Estimating Risk Associated with Wind Damage over Europe

I. Introduction

Extreme wind is one of the costliest natural hazards that can damage to not only infrastructures, such as buildings, power cables, and others, but also people. The hazard usually impacts to Northern Europe associated almost exclusively with the passage of extratropical cyclones and the mesoscale structures, such as fronts and sting jets, where these events vary in severity across the geographical of Northwest Europe. This study focuses on the study of the spatial distribution of extreme winds, especially in three high-population locations, such as London, Paris, and Hamburg, aiming to analyse the spatial impact of loss potential and these three locations, so as to estimate the potential risk of loss caused by extreme winds. Analysis is performed using reanalysis wind data from ECMWF Reanalysis v5 (ERA5) from 1979 to 2018 and forecast wind data from European Centre for Medium-Range Weather Forecasts (ECMWF) and National Centers for Environmental Prediction (NCEP) derived from seasonal forecasts.

The investigation included analysis of the distribution of wind speed and their percentiles across forecast and reanalysis data for each location, a geographical view of the 98th percentile of wind speed, and the accumulation of potential loss or Storm Severity Index (SSI) (using Eq. 2) in Northwest Europe. The wind speed and SSI can be calculated using Eq. 1 and Eq. 2, as follow:

$$v_{mag} = \sqrt{u^2 + v^2} \qquad \text{(Eq. 1)}$$

$$SSI = p\left(\frac{v_{mag}}{v_{98}} - 1\right)^3 \text{ for } V_{mag} > V_{98} \qquad \text{(Eq. 2)}$$

$u, v = daily\ zonal\ and\ meridional\ wind\ data$
$v_{98} = wind\ speed\ at\ 98th\ percentile$
$v_{mag} = magnitude\ wind\ speed$
$p = population\ density\ (assume = 1)$

Moreover, lead time data for model forecasts are also examined for each location. The study further calculated the SSI for each model during the case study of storm event, with Lothar Storm of December 23-28, 1999, peaking on December 25. Furthermore, determining how quickly the model can predict the likelihood of storm events. Finally, this study uses the SSI values of the Lothar storm events at the three locations, to determine the probability of storm events similar to or even more than the Lothar storm during the reanalysis data range at each location. This can assist in giving an idea of the frequency and predictive ability of severe wind storms.

II. The statistical distribution of observed wind near three locations

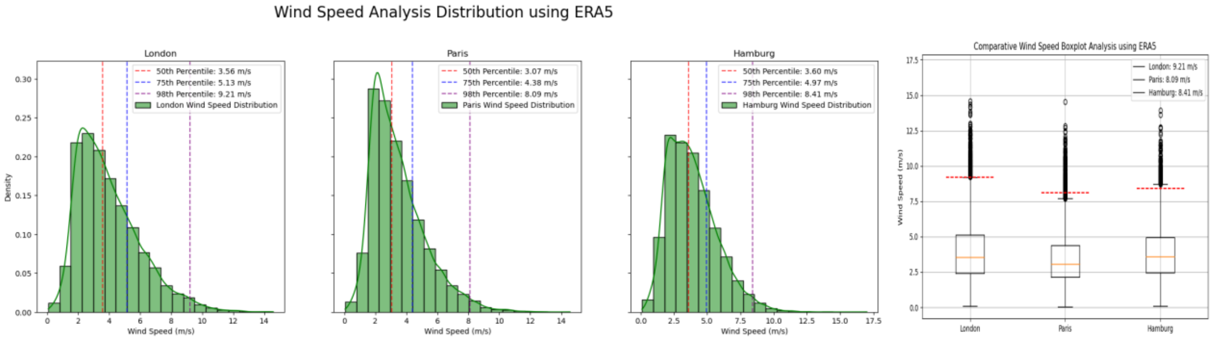


Figure 1. Wind speed distribution reanalysis for London, Paris, and Hamburg

Figure 1 shows the wind speed distribution based on multi-decadal observational records spanning from 1979 to 2018 for London, Paris, and Hamburg. The wind speeds observed vary from 0 to around 17.5 m/s. The histograms for each city illustrate a right-skewed distribution, indicating a higher density of lower wind speeds and gradual decrease for higher wind speeds. The 50th percentile (Median) values – London is 3.56 m/s, Paris is 3.07 m/s, and Hamburg is 3.6 m/s. This median value represents a pivotal point that half of all recorded wind speeds fall below median values. Advancing to higher percentiles, the 75th percentile shows a noticeable increase in wind speed, for London at 5.13 m/s, Paris at 4.38 m/s, and Hamburg at 4.97 m/s. This shows that wind speeds generally do not tend to be strong, a quarter of the time wind speeds can exceed this high threshold. The analysis further extends to the 98th percentile values, where London is at 9.21 m/s, Paris is at 8.09 m/s, and Hamburg is at 8.41 m/s, highlighting how such strong winds are quite rare events in the overall distribution.

III. The 98th percentile of observed wind speed using ERA5

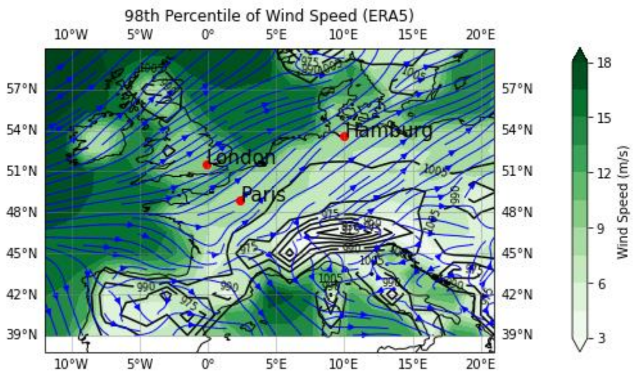


Figure 2. 98th Percentile of observed wind speed reanalysis

The map in Figure 2 shows the geographical variability of extreme wind speeds, represented by the 98th percentile, across Northwest Europe from 1979 to 2018. The wind speeds vary from 0 to around 16 m/s. The wind speed observed in the coastal and offshore areas is dominantly higher than inland areas, highlighting in the North Sea, where is located between the UK and Netherlands and Germany. In this area, the wind speeds can exceed 18 m/s, primarily due to the minimal of obstructions at the sea that allow winds to become stronger. In contrast, wind speeds over land are noticeable slower, which is caused by frictional forces from topographical features. Examining the three locations, there is small variation in wind speeds among them. London, being close to the coast or English Channel, shows higher wind speeds at the 98th percentile. Paris, located further from the coast, shows lower extreme wind speeds. Meanwhile Hamburg, although closer to the coast than Paris, shows wind speeds at the 98th percentile that are slightly lower than London. Examining the spatial gradient of wind speeds, the speed at the 98th percentile can exceed 15 m/s over the ocean, while inland, wind speeds range between 3 m/s and 8 m/s.

IV. Accumulated loss potential (ERA5) across Northwest Europe

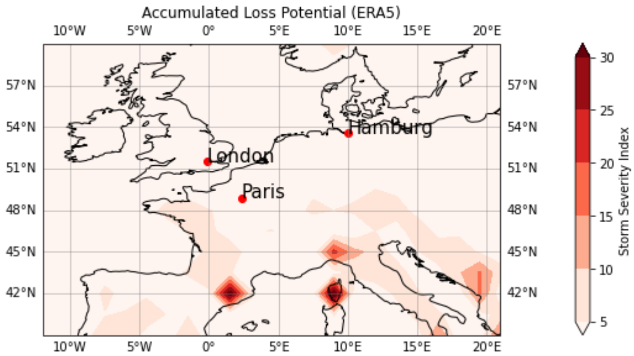


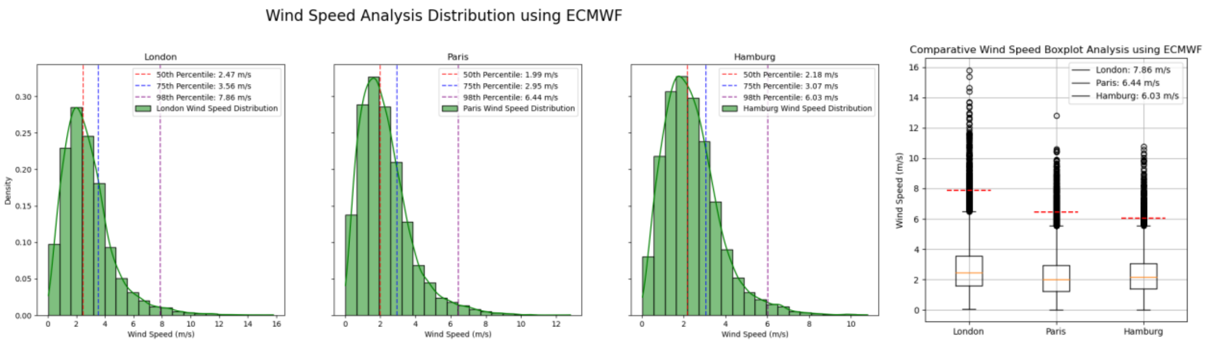
Figure 3. Accumulated loss potential reanalysis

In this section, wind damage will be estimate using accumulation of SSI, as follow:

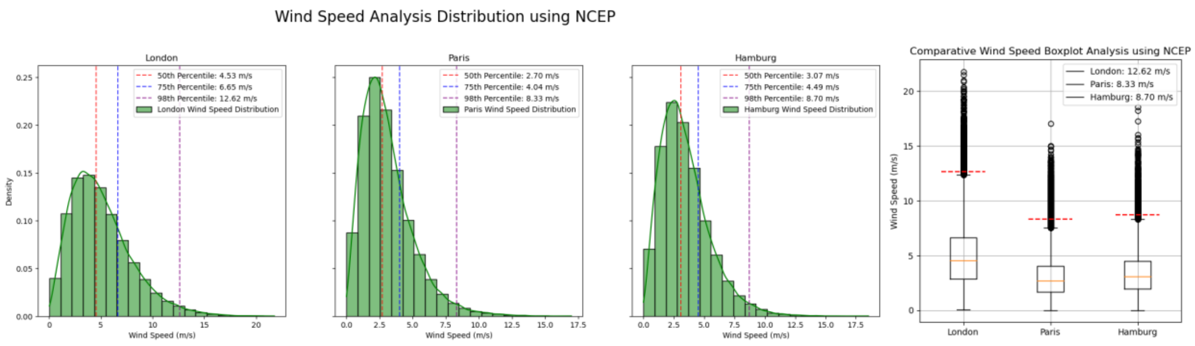
$$SSI_{acc} = \sum_{n-1}^{N} SSI \qquad \text{(Eq. 3)}$$

Figure 3 shows a geographical analysis of the accumulated loss potential (ALP) across Northwest Europe, which estimates from the sum of the Storm Severity Index (SSI) (Equation 2) using daily data from 1979 to 2018. The colour gradient shows different levels of ALP, with darker red colours indicating higher potential losses. In the coastal areas, the Atlantic coast of France, the Balearic Sea coast of Spain, and the coast of the Ligurian Sea, and the coast bordering Italy, indicates a higher potential for loss accumulation as indicated by the increasing colour gradient. This indicates that the losses caused by the increased frequency of strong winds are greater. In contrast, inland areas generally show lower potential losses, however, certain inland areas show higher loss potential, which may be influenced by local geographical features.

V. Distribution of forecast wind and the values of the 98th percentile vary with forecast lead time



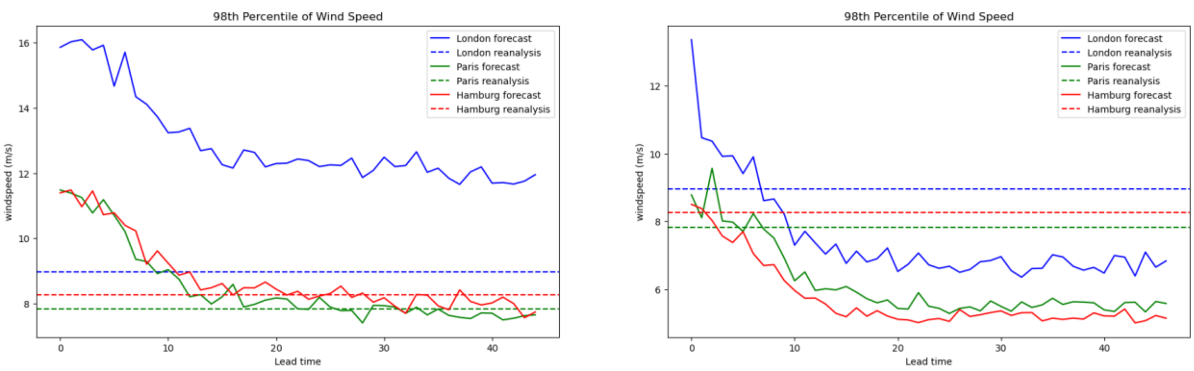
(a)



(b)

Figure 4. Histogram and boxplot of wind speed distribution S2S model (a) ECMWF and (b) NCEP

Figure 4 shows the wind speed distribution-based forecast model (ECMWF and NCEP) spanning from 1999 to 2010 in winter season for London, Paris, and Hamburg. The histograms for each city illustrate a right-skewed distribution, indicating a higher density of lower wind speeds and gradual decrease for higher wind speeds. The NCEP model (Figure 4 (a)) shows a marked difference with the ERA5 observational data (Figure 1), particularly for London, where the 98th percentile is projected at 12.62 m/s, significantly exceeding the 9.21 m/s observed, leading a potential overestimate in model predictions for extreme wind. The NCEP output for Paris is better agreed with the ERA5 output, predicting a 98th percentile of 8.33 m/s compared to the observed value of 8.09 m/s, suggesting a relatively accurate representation of extreme winds. The NCEP Hamburg forecast shows a similar trend, with the 98th percentile predicted at 8.70 m/s is only slightly higher than the ERA5 recorded value of 8.41 m/s, indicating a slight overestimation of the model. In contrast, the ECMWF model forecast (Figure 4 (b)) shows consistently underestimates the 98th percentile wind speeds for all locations, 7.86 m/s for London, 6.44 m/s for Paris, and 6.03 m/s for Hamburg, which is the ECMWF model outputs are lower than the ERA5 observations. The difference ranges from 1.35 m/s to 2.38 m/s from the observational data, which is considerable, indicating the tendency of the model to forecast high percentile wind speed intensity.

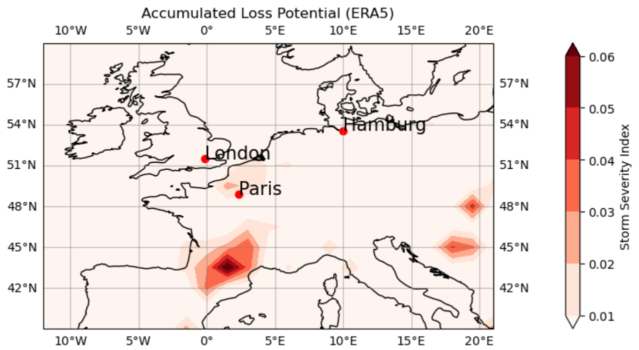


(a) (b)

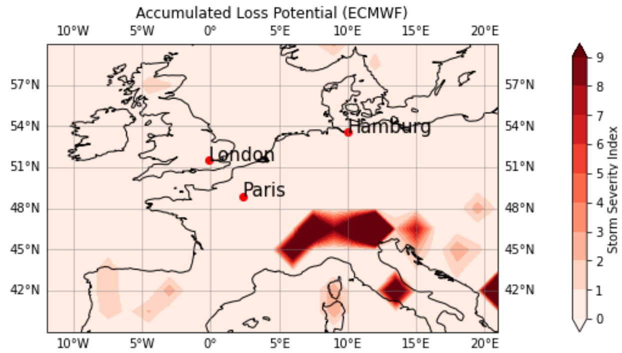
Figure 5. 98th percentile of wind speed lead time using (a) ECMWF and (b) NCEP

Figure 5 presents a comparative analysis of forecast lead time for the 98th percentile wind speeds using ECMWF and NCEP forecast model. ECMWF data (Figure 5 (a)) shows the initial London forecast starting a significantly higher 98th percentile wind speed that gradually decreases over time. This suggests that the ECMWF model may start with a stronger signal of extreme wind speeds which attenuates with the increase in lead time and dominantly overestimate it. In contrast, Paris and Hamburg forecasts begin lower and decrease more gradually, maintaining closer proximity to the reanalysis data. Besides that, NCEP data (Figure 5 (b)) shows initial forecasts for each city start with lower than the ECMWF data. For London the wind speed value starts above the observed value and then decreases gradually and passes the observed value at the 8th lead time. For Paris and Hamburg also decrease, but start close to their reanalysis data over lead time. This indicates that the NCEP model provides more stable forecasts for the 98th percentile wind speed.

VI. Accumulated loss potential of the Lothar storm



(a)



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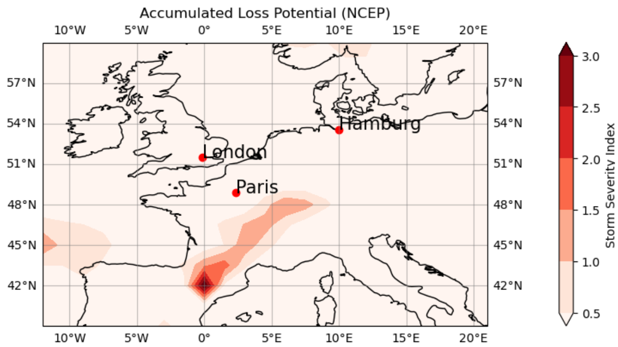


(c)

Figure 6. Accumulated loss potential impacted by Lothar Storm (a) ERA5, (b) ECMWF, and (c) NCEP

Figure 6 provides the accumulated loss potential impacted by Lothar Storm from reanalysis and forecast model output. The storm starts from December 23 to 28, 1999, which affected some areas of France, Germany, and Switzerland. Based on reanalysis model output (Figure 6 (a)) that shows a marked potential for losses in the French region, bordering Spain, with the SSI value reaches up to 0.06. The concentration corresponds to the severe impact from the storm. Figure 6 (b) presents the ECMWF model output that shows a wider area of accumulated loss potential which extends significantly to into Switzerland and Italy with SSI value is greater than 9, indicating a much wider impact from the model output. However, it seems to overestimate the accumulated potential loss compared to the reanalysis output. In contrast from ECWMF model output, NCEP model (Figure 6 (c)) shows a different spatial distribution of SSI, with the high value extending from France to the border region of Germany and Switzerland. The peak SSI values greater than 3 are recorded at the border of France and Spain. In addition, the results from the model spatially tend to be closer to the reanalysis data where the highest concentrations are in the same location.

VII. Detecting the signature of the storm earlier

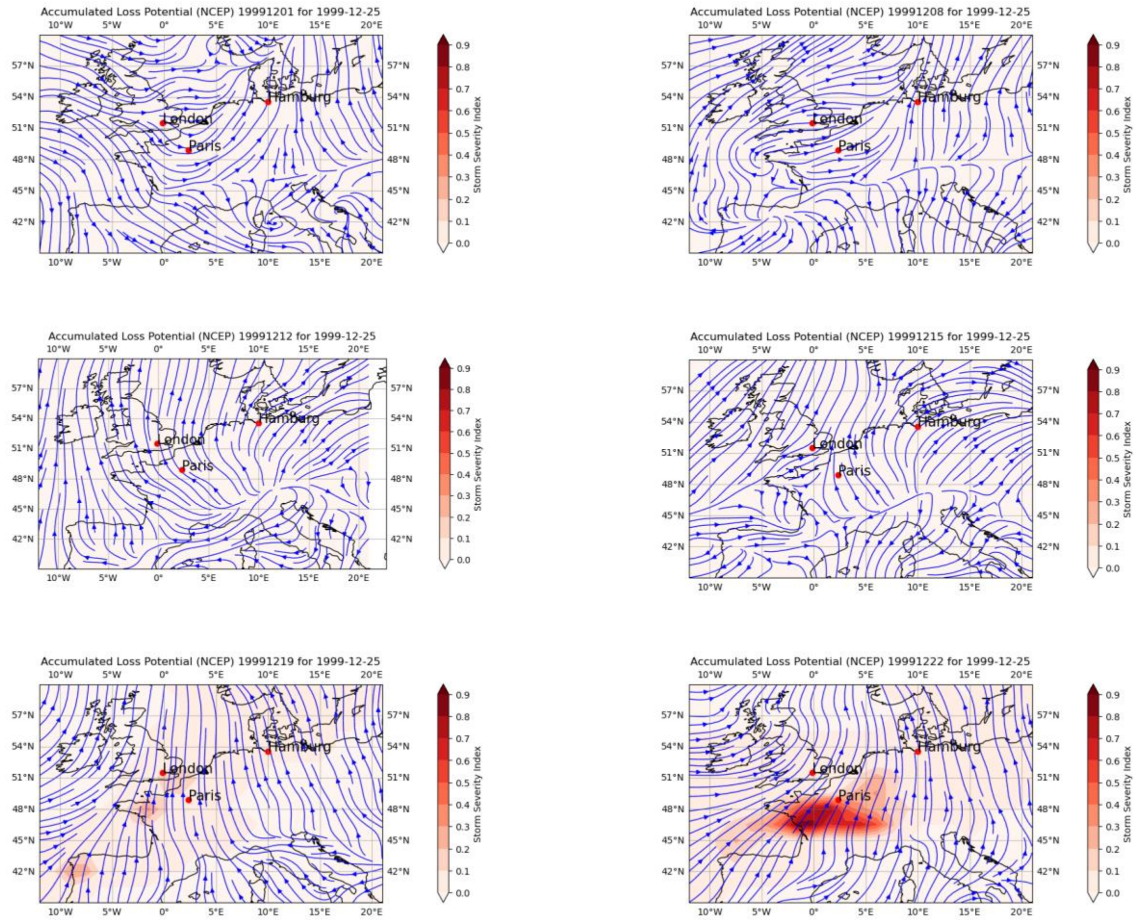
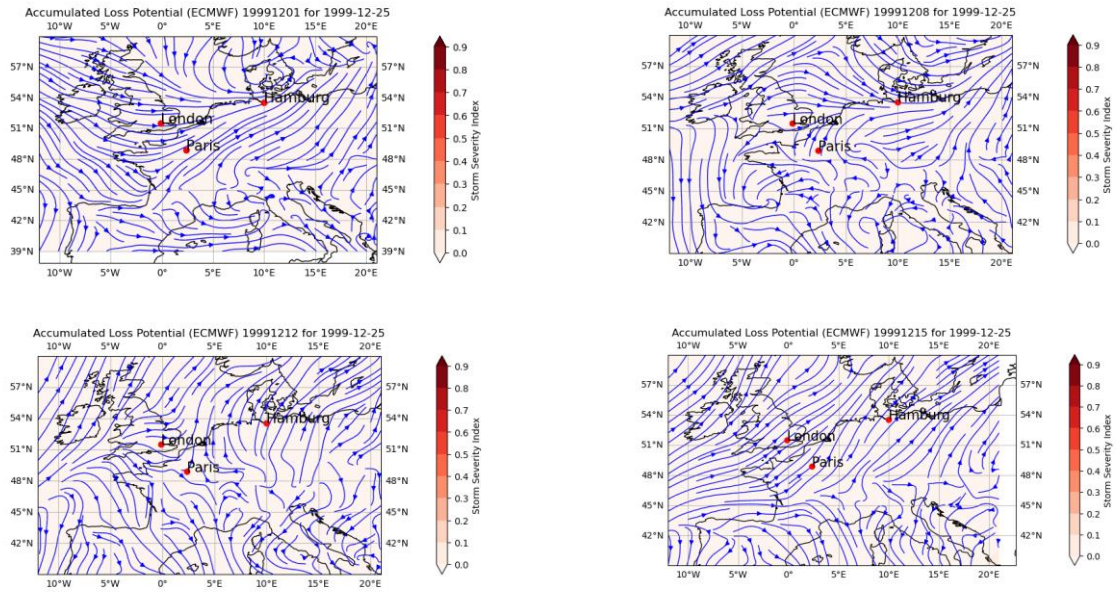


Figure 7. Multi-day forecast and warning of potential high severity wind storm using NCEP model



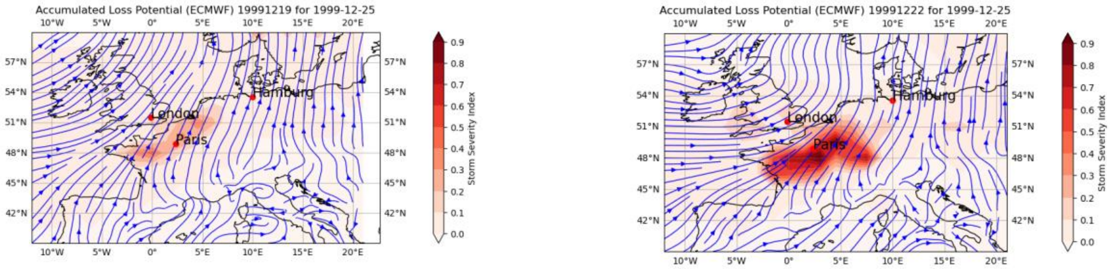


Figure 8. Multi-day forecast and warning of potential high severity wind storm using ECMWF model

Figure 7 shows the NCEP model outputs leading up to the peak of the storm of December 25, 1999, demonstrates the evolving forecast of accumulated loss potential to give signal upcoming storm. Starting from December 1 to 15, 1999 (10 days before peak storm), there is no signature of the potential loss of the model and no strong indication of storm. However, December 19 (6 days before peak storm), there are indications of a storm characterized by an increase in SSI values on the French Atlantic coast, but further analysis is needed as the values are still low. By December 22 (3 days before peak storm), there is a marked increase in the accumulation of potential losses in the forecast, in French regions, indicating that the model begins to capture the potential of the storm three or four days earlier. The ECMWF model forecast outputs (Figure 8) are in line with the NCEP forecast model output, which started indicating potential loss on December 19, but the signal is not clear. By December 22, the forecast data shows a marked increase in accumulated potential losses, indicating that the model begins to capture the potential of the storm three or four days earlier. As a result, it can be concluded that the potential for severe storms can be clearly identified 3 to 4 days prior to their occurrence.

The spatial distribution between the NCEP and ECMWF forecast models shows similar results in the French region. In addition, when comparing the forecast model (NCEP and ECMWF) model outputs on December 25 with the reanalysis data (Figure 9), both forecasts can provide similar spatial distribution, although the values tend to be higher than the reanalysis data.

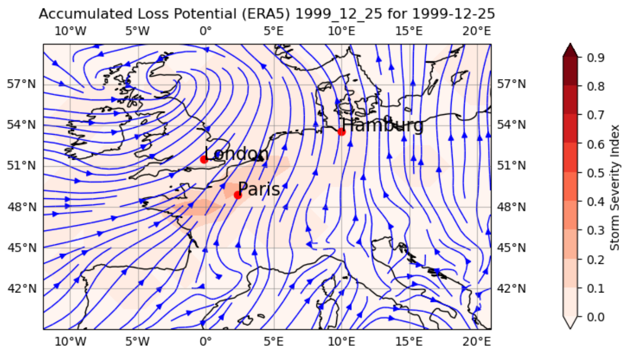
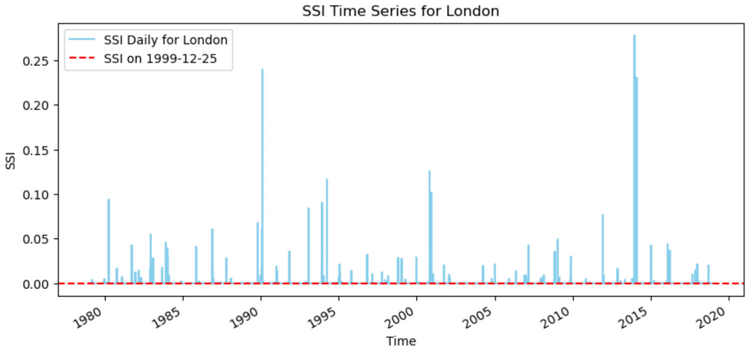
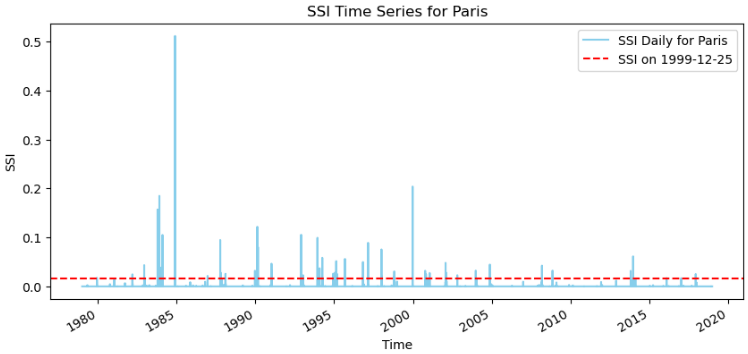


Figure 9. Accumulated Loss Potential using reanalysis data

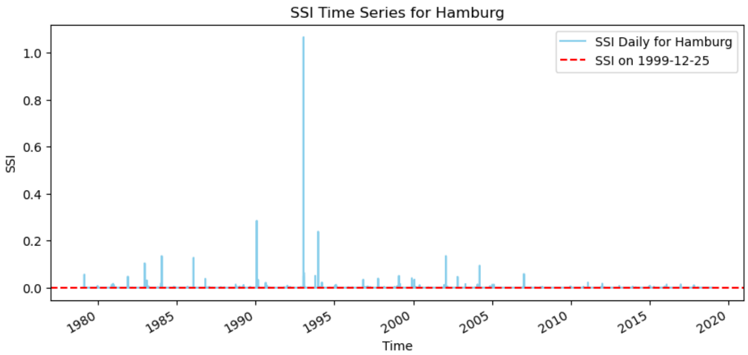
VIII. The probability of Lothar storm using ERA5



(a) Probability SSI Daily ≥ SSI Storm in London: 1.54%



(b) Probability SSI Daily ≥ SSI Storm in Paris: 0.38%



(c) Probability SSI Daily ≥ SSI Storm in Hamburg: 2.00%

Figure 10. Temporal analysis of SSI and probability of storms for (a) London, (b) Paris, and (c) Hamburg

Figure 10 shows the historical daily SSI for London, Paris, and Hamburg, highlighting the SSI of the Lothar Storm on December 25, 1999, relative to other days in the time series from 1979 to 2018. In London, the SSI time series shows that daily probability of a storm exceeding the intensity of Lothar Storm event is around 1.54%, indicating that storms of such strength are relatively rare in London. The Paris SSI time series shows a lower probability of 0.38% for storm exceeding the Lothar Storm event, indicating that storms are rarer in Paris than London. In contrast, Hamburg SSI time series shows a slightly higher daily probability of 2.00%, indicating a slightly greater than those locations, but still rare for similar or exceed the intensity. Time series analysis shows some significant spikes in the SSI, even exceeding the peak observed during Lothar Storm, which indicate the potential for other severe storm that exceeds the Lothar Storm.

IX. Conclusion

The investigation into wind-related natural hazards in Northern Europe has shed light on the distinctive distribution patterns of wind speeds across London, Paris, and Hamburg. The analysis indicates a right-skewed distribution, with most wind speeds not exceeding the median threshold. However, extreme wind speeds that surpass the 98^{th} percentile have been observed to be significantly higher in London for all the model data (9.21 m/s for ERA5, 12.62 m/s for NCEP and 7.86 m/s for ECMWF), likely due to closer to coastal. Furthermore, ECMWF model shows a tendency for underestimation values of distribution, while NCEP model shows an agree value with ERA5 model. In addition, lead time analysis for the 98^{th} percentile wind speeds indicate an ECMWF model overestimation for London when compared to reanalysis data, while other locations show results closer to the reanalysis data at lead time 8. Meanwhile the NCEP model, it tends to underestimate all the location after lead time 8. For statistical distribution, NCEP shows better result than ECMWF output due to an agree of statistical distribution and lead time that tends to be stable.

Geographically, Ocean regions exhibit higher 98^{th} percentile wind speed, up to 18 m/s, compared to inland areas, ranging between 3 – 8 m/s), attributed to fewer obstructions at sea. Among the three locations, London has higher 98^{th} percentile values of wind speed, due to closer to the sea. While Paris shows the lowest values, being more centrally located inland. Further analysis reveals that SSI values are notably higher along coastlines, especially in France and Italy regions. Moreover, the highest SSI values is recorded near the Balearic and Ligurian Seas, reaching SSI values of 30, indicating greater potential loss in the storm events.

In the case of the Lothar Storm, reanalysis data show a dominant accumulated loss potential in regions of France bordering Spain, with the SSI values reaching 0.06. The NCEP model shows a similar spatial pattern for the higher SSI values (reaching 3.0) in this area. Although, the lower SSI values extend to the borders with Switzerland and Germany. In contrast, the SSI values of ECMWF model reaching more than 9, are situated in Switzerland and Italy. So, NCEP shows a better result because of the spatial distribution and SSI values are not overestimate too far.

Moreover, the location is significant far from reanalysis data and considerable overestimation. However, the forecast models agree that it is possible to detect a storm about 3 to 4 days before its peak, even 3 to 4 days before the storm arrives (or about 6-7 days before the storm peak). In addition, the spatial distribution of SSI values in the forecast models closely matches the reanalysis data shown along the French Atlantic coast. For this case, NCEP and ECMWF agree that storm can be detected 3-4 days before event.

Examining the daily probability of SSI values equalling or exceeding SSI values during Hurricane Lothar for each location, shows that London has a higher probability than Hamburg and Paris, at 2.00%, 1.54%, and 0.38% respectively. Nonetheless, the probabilities are very low, leading to the conclusion that events similar to or exceeding Hurricane Lothar are rare.