributions from three different drivers: (i) the observed losses used in validation contain too great a decline from the last two decades of the 20th century to the 2010s, or (ii) the relation between hazard and loss is non-stationary, whereas the modelling presumes it is homogeneous, or (iii) ERA5 winds are not representing the true trend in the hazard quantity causing windstorm damage. These three possibilities are now investigated.

There is high confidence in the observed data which define the declining trend in losses, and as a result the first potential driver above is considered to contribute little to different trends in observed and modelled. Both older and modern observed losses are based on surveys of companies incurring losses, and both regulatory controls and intense scrutiny of the older, extreme events ensure the industry has accurate information on reported losses. It is also considered unlikely that an overestimation of trending of older costs to the present day is responsible. For example, the reported losses in 1990 from Munich Re (2002) would need trended by 1% p.a. to produce a relativity to the 2021/22 losses similar to the modelled value (a factor of three).

Such low indexation does not fit with observed data: for instance, the factor 1.8 to 2 in the decade of the 1990s found by Munich Re (2002) suggests a 1% p.a. trend is not credible.

The second potential driver would be wholly responsible if the hazard produced twice as much loss in the 1970s to 1990s period, than if the same hazard occurred in the present day. Possible causes of such a ~~trending bias are now considered. A changing relation between incurred loss for a given wind speed could explain the trend. Examples~~ non-stationarity include ~~improved~~changes in building practices ~~towards stronger roofs in modern times, or a greater reluctance for the insured to make a claim given damage. However,~~ which alter the vulnerability of roofs to damage from winds, or a social change in claiming practice (such as the insured's disposition towards making a claim) or repair methods (e.g. modified safety regulations governing roof repair). Such non-meteorological drivers of severe weather loss trends have been detected in the United States (e.g. RMS, at https://www.rms.com/blog/2018/08/03/us-severe-convective-storm-claims-going-through-the-roof) though they act to boost rather than reduce modern day losses, hence the opposite direction from what is required to explain the deficit in the modelled loss trend. Irrespective, there is no empirical evidence of ~~significantly decreasing trends in~~this type of loss inhomogeneity for ~~the same storm gusts over the past 3 or 4 decades.~~Europe windstorms. On the ~~other hand~~contrary, there is ~~evidence that~~ indirect evidence of a stationary relation from hazard to loss from catastrophe modelling vendors. For example, the RMS estimates of storm losses in Table 1 are based upon reported hazard, which are input into damage functions calibrated to losses chiefly from modern times, and this produces total losses which fit with other empirical estimates (see Table 1). Therefore, the existing evidence suggests this driver contributes little to the tendency for the modelled dataset to have a different loss trend from observed.

The above considerations led to a deeper study of the third potential driver: whether ERA5 winds could contribute to an underestimated decline in losses. There are two different types of evidence suggesting winds from reanalyses may provide imperfect long-term trends. First, it is well established how reanalyses may contain non-meteorological trends due to changing observation systems, ~~which depends~~depending on meteorological variable, time period and region being studied (e.g. Bengtsson et al., 2004; Thorne and Vose, 2010). ~~Feser et al. (2015) reviewed a wide variety of studies of wind speeds in Europe over the past several decades and their results suggested reanalyses and models tend to produce more positive storm trends than observational-based studies. Recent studies (Kreuger~~Second, storm damage is most closely associated with gusts rather than winds, and there is potential for these two quantities to have different trends, since gusts depend on additional small-scale processes which are less well resolved by mean winds representing longer timescales. Given these uncertainties in reanalyses and time-mean winds, multidecadal trends in ERA5 winds have been compared to those from observed gusts.

Figure 4a shows the trend in ISD gusts from 1980 to 2022 for those 221 stations with at least 38 years of non-missing gust data in this time period. Annual averages of the top five gusts per year were computed, then re-scaled with the station's long-term mean value of this quantity, so that the resulting fitted linear trends at each station can be expressed in units of % change per year. The method was repeated for ERA5 reanalyses winds at the same locations as the surface weather stations, and their trends are shown in Figure 4b.

In general, the plots show a magnitude of downward trend in observed extreme gusts which is not replicated in ERA5 reanalyses winds. For example, observed gusts have a more negative trend than ERA5 winds at 180 of the 221 stations (Figure 4c), and such a preponderance of more negative gust trends has a vanishingly small chance of being produced by random sampling error. The U.K. data are now selected to study this issue in more detail, because of its good station density (51 in total) and relatively consistent signal in Figure 4c.

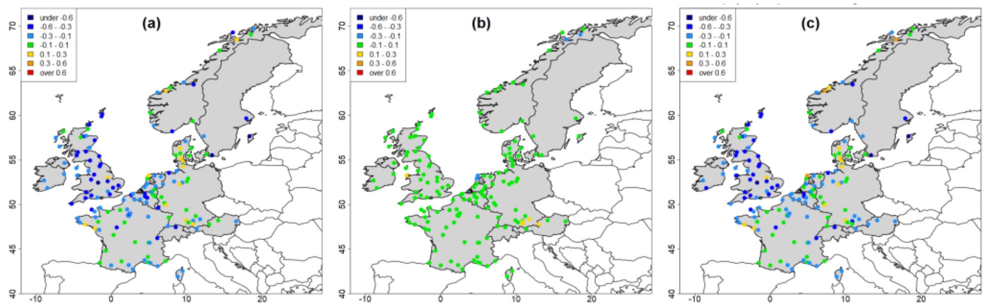


Figure 4: the linear trend (in % per year) from 1973 to 2022, for (a) ISD gusts, (b) ERA5 winds, and (c) their difference.

Using the same method as before, each station record was processed to obtain the annual average of the top five values of wind or gust, then re-scaled with its timeseries average. Finally, the annual means are averaged over all UK stations to produce the plotted values in Figure 5a from ISD and ERA5 datasets. On the face of it, all three timeseries appear quite similar, though closer inspection reveals how ISD gusts tend to be above the other two in the first half of the record, then mostly below them in the second half. Figure 5b shows this behaviour more clearly: the ratio of ISD gusts to ERA5 winds (black solid line) has a downward trend indicating the relativity of ISD gusts to ERA5 winds is declining over the past four decades. In contrast, extreme gusts from ERA5 have a similar trend to their winds over this period.

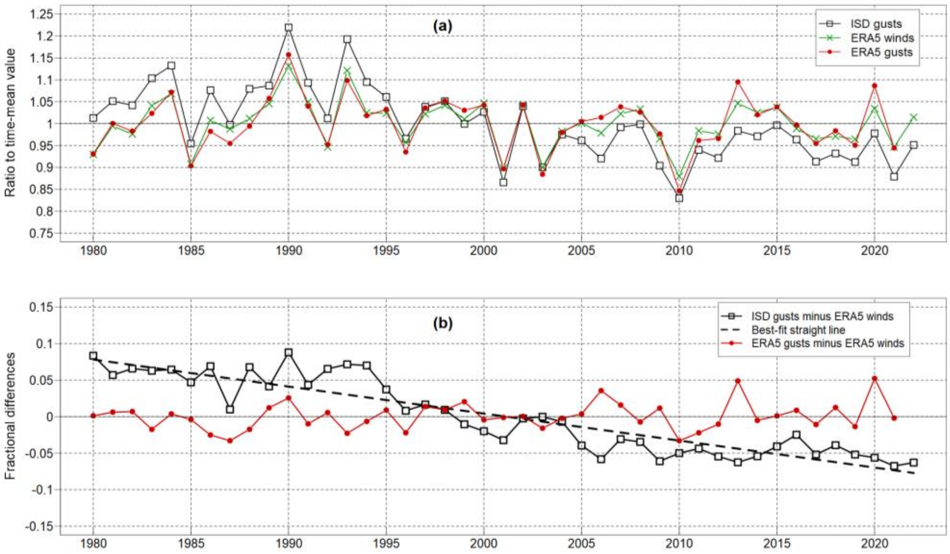


Figure 5: (a) U.K. average timeseries for ISD gusts and ERA5 winds and gusts, re-scaled by their climate means, and (b) timeseries of the difference between each of the gust datasets and ERA5 winds.

Observed trends in measured gusts are not without uncertainty too, due to evolving sensors and logging systems, and changes in location and surrounding land-use (e.g. Minola et al., 2016). It is feasible that the large spatial scale of the signals in Figure 4c are explained by a systematic change across many stations. Indeed, the history of U.K. gust observing systems in Sloan and Clark (2012) does indicate a nationwide change in cup anemometers from 1997 onwards. However, side-by-side testing by Sloan and Clark (2012) indicate the newer U.K. wind sensors measure about 5% higher two-minute wind speeds. Safaei Pirooz and Flay (2018) performed a comparison of similar anemometers and found measured gusts increased by a slightly higher amount of 7 to 13%. In addition, an inspection of Figure 4a reveals an area of declining gust trends in northwest Europe which is more consistent with a change in the storm track, rather than weather station changes across quite independent national meteorological services of U.K., Ireland, Benelux and northern France. These considerations point to the declining gust trends found across the U.K. to be meteorological in nature.

In conclusion, the evidence suggests modelled losses are too high in modern times because ERA5 winds do not capture the magnitude of declining extreme gusts from the late 20th century to the present day. The next section describes a correction to ERA5 winds to include this trend, towards forming a new modelled loss dataset.

4.3 The final set of historical losses

The trends in observed gusts were imposed on the ERA5 event-maximum winds to produce the final loss record. The first step was defining the trend to imprint onto reanalyses winds. This trend is defined uniquely at each ERA5 grid cell to capture the spatial variations in Figure 4c, such as smaller-sized trends in central versus northern France. If $T_{G,S}$ is the trend in observed gusts (from ISD) from 1980 to 2022 at station *s* in units of % per year, and $T_{W,S}$ is similar for ERA5 winds, then the difference $T_{D,S}$ is given by ($T_{G,S} - T_{W,S}$). These quantities were calculated at all 221 stations, then spatially interpolated to form $T_{D,i}$, the deficit in the ERA5 wind trend at every grid cell *i* of the domain, using exponential weights, as follows:

$$T_{D,i} = \frac{\sum_S T_{D,S}.\exp\left(-\frac{d_{s,i}}{A}\right)}{\sum_S \exp\left(-\frac{d_{s,i}}{A}\right)}$$

where $d_{S,i}$ is the distance from station *s* to grid cell *i* in km, and A is a radius of influence and set to 75 km to produce reasonably smooth variations across the domain.

Figure 6 shows a map of the annual difference in trend between observed station gusts and ERA5 winds using the above equation. Negative values are dominant in a swathe from about 48°N to 60°N, where much wind damage occurs due in large part to higher exposure density. The most negative values are in Ireland and the U.K., with quite neutral values in the northernmost and southernmost parts of the domain, off the main Atlantic storm track.

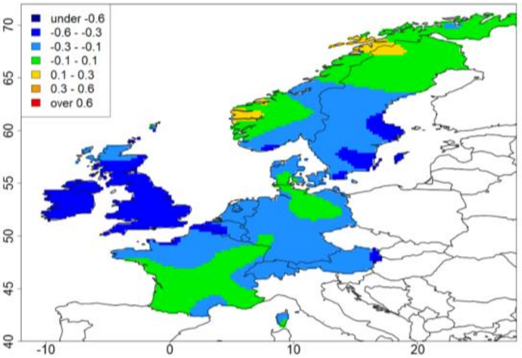


Figure 6: map of station values of the difference in trend (% per year) between ISD gusts to ERA5 winds, over the period 1980-2022, spatially interpolated to the full domain.

A scaling factor $F_{i,y}$ is then defined for each grid cell *i* and year *y* from 1980 to 2022, as follows:

$$F_{i,y} = 1.0 - T_{D,i}.(y - 1980)$$

By design, scaling factors are smaller in later years, if observed gusts decline more strongly than ERA5 winds in the area. There is little information to define scaling factors prior to 1980. The difference between ISD gusts and ERA5 were extended back to 1973 with a reduced set of stations, and it was found that the 1970s had similar or slightly lower scaling factors compared to the early 1980s. There are almost no ISD gust data before 1973, and the absence of information suggests a long-term average scaling factor is appropriate. Following these considerations, the values in 1950 to 1970 were defined to equal the long-term average scaling factor in 1980-2022, then the years 1971 to 1979 were based on a linear interpolation in time between values in 1970 and 1980. Finally, the scaling factors defined for each year from 1950 to 2022, for each grid cell *i*, are applied to the appropriate event-maximum winds from ERA5.

Figure 7 shows the annual losses of this new dataset (blue bars) alongside the original data plotted in Figure 2 (red bars). Both versions are scaled such that 1990 losses equal €30 billion, and the new gust-corrected version has notably smaller values in the 21st century. This is because the trend in observed gusts compared to ERA5 winds over the past few decades is generally quite negative (Figure 6c), hence domain-wide losses will be lower in the new dataset.

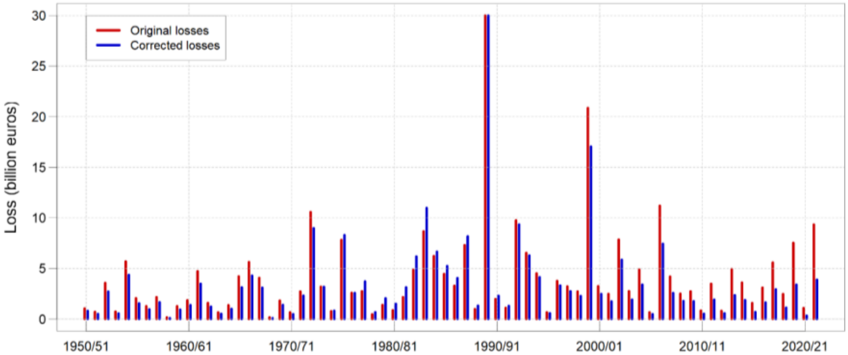


Figure 7: timeseries of Europe-wide annual windstorm losses, both original (black bars, from Figure 2) and corrected versions.

The modified losses lead to improvements with respect to observed losses in Table 1. Both seasons 1975/76 (incl. Capella) and 1987/88 (incl. 87J) now exceed the 2006/07 winter losses mainly caused by Kyrill. Inspection at the storm level reveals modelled losses of €8 billion for Capella and €6.5 billion for Kyrill, comparing well to observed values. While the modelled 87J loss is €5.2 billion is higher than the original value, it remains significantly below the best estimate in Table 1. The 87J storm contained many small-scale processes such as deep convection and a sting jet which boosted its peak gusts (Browning, 2004) but may not be captured by the reanalyses winds, and further, the incurred losses were boosted by unusually severe amplification of repair costs due to demand surge (RMS, 2007) which the loss equation does not model. Overall, the relativity of these older storms to Kyrill is much better in the new dataset, though 87J has room for further improvement.

Modelled losses for extreme events in the 20th century contain a second feature of note. The losses in 1999 are lower than the best estimate of €22 billion insured loss, and observed costs seem well defined considering the small spread in losses from different sources in Table 1. Further inspection revealed the ERA5 wind footprint for Lothar failed to capture a secondary feature which developed to the south of its main wind swathe and caused severe damage in northern Switzerland, while the modelled Anatol loss is less than half of the value based upon PERILS, and its footprint swathe also seems less extensive (not shown). Fixing these features would raise modelled losses significantly, and much closer to the best estimate. The mere strips of wind missing from these footprints highlights the difficulty of producing accurate national losses for extreme storms.

The separate validation using PERILS losses in the 21st century indicates the revised loss dataset is a major improvement. Figure 8 is a copy of Figure 3 with the new, gust-corrected annual losses plotted as blue bars. The large positive bias of 107% found in the original dataset becomes a 3% deficit in the gust-corrected version. While the smallness of the bias in the new dataset is fortuitous, it was reasonable to expect a large step in the right direction from the correction.

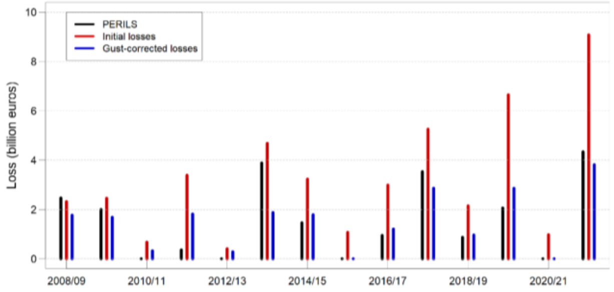


Figure 8: a barplot of Europe-wide windstorm losses for the past 14 seasons, from PERILS and both initial and corrected modelled loss records.

4.4 Discussion

There is relatively high confidence that observed windstorm losses are significantly lower this century, and that declines in observed gusts bolster this view since gusts are the hazard quantity most closely associated with windstorm damage. This leads to the question of why ERA5 winds do not carry this longer-term trend. Two different possibilities for imperfect long-term trends in ERA5 winds were mentioned earlier. First, non-stationary observing systems can drive non-meteorological trends in reanalyses (e.g. Bengtsson et al., 2004; Thorne and Vose, 2010; Wohland et al., 2019~~; Feser et al., 2021) indicate surface pressure gradients in reanalyses are consistent with observed (stationary) values over the past few decades, at scales of several hundred km. Therefore, any non-stationarity in~~), and while Europe has had a dense observation ~~systems would have to occur in the range from a~~ coverage for decades, the occurrence of event peak winds is often focused on small spatial scales around fronts, and it is plausible that their representation in reanalyses has sharpened over recent decades. Future study of the intensity of fronts in European storms, preferably using observations, and the lessons in Thomas and Schultz (2019), would address this issue. A second possible cause is that the trends in gusts have quite distinct changes not present in longer time-mean winds (and the gust modelling in ERA5 does not capture either). This too is plausible, since the shorter timescales of gusts are associated with processes at smaller spatial scales, hence different trends are feasible. Mechanisms that bring upper-level winds to the surface, such as convection (vertical and slantwise) and enhanced downward mixing near the cold front, are found to be important drivers of some of the strongest gusts in extreme storms (e.g. Browning, 2004; Fink et al., 2009). More generally, the low-level stability influences the vertical extent of mixing by small-scale mechanisms hence the gustiness of storms. Hewson and Neu (2015) gave a very interesting example of this effect. They found that the destruction caused by storm Daria, the most damaging wind event in the U.K. for many decades, was enhanced by the weak afternoon sun in January in England and Wales: it was sufficient to reduce low-level stability which enhanced the downward mixing of momentum which in turn intensified near-surface gusts, and a little boost to strong winds can create a lot more damage. More generally, an examination of trends in low-level stability, specifically at those times when lower troposphere winds are near peak per location, may possibly provide insights into the multidecadal reduction in storm gustiness found in the ISD observations.

A limitation of the loss dataset is also worth highlighting. The wind scaling factors in the bias-corrected dataset for 1950-79 are based on assumptions, which will need considered when interpreting the loss record in the earlier period. Research towards a better understanding of what has influenced the relativity of extreme ISD gusts to ERA5 winds over the past few ~~hundred km down to the sub-km scale of wind gusts that cause damage, in order to explain the loss trend. This is not implausible, and would fit with the abovementioned tendency for reanalyses and models to produce more positive trends in~~ decades may provide better guidance on their relativity in earlier times.

The biggest annual loss occurred in 1989/90, and was caused by the combination of a cluster of severe storms hitting dense exposure. The extent to which 1989/90 makes that late 20th century period appear stormy, versus the alternative – that a stormy period made 1989/90 more likely – is unclear. The new storm dataset can inform this debate. The effects of variable exposure density on annual losses are simply removed from the Klawa and Ulbrich (2003) loss equation by deleting the population term (P_i) to leave what is commonly referred to as a Storm Severity Index (SSI). Figure 9 shows the timeseries of standardised losses and SSI, together with their low-pass filtered versions. The Pearson correlation of annual values of SSI and loss is 0.901, and this rises to 0.948 for the low-pass filtered versions, suggesting exposure variations play a much smaller relative role than the hazard towards temporal variations in loss. Moreover, the SSI timeseries show higher storminess ~~over the past several decades.~~ levels throughout the 1980s and ‘90s, with 11 years above the long-term average versus three in the past 20 years. The hypothesis that the mean SSI value from 2002/03 to 2021/22 is the same as the mean from 1980/81 to 1999/00 is rejected at the 5% level, with a p-value of 0.004. A similar test on losses also rejects the hypothesis at the 5% significance level, with p-value of 0.019. The new storm dataset suggests the last two decades of the 20th century were stormier as a whole, which raised the probability of occurrence of extreme annual losses such as the 1989/90 season.

~~In summary, observations of storm losses indicate the new timeseries has a bias towards overestimating losses for more modern storms, and reanalyses are a likely source of such a trend. In the next subsection, the new timeseries is recalibrated to reduce modern storm losses relative to those from older events.~~

~~3.3 A corrected loss history~~

~~The review by Feser et al. (2015) concluded there was little long-term trend in storminess over 100 yr time horizons. More specific to losses, Cusack (2013) developed a damage index for the Netherlands and found similar lulls in decadal losses in the 1960s and 2000s, with slightly lower values in the modern period, confirmed by an updated timeseries from RMS (at https://www.rms.com/blog/2020/03/05/update-on-multidecadal-variability-of-european-windstorms). While the Netherlands is a spatially small area, the large-scale nature of decadal signals and high total exposure in this country and neighbouring areas (including Belgium, southeast England and North Rhine-Westphalia) suggests this loss signal is material to Europe. Based on these studies, a scaling factor was created which decreases from unity in a linear trend from the start to end of the study period, and its trend was constrained to produce losses in the PERILS period (2008/09 to 2021/22) similar to the lull in the 1960s (1958/59 to 1971/72). In this way, the adjusted loss timeseries contained no trend from the 1960s lull to the one in recent times.~~

~~The losses for the final timeseries are shown in Fig. 1 (red bars and line) and Fig. 2 (green bars). The detrending has reduced the high bias of 100% versus PERILS losses to 55%. Some of the remaining high bias is due to the inclusion of four extra countries in the new timeseries versus PERILS (Finland, Poland, Czech Republic and Slovakia), and when they are excluded for the purpose of comparison, the timeseries has a high bias of 44%. In addition to a better comparison with PERILS, the detrending has improved the relativity of modern losses to earlier times. For example, 2021/22 losses are now below those of 1975/76 and a smaller fraction of 1999/00 losses. To place the remaining 44% high bias of modern storms in context, the study focuses on multidecadal variations which exceed a factor two (Fig. 1). The conclusions drawn from results shown later in this study are not affected by the remaining high bias for modern storms.~~

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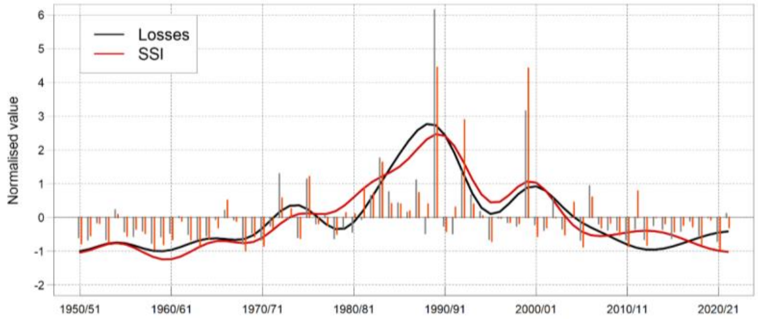


Figure 9: timeseries of losses (black) and SSI, in normalised values, both for annual values (bars) and low-pass filtered versions with 10-yr cutoff frequency.

5 Comparison of large-scale climate indices to European wind losses

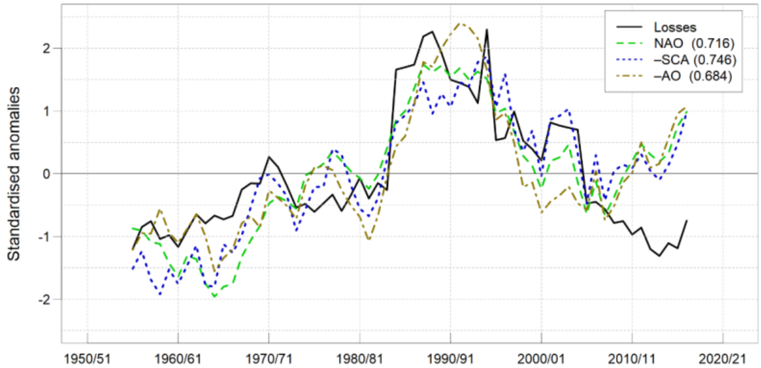
~~Researchers most commonly use indices of large-scale circulation anomalies to draw inferences on local storminess. They are usually drawn from studies at annual scales, where indices are known to explain a significant fraction of all interannual variance, and the question arises as to how much of the variations at decadal scales are explained. This section aims to quantify the~~The strength of connection between ~~large-scale~~commonly used indices of winter-mean climate ~~indices~~anomalies and losses ~~at~~ is analysed in this section, with more focus on the decadal scales~~. The most commonly used indices~~ that fit with the response times of the bulk of the insurance industry, though correlations at interannual timescales are ~~examined in the first subsection, then a new index is~~ presented ~~in the second, and followed by further analysis and discussion of their fidelity with losses.~~too. All timeseries are normalised using their respective means and standard deviations~~,~~ for comparison purposes~~.~~, as outlined in Section 2.

~~4.1 Standard climate indices~~

The NAO, Scandinavian Pattern (SCA) and the Arctic Oscillation (AO) are modes of interannual variability of circulation ~~with relevance to~~ that are often regarded as proxies of European storminess, and ~~in particular, the NAO and AO have been commonly used as indices of storm climate at decadal scales. These indices are defined in various ways, such as using surface pressures or geopotential heights at 500 hPa, and with a spatial representation based on either anomalies at locations, or a principal components analysis (PCA) of interannual variations in a specific sector. The impact of different definitions on correlations is quite significant. For example, the NAO defined by Hurrell et al. (2003) shown in Fig. 3 is based on a PCA of~~

~~interannual variations of sea level pressure in the North Atlantic, and has a correlation of 0.72 with losses. A similar NAO definition with surface pressures replaced by 500 hPa heights has a correlation of 0.56 with losses, while the difference in surface pressure observations between stations in Iceland and Azores has a correlation of 0.60, and finally, the mean surface pressure difference between two regions used in Smith et al. (2020) had a correlation of 0.54, when using ERA5 surface pressures.~~

Figure ~~3~~10 shows ~~those tested versions of each index with the highest correlation to variations in loss. In general, all three indices have significant correlations to loss, due to~~ their ~~capture of the lull around the 1960s, followed by the rise to a peak around 1990, then a decline into the first decade of the 21st century. Thereafter, the three indices have a common divergence from losses in~~ low-frequency variations alongside losses over the past ~~15 years. There is high confidence that the index values have been trending recently to values seen 30 years ago, yet there are similar levels of certainty that storm damages are far below values in the 1980s and '90s. This recent difference between standard indices and decadal losses is a key issue for insurance applications, because skilful forecasts of NAO translate to misleading forecasts of decadal storminess in recent times. The next subsection explores this modern-day breakdown between losses and common proxies.~~



~~Figure 3: timeseries of standard climate indices together with European wind losses, at decadal timescales. Correlations between the index and losses are given in parentheses in the legend.~~

~~4.2 The Hemispheric Geostrophy Index~~

~~Earlier studies found evidence that indices are not perfectly consistent with decadal storminess. Chang and Fu (2002) studied the northern hemisphere winter storm tracks and reported how a significant portion of interdecadal variations are not linearly explained by the hemisphere-scale AO. Results in Woollings et al. (2015) also contain such a sign too. They split NAO~~

~~variations into interannual and multidecadal, and based on NCEP-NCAR reanalyses, the longer timescale variability has slightly weaker surface pressure changes (middle panels of their Fig. 5), yet much stronger storm track changes over Europe (upper panels in their Fig. 6). Evidently, time-mean surface pressure anomalies do not linearly explain all variations in transient storms over Europe, and raises the question of what other ingredients are required to make a storm proxy which is as reliable today as it was throughout the second half of the 20th century.~~

~~New diagnostics are now tested, to provide initial guidance for future research. First, both studies mentioned above found longer-timescale changes are linked to larger, hemispheric-scale anomalies in storm tracks, which suggests a larger-scale surface pressure index. Moving to larger spatial scales is also suggested by studies of longer timescale variations due to anthropogenic climate change (e.g. Yin, 2005). A measure of the tropics-to-Arctic gradient in surface pressure was trialled, and it was found to be very highly correlated (above 0.9) with both the AO and NAO in Fig. 3, and of most relevance, it contained the same divergence from insured losses in recent times. Thus, boosting the indices to larger spatial scales does not resolve the key issue.~~

~~Storm damage is caused by maximum near-surface gusts, and Chang (2018) discusses how these gusts may be better represented by the winds at 850 hPa. In essence, the strongest gusts are associated with boundary layer eddies dragging stronger winds in the free troposphere down to the surface. In this framework, indices based on surface pressure gradients provide information on surface winds, and may be sub-optimal since storm damages depend on winds at higher altitudes. A hemispheric index was created as the difference in the geopotential heights at a fixed pressure level, between the tropics (20° S to 20° N) and the Arctic (north of 60° N). It will be referred to as the Hemispheric Geostrophy Index (HGI) since it represents the zonal geostrophic wind in mid-latitudes. The most suitable pressure level depends upon the depth of the mesoscale processes responsible for those strongest gusts causing most damage, and this is difficult to know a-priori due to the rich variety of mechanisms (exemplified by the study of a single storm in Browning, 2004). Results for different pressure levels will be shown.~~

~~Figure 4 shows the timeseries of the HGI based on heights at 500, 700 and 850 hPa. All three HGI versions are similar, capturing the lull at the start, then the rise to the 1990s and subsequent decline to 2010. Crucially, the HGI is also a closer~~seven decades. The first finding from this comparison is how NAO values based on station data are a considerably poorer match to ~~decadal loss variations in the recent period, and this leads to its higher correlation with damage~~ losses than ~~obtained with the indices based on surface pressure. Evidently, decadal anomalies in zonal winds and European storm losses are closely connected through the entire timeseries~~the other three, explaining only 15% of the variance of loss at these long timescales. The main cause of this lower skill is its highest values occurring in the 2010s when losses were below average. NAO values based on fixed spatial points provide less benefit for management of windstorm risk. The second main finding is that the other three indices provide reasonably good guidance of decadal variations in losses over the whole 70 years. There is a caveat though: the three climate indices perform relatively poorly in recent times, with the 2010s containing the second highest decadal values, in contrast to low losses. This is a concern, since the most recent period is most relevant for pricing of near-term risk, and is investigated further after presenting more results from analysis.

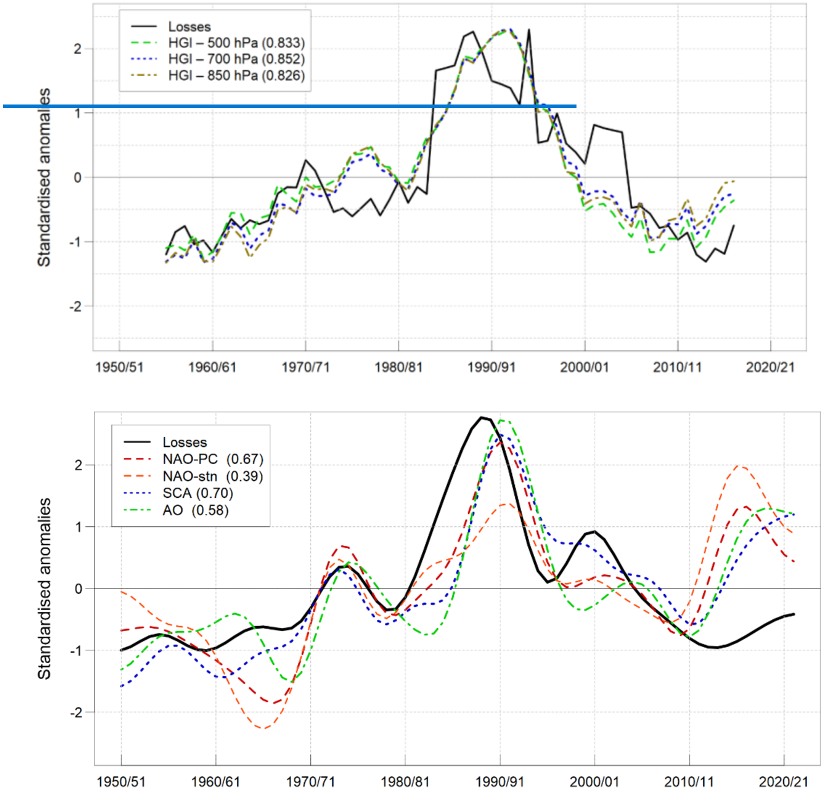
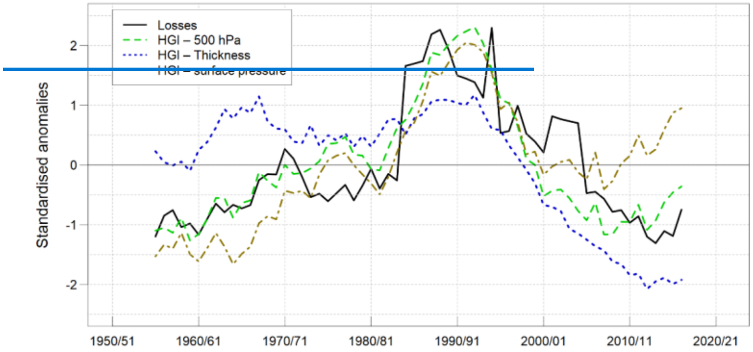


Figure ~~4:~~10: low-pass filtered timeseries of ~~the HGI at different pressure levels together with~~ European wind losses, ~~at decadal timescales. Correlations between each index and losses are given~~ and standard climate indices. The Pearson correlations between the climate indices and the loss dataset are shown in parentheses in the legend.

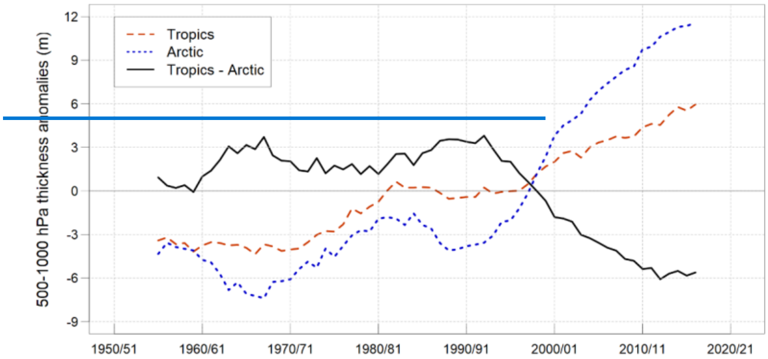
~~Insight into the different values between HGI and other indices in the recent period can be obtained from their definitions. The interannual indices are defined in terms of surface pressure gradients, whereas HGI is based on geopotential height anomalies at a fixed height above the surface and thus depends on gradients in both surface pressure and atmosphere thickness, or heat anomalies. Figure 5 shows the timeseries of these two components of the HGI at 500 hPa, and the surface pressure contribution~~

~~has very similar behaviour to interannual indices, as noted earlier. Instead, the key to HGI's improved consistency with losses in recent times is the negative contribution from the tropics-to-pole gradient in thickness (blue dotted line). From the 1950s to 1990s the poleward thickness gradient was relatively stable and HGI values largely followed surface pressure changes, then the weaker poleward heat gradients from the mid-1990s to mid-2010s has coincided with declining storm losses.~~



~~**Figure 5: timeseries of the HGI at 500 hPa, and a breakdown into its two constituent parts, namely surface pressure and (1000 to 500 hPa) thickness anomalies. Note all three timeseries have been standardised using their own mean and standard deviation.**~~

~~Figure 6 decomposes the poleward heat gradient into its two nodes, and it can be seen that the well-known accelerated warming of the Arctic area in the past 20 or so years relative to the tropics (e.g. Rantanen et al., 2022) is the cause of the declining lower-level baroclinicity in Fig. 5 (blue dotted line). This finding is consistent with the results in Wang et al. (2017), who found a marked weakening of the North Atlantic storm track in the 21st century, and identified the rapid warming in the Arctic as the root cause, leading to reduced lower-level baroclinicity then on to the weaker storm track. The HGI based on 700 hPa heights combines an observed close connection to decadal storm variations, with a sound physical basis in terms of geostrophy (and vertical mixing of 700 hPa momentum to the surface), and is recommended for consideration in future decadal storm research.~~



~~**Figure 6: 9-year running means of 500-1000 thickness anomalies (m) for the tropics (red dashed), Arctic (blue dotted) and the difference (tropics – Arctic).**~~

~~There are signs that the HGI is a more robust statistic than the NAO, hence may reduce the compute burden associated with decadal climate research. As mentioned in the Introduction, formidable ensemble sizes are needed to realise the potential skill from climate models. Scaife et al. (2019) conclude smaller ensemble sizes may be sufficient for models with a much higher horizontal resolution, which in turn requires many years of compute power growth. The signal-to-noise (S2N) of the HGI-500 has been measured here by comparing the change in the index from 1980-94 to 2000-14 (the signal) to the standard deviation of the timeseries of 72 seasonal values (the noise), and it was found that the HGI has slightly more than double the S2N value of the historical NAO based on the Smith et al. (2020) definition. The larger spatial scales of the HGI could be responsible for the improved S2N. If the better S2N of HGI is also present in model simulations, then smaller ensemble sizes by a factor four would produce the same S2N magnitude (since noise in the ensemble mean varies inversely with the square-root of ensemble size). In this way, the HGI would be of benefit both to insurance, via more reliable indications of storm losses, and to research, by releasing their finite compute resources for other experiments.~~

~~5~~ Figure 11 provides more quantitative details on Pearson correlation values between each of the four indices and losses, at both interannual and decadal timescales. The correlations are computed both over the full time period, and a shortened version up to 2009/10 to isolate the contribution from the recent period. Correlations are around 0.4 at interannual timescales, suggesting that even a perfect forecast of seasonal mean surface pressure anomalies is of limited benefit to pricing windstorm risk. At decadal scales, correlations rise up to 0.7, and if it is presumed that the NAO metric in Athanasiadis et al. (2020) behaves like NAO-PC and asymptotes towards 0.7, then current systems may explain around 25% of the variance in decadal losses.

Returning to the concern about the recent period, it is notable how decadal correlations of climate indices with loss fall from about 0.85 to 0.7 when the most recent 12 seasons are included. The hypothesis that this divergence could occur randomly by sampling error was tested by calculating mean values over 2010/11 to 2021/22 for all five timeseries in Figure 10, and it revealed the values for all four climate indices were significantly different from losses at the 5% level (p-values around 0.02, except NAO-stn at 0.005). This result suggests users ought not to equate decadal variations in meteorological indices with loss anomalies in recent times. However, this evidence is merely statistical in nature and falls far short of conclusive proof that the relationship between winter-mean winds and extreme gusts is different between the late 20th and early 21st centuries. Further research into the processes causing time-mean winds and extreme gusts would help understand whether their relationship is non-stationary, and is suggested as high priority to shore up confidence in modern-day forecasts.

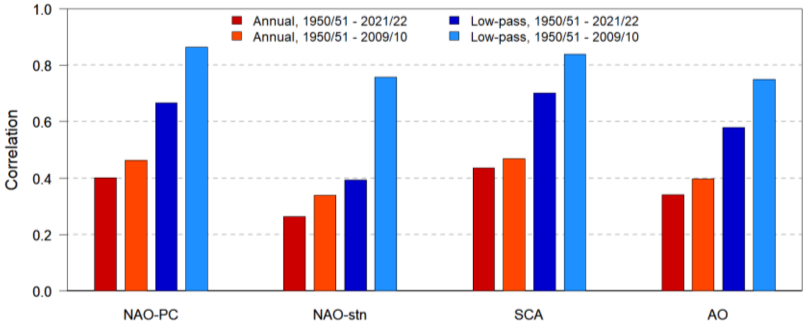


Figure 11: correlations between each of four climate indices and losses for annual and low-pass filtered timeseries, calculated for two different time periods: the entire study period, and a shortened version excluding the final 12 seasons (i.e. 1950/51 to 2009/10).

It is not novel to find climate indices do not explain all European storm variations. For example, Woollings et al. (2015) resolved climate variations into two timescales using a 30-yr cutoff, and their Figure 3 shows the NAO is linked to very different changes in the North Atlantic jet between the two frequency ranges. Variations of NAO at annual-to-decadal scales were linked to latitudinal changes in the jet which is expected to have less impact on losses, consistent with the quite low correlations in Figure 11. However, similar NAO variations were associated with a strengthening and extension of the jet into Europe at longer timescales, which would be expected to have a significant impact on losses. Clearly, variations in long-term mean surface pressure patterns are not tied tightly to the occurrence of extreme event losses.

Finally, it is interesting to note how modelled losses based on uncorrected ERA5 winds have a close connection to observed climate indices in the most recent period. It suggests ERA5 extreme winds are reflecting winter-mean circulation anomalies, whereas losses have separated from time-mean winds. Though the puzzle remains as to why observed gusts and damages have a different long-term trend from time-mean winds.

6 Conclusions

~~A~~ERA5 near-surface peak winds provide a solid foundation to build a long timeseries of European windstorm insured losses ~~from 1950 to 2022 has been developed by converting ERA5 near-surface winds to losses using a standard damage model. It contained~~, correctly identifying those years with landmark storms and simulating the well-known multidecadal pattern of lower values in the 1960s, rising steeply to a peak in the 1980s and ‘90s, then decline into the 21st century. ~~More detailed validation with industry losses revealed a trend towards a high bias in modern times, and a recalibration was performed which reduced this down to a 40% high bias, versus an industry reference observed dataset over the past 14 storm seasons. The subsequent analysis and findings were not affected by this remaining bias~~However, the recent downward trend in losses from the 1990s to the 2010s was less steep than observed. Various potential causes were considered, including the accuracy of observed losses and ERA5 winds, and a non-stationary relationship between wind and damage. It was found that ERA5 winds simply contained a different long-term trend from damage. Further, the ERA5 winds did not match gust trends in ISD observations, and the latter were considered reliable because they consisted of a large-scale signal measured by many coastal and inland stations. Given the close relation between damages and peak gusts, a revised loss dataset was built with observed gust trends imposed on ERA5 winds, and its decline from the 1990s to 2010s was much more consistent with observed losses. Further, it improved the estimates of event losses for some of the most severe historic storms.

The skill of ERA5 winds as the basis for storm losses is most notable given the high sensitivity of damage amounts to wind speeds. Nevertheless, its limitations should be considered too. Besides the long-term trend feature mentioned above, the footprints did not capture the extent of damage in a few key storms, such as Lothar, 87J and Anatol, and indicate the new dataset is likely to have larger relative errors in national-scale losses, compared to domain-wide. Further research could improve aspects of the final dataset. First, the long-term trend correction to ERA5 winds had no information pre-1973. A greater understanding of the mechanisms causing the mis-match between observed gusts and ERA5 winds may help infer pre-1973 trends. Second, local storm wind details could be boosted by combining observed gust information with ERA5 winds to produce better modelled national losses. The quality of the resulting dataset would be non-homogeneous, in the sense of greater accuracy in the period of better gust data from 1970s onwards. Extra care would be needed to avoid confounding climate variability with non-meteorological trends.

The new loss dataset was used to assess some ~~climate~~ indices commonly used ~~by research to infer European~~to summarise Europe-wide winter climate anomalies. ~~While the tested~~At interannual timescales, correlations are around 0.4 and point to a modest association between climate indices and losses. At longer timescales, the indices generally have correlations around 0.7 because they capture the observed multidecadal variations of storm loss from 1950 to the early 2000s. However, all of them diverge from loss experience over the past 15 years. ~~This divergence is robust, with~~In a context of relatively small observational errors, there is high confidence that ~~indices currently have decadal~~climate index values ~~close to~~in the 2010s approached those last seen ~~in the early 1990s~~30 years ago, yet a similar ~~levels~~level of certainty that ~~recent~~ storm ~~losses are~~

~~well~~damages were far below ~~the levels of the big peak, 30 years ago. Resolving this issue will help connect research to insurance applications.~~

those in the 1980s and ‘90s. Such a decoupling was noted in previous research on the inability of the NAO to distinguish between very different changes in storm tracks over Europe. This is a key issue for insurance, because it implies the reported correlations based on the whole timeseries are not appropriate for the present-day. The available evidence suggests lower than average losses are occurring, and being driven by declining wind hazard (gusts), and standard climate indices do not reflect this reality. Intriguingly, ERA5 extreme winds have a similar flattish trend to observed time-mean winds represented by climate indices. The non-stationary relations to the climate indices are restricted to observed extreme gusts and damages. Further investigation of ~~why typical climate indices are misleading for current windstorm risk pricing revealed one possible reason. Standard climate indices are based on surface pressure gradients, which inform on surface geostrophic winds, whereas the momentum source for peak storm gusts is from a higher level in the free troposphere, and brought down to the surface by mesoscale and microscale dynamics, often near fronts. A new climate index (HGI) was defined as the tropics-to-Arctic differences in geopotential height of the lower troposphere, to simulate the origin of the peak gusts, and its large spatial scale is commensurate with long timescales. The HGI based on 700 hPa heights parallels decadal storm variations throughout the entire record. Crucially, it is consistent with smaller observed losses in recent times, because HGI values reflect the reductions in baroclinicity at low levels from the rapid Arctic warming in the past 20 or so years. On a practical note, the HGI has signs of better signal-to-noise relative to another index in common use, and hints at a smaller compute burden for~~ the weak link between anomalies in storm damages and climate indices over the past 15 years may help connect decadal ~~modelling. These are initial steps towards linking decadal climate research to insurance, and future work on two key issues could bolster this bridge. First, what is the relativity between major storm losses in the 1970s, ‘80s and ‘90s, and those in recent years? Learning more about the contrasting losses between the two periods will improve our knowledge of decadal variations of storm damage. Second, to what extent do climate indices based on surface pressure gradients misrepresent the climate of extreme gusts, in the context of changing baroclinicity? A greater understanding of why standard indices are not tracking~~ climate research to windstorm ~~losses in recent times is necessary for~~ insurance ~~applications.~~ .

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Code/Data availability

ERA5 data (Bell et al. 2021) were downloaded from the Copernicus Climate Change Service (C3S) Climate Data Store at https://cds.climate.copernicus.eu/cdsapp#!/home.

~~NCEP-NCAR Reanalysis 1 data provided by the NOAA PSL, Boulder, Colorado, USA, from https://psl.noaa.gov.~~

The population data used in the loss index are available from https://sedac.ciesin.columbia.edu/data/collection/gpw-v4.

GSOD weather station data were downloaded from https://www.ncei.noaa.gov/data/global-summary-of-the-day/.

Author Contribution

The design and analysis of tests, and manuscript preparation were all performed by the author.

Competing Interests

The author declares no competing interest.

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