https://doi.org/10.5194/nhess-2022-268
Preprint. Discussion started: 20 December 2022

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Decadal variations of European windstorms: linking research to insurance applications

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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.

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 storms with losses exceeding 20 billion USD, and the annual average from the top 25 events is around 7 billion USD. Such impacts motivate 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), while forestry suffers a significant part too (e.g. Gardiner et al., 2010). Traditional insurance manages their exposure according to a view of the windstorm risk 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 storm climate variations at these, or longer timescales.

Several studies document significant variability of the European wind climate at decadal and longer timescales (e.g. WASA Group, 1998, Dawson et al., 2002, Brázdil et al., 2004; Cusack, 2013; Stucki et al., 2014; Feser et al., 2015; 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, 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 decadal and longer timescale anomalies are 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 climate system parts have 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 in the North Atlantic sector. Decadal prediction systems integrate the set of diverse drivers into a unified view of the future climate, and skilful North Atlantic decadal forecasts in Keenleyside et al. (2008) helped focus research onto this area. Eade et al. (2014) found prediction systems contained more skill than implied by signal-to-noise ratios, and it could be extracted by using larger numbers of forecast ensemble members. Recently, hindcast tests conducted by Athanasiadis et al. (2020) find correlations of 0.63 between forecasted and observed decadal NAO anomalies for a 40-member ensemble, together with the promise 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 variability in Europe and the wider North Atlantic sector, and skilful decadal forecasting, there has been no known application of it to European windstorm insurance. The main reason is the uncertain relation between the metrics of wind risk used in published research and the windstorm losses of most relevance 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.

A long windstorm loss history in Europe is needed, to quantify the relation between published climate indices and insured windstorm damages at multidecadal scales. 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 the Europe-wide scale, for significant storms since 2009, and five earlier storms in the previous

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ten years. The commercially confidential nature of insured losses may have contributed towards this incomplete picture of loss in the public domain.

The first part of this study creates 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.

2 Data 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 European 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 Data processing

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.

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, were used to construct a record of storm damage from 1950 to the present day. In brief, the maximum daily winds were found, then merged into the maximum per storm event defined as up to a 3-day window, for every grid cell in Europe. These maximum winds were converted to grid cell losses using the model from Klawa and Ulbrich (2003):

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

where there are N grid cells in the domain, and 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. The constant of proportionality c in this model has been defined to produce 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) the cube of the wind excess above the local 98th percentile, and (b) the exposure, represented by population density.

Figure 1 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. At a high level, the model compares well to observed losses for key storms: the historic years of 1990 and 1999 are captured, as are other large loss years containing benchmark storms (most notably Kyrill in January 2007; Lower Saxony storm in November 1972; Capella in January 1976, and the stormy period in the early 1980s following the El Chichón eruption).

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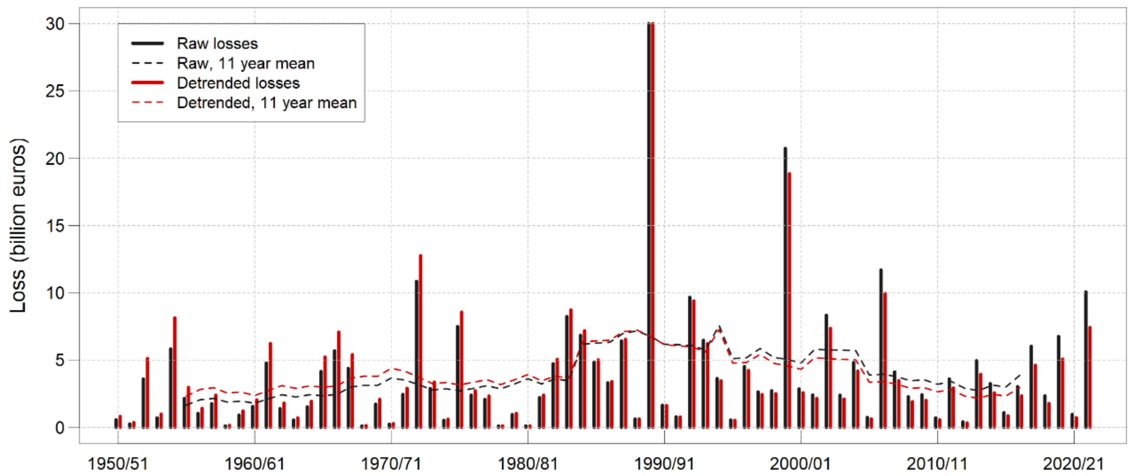

Figure 1: timeseries of Europe-wide annual windstorm losses, and their running means over 11 years.

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.

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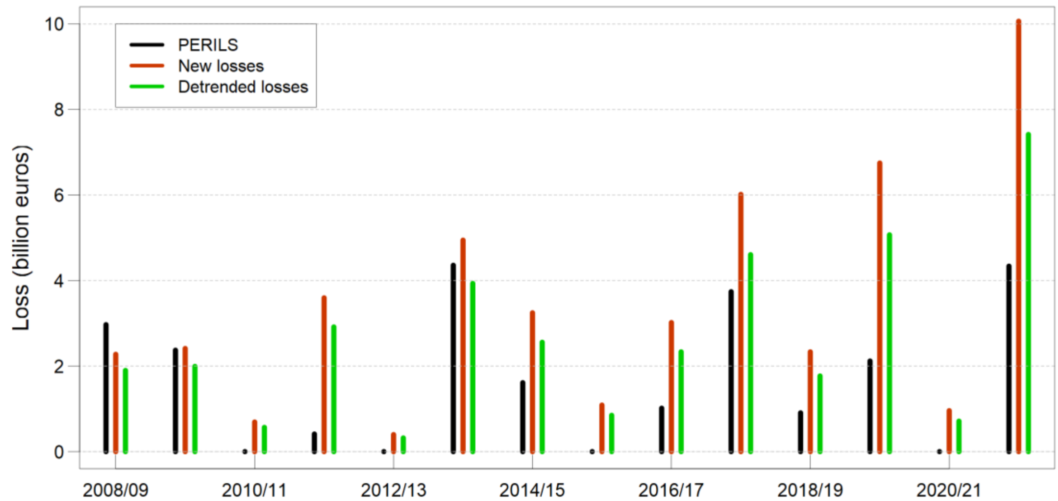

Figure 2: a barplot of Europe-wide windstorm losses for the past 14 seasons, from PERILS and the new dataset.

The potential 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 include improved building practices towards stronger roofs in modern times, or a greater reluctance for the insured to make a claim given damage. However, there is no evidence of significantly decreasing trends in loss for the same storm gusts over the past 3 or 4 decades. On the other hand, there is evidence that long-term reanalyses may contain non-meteorological trends due to changing observation systems, which depends on meteorological variable, time period and region being studied (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 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 observation systems would have to occur in the range from a 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 storminess over the past several decades.

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.

4 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 strength of connection between large-scale climate indices and losses at decadal scales. The most commonly used indices 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. All timeseries are normalised using their respective means and standard deviations, for comparison purposes.

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 European storminess, and in particular, the NAO and AO have been commonly used as indices of storm climate

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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 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 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.

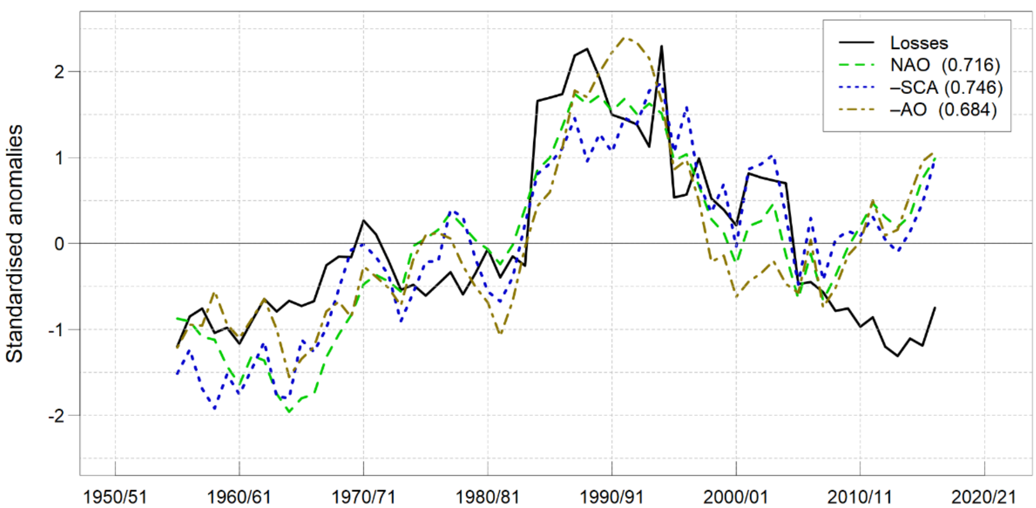

Figure 3: timeseries of standard climate indices together with European wind losses, at decadal timescales. Correlations between the index and losses are given in parentheses in the legend.

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 match to decadal loss variations in the recent period, and this leads to its higher correlation with damage 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.

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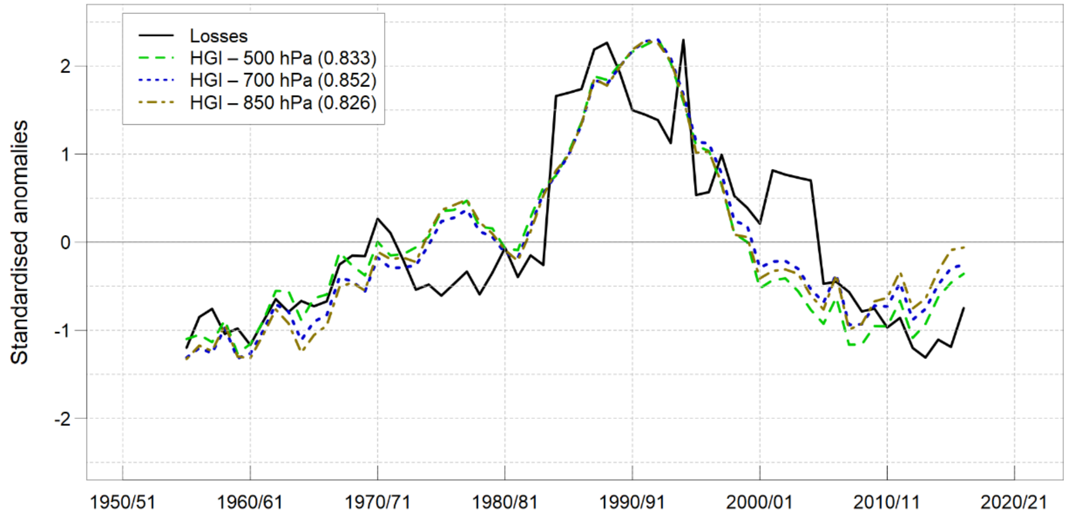
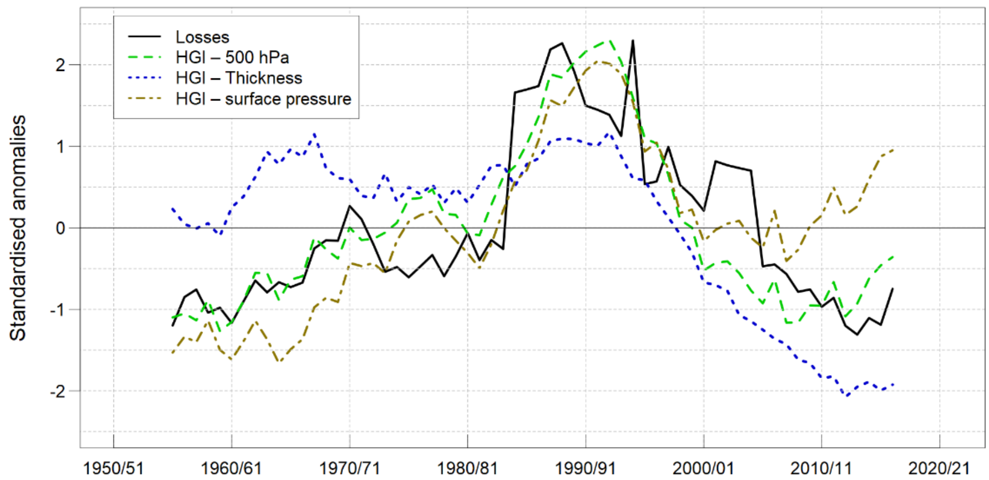


Figure 4: timeseries of the HGI at different pressure levels together with European wind losses, at decadal timescales. Correlations between each index and losses are given in parentheses in the legend.

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.



265 **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.

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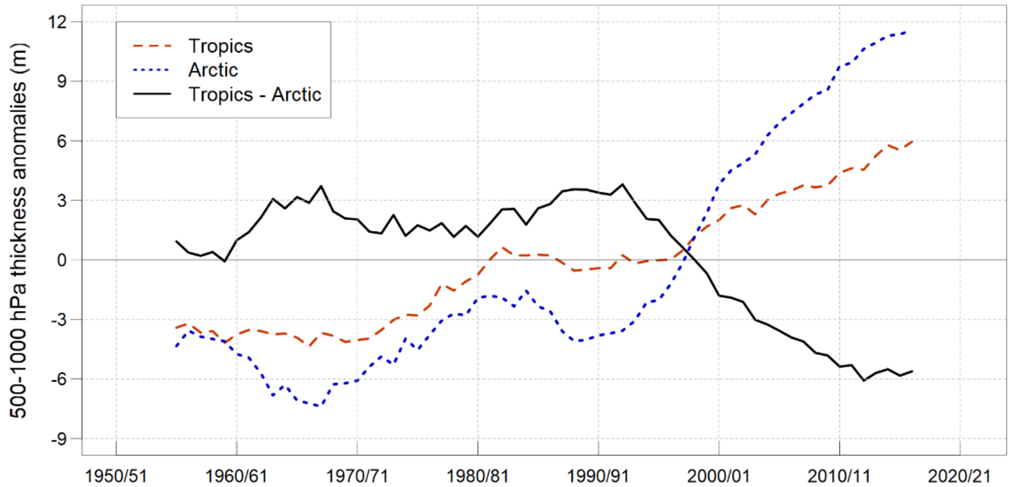

Figure 6: 9-year running means of 500-1000 thickness anomalies (m) for the tropics (red dashed), Arctic (blue dotted) and the difference (tropics – Arctic).

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 Conclusions

A 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 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.

The new loss dataset was used to assess some climate indices used by research to infer European winter climate anomalies. While the tested indices capture the observed multidecadal variations of storm loss from 1950 to the early 2000s, all of them diverge from loss experience over the past 15 years. This divergence is robust, with high confidence that indices currently have decadal values close to those last seen in the early 1990s, yet similar levels of certainty that recent storm losses are well below the levels of the big peak, 30 years ago. Resolving this issue will help connect research to insurance applications.

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 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 windstorm losses in recent times is necessary for insurance applications.

Acknowledgements

Thanks to ex-colleagues at Risk Management Solutions for many interesting discussions of storm variations, over the past decade and more.

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.

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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Preprint. Discussion started: 20 December 2022

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