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RESEARCH ARTICLE

Loss potentials based on an ensemble forecast: How likely are winter windstorm losses similar to 1990?

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In this paper we investigate the feasibility and added value of using the seasonal hindcasts of the ECMWF System 4 as a hazard event set for European winter windstorms damage calculations. The windstorms are identified for every ensemble member and every year by an objective windstorm tracking algorithm. The damages are calculated directly from the obtained wind footprints via the open source natural catastrophe damage model *CLIMADA* for Germany, the UK, France and Spain and compared to the loss from ERA-Interim. The results show that the ensembles of losses in System 4 nicely capture the inter-annual loss variability of the reanalysis. Due to more than 1,500 years of "virtual reality" windstorm data from the hindcasts, the return levels of extreme losses can be estimated fairly accurately. Based on System 4, the losses in the scale of 1990 (January, February, March and December including the prominent windstorm *Daria*) represent a 20-year event in Germany whereas they represent a 100-year event for the UK. Thus, a considerably shorter return period compared to return periods calculated from ERA-Interim alone.

Further we investigate the link between the annual losses and large-scale drivers derived from mean-sea-level-pressure (MSLP) data in System 4. We can show that within System 4 there is a significant link between increased loss potentials for strongly positive North Atlantic Oscillation (NAO) phases for Germany and the UK as well as a reduced loss potential for Spain. The link between the other analysed indices is weak bar the East Atlantic (EA) pattern index. Thus, if the NAO in System 4 is correct we can assume that the windstorms in System 4 are useable. If this premise is given our study shows that the loss estimates and ultimately the return levels of losses from System 4 can be used in an operational way.

KEYWORDS

European winter storms, insurance loss, North Atlantic Oscillation, hazard set, seasonal forecast

1 | INTRODUCTION AND MOTIVATION

European winter storms are extreme events that lead to considerable damages across Europe. Damages in this study refer to structural damages to buildings. Due to the large year-to-year variability in number and intensity of these storms the observational record of these high impact events is fairly small. Recent reanalysis projects like ERA-20C (Poli *et al*., 2016) cover a period of around a 100 year, however given the extremity of certain events (e.g., *Daria* 23–29 January 1990) the tail of the loss distribution still only features a handful of extreme losses associated with windstorms. Benchmarking a 100-year event for example is thus quite difficult and associated with very large uncertainties. As recent studies have shown there is also a spurious trend in this reanalysis data set (Befort *et al*., 2016; Bloomfield *et al*., 2018). The lack of observations is often tackled by producing probabilistic event sets based on alteration of observed events (e.g., Schwierz *et al*., 2010). The way stochastic event sets are generated, however, does not necessarily require or account for physical consistency within an event as it evolves through time. Thus, a key part of the loss modelling, the uncertainty in the hazard, is not adequately understood. This paper aims to investigate the feasibility of generating a set of physical consistent events to assess the related uncertainties in potential damage and loss.

The fundamental idea is to identify windstorms in the 51 members of the ECMWF System 4 seasonal forecast system (Molteni *et al*., 2011) and treat each member as a physically consistent realisation of a potential reality. This approach is similar to Osinski *et al*. (2016) who used the ECMWF EPS model to build a windstorm "hazard set." This will lead to a substantial increase in the available physically consistent sample of extreme events. The annual losses for four different European countries for every member of the ensemble are estimated from the tracked windstorm events with the help of the open source natural catastrophe damage model *CLIMADA* (Bresch, 2017).

Various previous studies have proposed the effect of large-scale drivers onto the intensity/frequency of cyclones (Pinto *et al*., 2009) and windstorms (Donat *et al*., 2010; Wa*lz et al*., 2018a; 2018b). In order to see whether this link is also represented within the seasonal forecast the estimated regional annual losses are set into context with model-internal large-scale driver time series (e.g., North Atlantic Oscillation [NAO]; Hurrell, 1995).

2 | DATA AND METHODS

The hazard event set is based on the ECMWF System 4 (which was the operational seasonal forecast system until 2017) hindcasts covering the years 1982–2014 (Molteni *et al*., 2011). There are 51 ensemble members which are initialised every 1 November. In order to exclude any potential "real" storms in November from the analysis, only the months December until March are included in the hazard event set; as we can assume that by December the effect of the initialisation has vanished. The events are identified for 6-hourly 10-m wind speeds within every single member using the WiTRACK algorithm (Leckebusch *et al*., 2008; Kruschke, 2015; Befort *et al*., 2016). By using a wind-speed-based tracking algorithm, we directly obtain the extreme wind field that can be used for loss estimation in *CLIMADA*. In total, this results in more than 1,500 years of "alternative reality" storms (32 years × 51 members). In order to set the loss estimated from System 4 in context with observations, windstorms are also tracked for the same years in ERA-Interim. The resolution of both the hindcasts and the reanalysis is T255 so that there is no systematic bias due to differences in model resolution. Large-scale driver time series are computed via an empirical orthogonal function (EOF) analysis using 6-hourly mean-sea-level-pressure (MSLP) again for both System 4 and ERA-Interim. The large-scale indices were calculated for every ensemble member individually. The damage calculation is done for the UK, Germany, France and Spain, thus the countries generating the most loss caused by winter windstorms. In accordance with the actuarial industry the loss is calculated for the entire year, thus damages for 1 year consist of January, February, March and December.

The *CLIMADA* model (Bresch, 2017) is an open-source is a natural catastrophe (NatCat) damage model that is based on four modules:

1. Assets → geographical distribution of houses/people etc. This is created from a satellite nightlight image on a 10 km scale for every country individually directly in *CLIMADA*.
2. Damage functions → The default damage function from the *winterstorm_europe* module (Schwierz *et al*., 2010) is heuristically adapted by a scaling factor to the wind speed values of System 4 and ERA-Interim so that the losses are at least within a reasonable absolute magnitude (~10^9 USD, see below for more exact figures). As the calibration of the damage function is neither our expertise nor possible due to the lack of actual loss data we scale all damages to the maximum loss in ERA-Interim. For the sake of simplicity we also use the same damage function for all four countries.
3. Hazards → *CLIMADA* is used to transform the windstorm footprints tracked with WiTRACK (see above) into hazard sets that can subsequently be used by *CLIMADA* for damage calculations (via an adaptation of the *climada_cosmo2hazard* function).
4. Adaptation measures → Not used for this study.

After the iteration of steps 1–4 we obtain an absolute annual expected damage (scaled to the maximum annual damage of ERA-Interim for the respective country) for all four countries for every year and all 51 ensemble members. Thus the loss will be presented as fractions of the costliest year in ERA-Interim.

CLIMADA as a tool offers a lot more functions, however as the scope of our study is simply to investigate the feasibility of creating a hazard set from ensemble predictions, we limit the usage of *CLIMADA* to simple annual loss calculations. For more details on all the capabilities of *CLIMADA* the reader is referred to the *CLIMADA* manual (Bresch, 2017) or other studies that have used *CLIMADA* or a precursor thereof (Della-Marta *et al*., 2010; Stucki *et al*., 2015; Welker *et al*., 2016).

The return level plots (section 3) were created fitting a generalised Pareto distribution (GPD) to the seasonal forecast ensemble with the help of the R package ismev (Heffernan and Stephenson, 2018). In order to investigate the proposed relationship between the intensity/frequency of European windstorms and large-scale indices we conduct a composite analysis and check whether the phase of the NAO (or other indices) has a significant impact on the windstorm-associated damages. A positive phase of a respective index is defined as exceeding the 95th percentile of all years across all 51 ensemble members. Likewise a negative phase of an index is defined as being below the 5th percentile for all years and ensemble members. Thus, 82 years out of the entire data set classify as positive/negative, respectively.

3 | RESULTS

3.1 | Estimated damages from System 4

Figure 1 shows annual damages for the four countries for both System 4 and ERA-Interim windstorms. The grey shading represents the standard deviation for the 51 ensemble members whereas the red line represents the mean loss over all 51 members. All values are scaled to the maximum annual loss in every region. The year 1990 represents the most loss-intensive year for the UK, Germany and France. As evidenced by Munich Re (2002) this is related to the series of windstorms that hit Europe in January and February 1990 (e.g., windstorm *Daria*; Heming, 1990). Years featuring other prominent windstorms like *Lothar* (Rivière *et al*., 2010) in 1999, *Jeanette* (Parton *et al*., 2009) in 2002 or *Kyrill* (Fink *et al*., 2009) in 2007 also show an above average loss. The highest relative loss in Spain was estimated for the years 1989 and 2001. Although no major storm hit Spain in 1989, the season was one of the stormiest in the recent past for Spain including, for example, an average wave height of 7.8 m in the Southwest of Spain (Rangel-Buitrago and Anfuso, 2012). The years 2009 and 2010 also mark years with extensive damages for Spain. These damages were caused by windstorms *Klaus* (Liberato et al., 2011) and *Xynthia* (Lumbroso and Vinet, 2011). *Xynthia* is particularly interesting as it occurred during an extreme negative phase of the NAO (see section below). For all other three countries the year 2010 was amongst the least intensive loss years. Just as a rough guide, damages for 1990 in ERA-Interim as calculated with our "arbitrary" damage function come to 15 billion USD for Germany and around 7.5 billion USD for the UK. Damage numbers (adapted for inflation) from Munich Re (2002) add up to 4.8 billion USD for Germany and 7.0 billion USD for the UK. Evidently, our values are not comparable (although not too far off for the UK) with real world damages. The order of magnitude appears to be correct however.

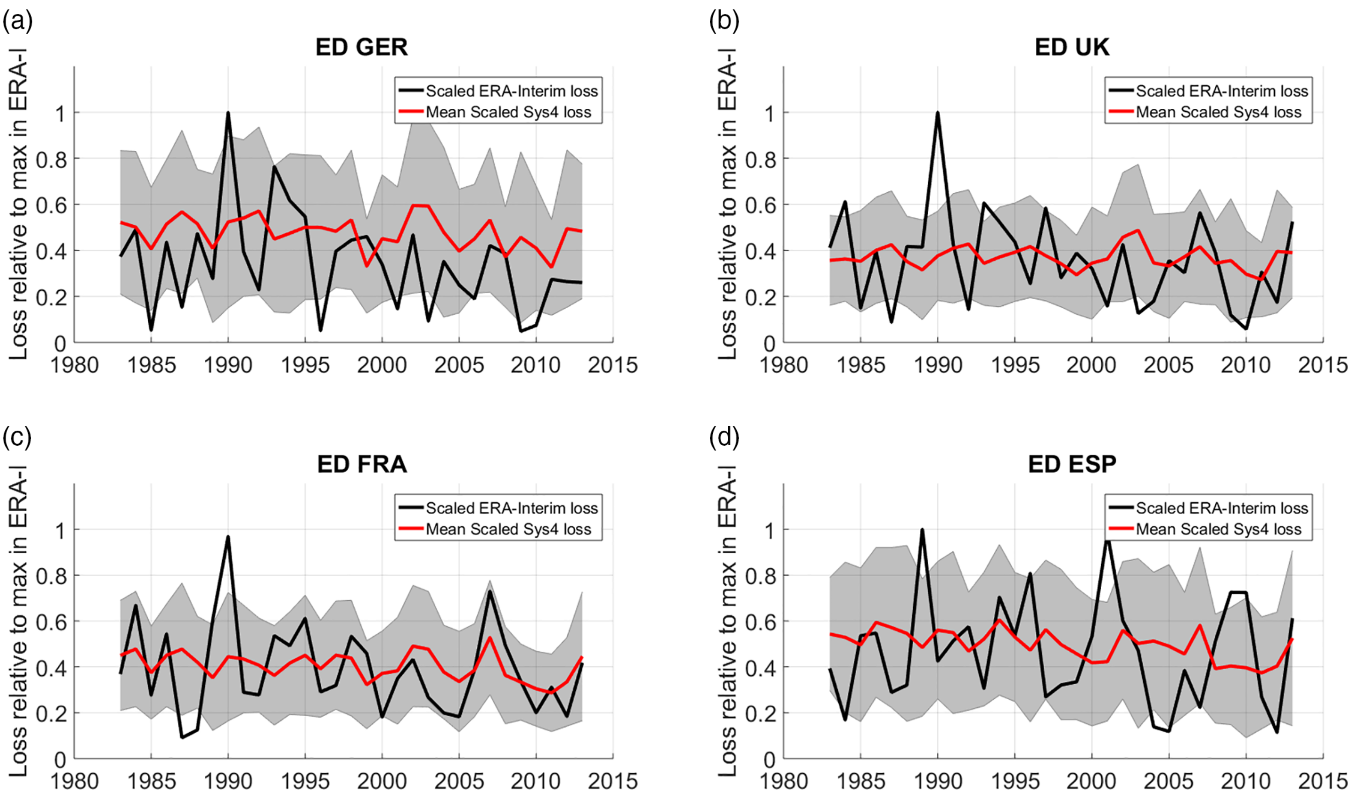

FIGURE 1 Expected damage (ED) calculated with *CLIMADA* for (a) Germany, (b) UK, (c) France and (d) Spain in ERA-Interim (black) and System 4 (red). The standard deviation of the ensemble of System 4 is given in grey shading. All values are scaled with the maximum of ERA-Interim

The mean of the annual loss as calculated by System 4 shows a reduced variability compared to ERA-Interim (underdispersion). This is in line with the findings of Walz *et al*. (2018a) who showed that the seasonal extreme wind speeds of System 4 also feature a reduced variability compared to the observations. This reduced variability, however is the result of averaging a large ensemble. The inter-annual variability of ERA-Interim is captured nicely, however, within the standard deviation of the System 4 ensemble. This means that System 4 correctly spans the "damage space" of reality. The mean loss over the entire period agrees well between ERA-Interim and System 4 for the UK (0.36 vs. 0.37), France (0.42 vs. 0.40) and Spain (0.47 vs. 0.50). The mean loss calculated for Germany however differs considerably (0.35 vs. 0.48). Germany is also the country where the spread of the ensemble is the largest, potentially due to the largest north/south gradient in storminess. This is in line with the extreme values of the ensemble distribution: The maximum annual loss generated by System 4 for Germany is more than double the loss estimated for 1990 (2.14) whereas the maximum for the UK is around 1.34 times the 1990 loss (1.31 times 1988 loss for France and 1.86 times 1989 loss for Spain). The inter-annual variability of ERA-Interim damages for Germany is well in line with Leckebusch *et al*. (2007). Although they were using the cubic exceedance of the 98th percentile of local wind speeds as a proxy for damage the main loss years are the same as in our study (1984, 1990, 1998).

The panels in Figure 2 depict the return level plots for Germany and the UK created via a GPD. From the plot, it becomes evident that damages in Germany are higher compared to the UK. The loss of 1990 (value of 1.0) for example is expected to happen within a return period of around 20 years whereas for the UK the same magnitude of loss represents a 100-year event. This is roughly the same return period for which a loss of 1.5 times the 1990 damages would be expected for Germany.

Della-Marta *et al*. (2009) estimated the return period of *Daria* between 24 and 39 years. Although an entire loss season is not easily related to a single storm, their estimate fits well for the loss return period for Germany. The higher return period for the UK can be potentially explained by the additional loss-intensive storms in 1990. The dashed grey lines in Figure 2 depict the uncertainties of the return levels if only calculated from ERA-Interim. Evidently the uncertainty of potential damage can be estimated considerably more accurately via System 4. The return levels of System 4 for Germany are almost completely outside of the range of ERA-Interim which means that when using ERA-Interim only, the potential loss would be severely underestimated. Thus, according to our results return periods of damage calculated from ERA-Interim should be treated with care.

3.2 | Estimated damage linked with large-scale driver indices

The relationship between three large-scale indices and the annual estimated loss for System 4 is investigated via a composite analysis. Table 1 presents the results thereof. To check for significance of the composite means, we performed a bootstrap sampling using $k = 100{,}000$ samples. See an example for the results of the bootstrap for the NAO case in Figure 3.

As previously shown by various studies (e.g., Donat *et al*., 2010) the NAO has a significant impact on windstorm-induced damages across Europe. The damages in Germany during the 82 strongly positive NAO phase years are significantly higher than the mean across all 1632 (virtual) model years. The reduced loss during the negative phase of the NAO is even more significant. The same result is apparent for the UK where there is also significant more (less) windstorm related loss during a positive (negative) NAO phase. The signal for France by contrast is not as strong, it even as a reversed sign compared to Germany and the UK. There is reduced loss during the NAO positive

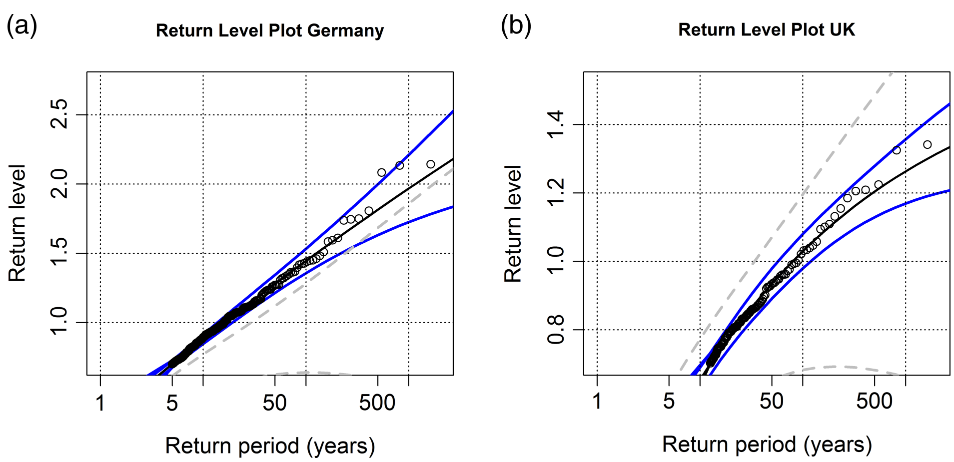

FIGURE 2 Return periods for Germany (left) and the UK (right) calculated from the entire ensemble of System 4. Note the different y-axis scales. The dashed grey lines depict return level uncertainties calculated from ERA-Interim only

TABLE 1 Normalized loss results of the composite analysis presented per country and positive (>95th percentile)/negative (<5th percentile) phase of the respective index

Country	NAO+	NAO−	EA+	EA−	SCA+	SCA−	Mean
Germany	0.54*	0.37**	0.44	0.49	0.47	0.48	0.48
UK	0.43**	0.27**	0.38	0.37	0.36	0.39	0.36
France	0.31*	0.35	0.40	0.38	0.36^{+}	0.40	0.40
Spain	0.26**	0.51	0.56*	0.44^{+}	0.47	0.50	0.49

Note. A + corresponds to a 90%, a * corresponds to 95% and ** to 99% significance. Again the losses are relative to the most extreme loss year in ERA-Interim.

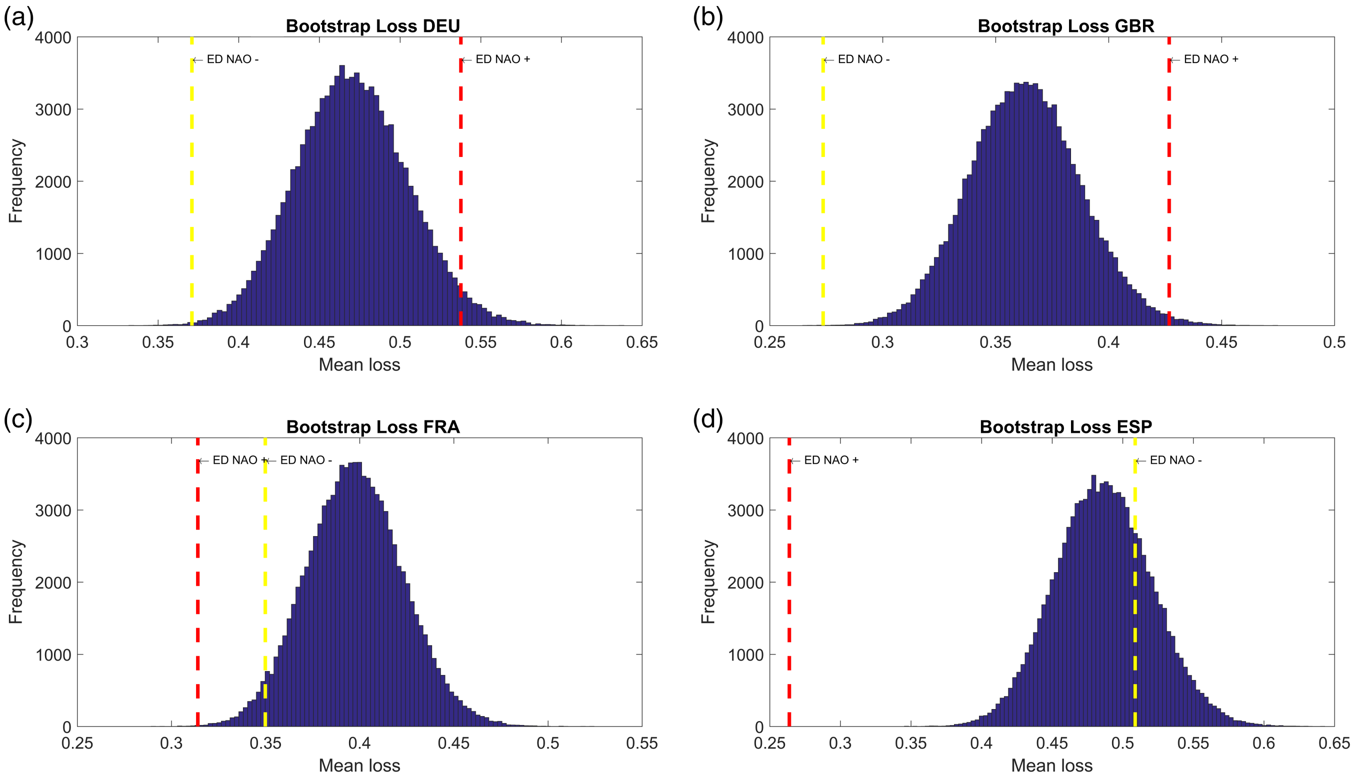

FIGURE 3 Example of the bootstrapping distributions for (a) Germany, (b) UK, (c) France and (d) Spain. The mean loss for the positive (negative) NAO phase is noted with a red (yellow) vertical line

NAO phase; however the loss during the negative phase is also lower than for the mean across all years and ensembles. Studies have shown that the NAO in seasonal forecasts can be predicted with significant skill (e.g., Scaife *et al.*, 2014; O'Reilly *et al.*, 2017). As a result, this would mean that a seasonal forecast exhibiting extreme NAO values for a season bears the potential of either above or below average windstorm damage. As the NAO in System 4 features a skill of around 0.5 (Walz *et al.*, 2018a) this could represent an information gain regarding loss potentials. There are reduced damages for France during a positive SCA phase.

Overall, there is little signal for the SCA pattern in System 4. This is somewhat curious as the SCA pattern has been shown to have a significant impact on windstorms (Mailier *et al.*, 2006; Walz *et al.*, 2018b). Walz *et al.* (2018a) however could show that especially the SCA pattern within System 4 looks considerably different to reality. The damages during the positive NAO phase for Spain is significantly lower compared to the entire mean. This is in line Walz *et al.* (2018a; 2018b) who show that there is a negative link between the NAO phase and the storminess for the Iberian Peninsula. There is no significant link for the rest of the large-scale drivers besides the EA index that shows some significance for the damages in Spain. This is again in line with the findings of Walz *et al.* (2018a; 2018b) who could show that the EA pattern is a significant driver for windstorm clustering and they could confine the area of impact of the EA pattern to the East Atlantic and the northern Spain (cf., their fig. 3a). Overall, there seems to be a strong link between the NAO and winter windstorm damages within System 4. The link between damages and the other two indices does appear not to be significant.

4 | SUMMARY AND DISCUSSION

This study proposes the utilisation of the ECMWF System 4 hindcast data as a hazard event set for winter windstorms in Europe. The windstorm events were identified for every year (December–March) and ensemble member using the wind-based tracking tool WiTRACK. The loss calculation was realised with the open-source NatCat damage model *CLIMADA* directly for the tracked wind fields. In order to compare the estimated damages for System 4 they were related to damages calculated from ERA-Interim over the same period. The overall damages agree well in their magnitude. The inter-annual variability of the ensemble mean is visibly smaller than in the observations however. This is in line with Walz *et al*. (2018a) who show a similar results for a seasonal extreme wind speed metric. The standard deviation of the loss ensemble does capture the inter-annual variability nicely, however.

In terms of observed loss the year 1990 (e.g., storm *Daria*) was the most loss-intensive year for both the UK, Germany and France. The maximum for Spain in 1989 is a bit curious; however, Rangel-Buitrago and Anfuso (2012) find 1989 to be one of the stormiest years with regards to wave height. The potential extreme damages in the System 4 event set differ considerably for the considered countries: The largest loss year in System 4 for Germany is more than double the 1990 damages whereas the largest loss year for the UK is "only" 1.34 times the loss in the year 1990. This is confirmed by the return level plot for Germany that shows considerably higher return levels compared to the UK equivalent. This means that years with double the loss amount of 1990 are physically possible. The return level plot also nicely shows the more accurate estimation of loss uncertainties when utilising System 4 as a hazard set compared to uncertainties calculated from observations.

In accordance with previous studies (Donat *et al*., 2010) the NAO is found to have a significant impact on the annual winter storm damages in Europe, especially for Germany, the UK and Spain. Our results are well in agreement with the literature showing increased (decreased) loss potentials for strongly positive NAO phases in the UK and Germany (Spain). The result for Spain is particularly striking and in line with Walz *et al*. (2018b) who showed a negative correlation between the NAO and windstorm occurrence for the Iberian Peninsula. Except for the EA pattern in Spain the other indices did not appear to have a significant impact on the potential loss. The SCA pattern that has been shown to have a significant impact on European storminess (Mailier *et al*., 2006; Walz *et al*., 2018b) does not seem to be linked with damages in System 4 except for a small signal in France. This could be in line with Walz *et al*. (2018a) who found the SCA pattern in System 4 to be different compared to the reanalysis.

Further research could entail using the new operational seasonal forecast system (ECMWF System 5) which has a higher resolution. Thus, it would potentially produce more accurate hazard footprints. The observed underdispersion for System 4 could be addressed by a post processing similar to Torralba *et al*. (2017). Given the format of this letter, this would exceed the scope of this study however.

In this paper we have demonstrated that the ECMWF System 4 provides a physically consistent and realistic hazard event set which can be used for loss estimation and a more accurate estimation of loss return levels as shown by the uncertainties in Figure 2. The question proposed in the title can be answered with a return period between 20 and 25 years for Germany and 50 and 100 years for the UK. We could identify a strong link between the NAO and damages for Germany and the UK in particular. This could prove to be vital information regarding future runs of seasonal forecasts as the there is a significantly larger chance of more loss occurring if the NAO is extremely positive in System 4. As the skill of the NAO within System 4 is about 0.5 this could represent an information gain regarding future loss potentials.

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