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European storminess: late nineteenth century to present

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Abstract Annual and seasonal statistics of local air pressure characteristics have already been used as proxies for storminess across Northern Europe. We present an update of such proxies for Northern Europe and an unprecedented analysis for Central Europe which together considerably extends the current knowledge of European storminess. Calculations are completed for three sets of stations, located in North-Western, Northern and Central Europe. Results derived from spatial differences (geostrophic winds) and single station pressure changes per 24 h support each other. Geostrophic winds' high percentiles (95th, 99th) were relatively high during the late nineteenth and the early twentieth century; after that they leveled off somewhat, to get larger again in the late twentieth century. The decrease happens suddenly in Central Europe and over several decades in Northern Europe. The subsequent rise is most pronounced in North-Western Europe, while slow and steady in Central Europe. Europe's storm climate has undergone significant changes throughout the past 130 years and comprises significant variations on a quasi-decadal timescale. Most recent years feature average or calm conditions, supporting claims raised in earlier studies with new evidence. Aside from some dissimilarity, a general agreement between the investigated regions appears to be the most prominent feature. The capability of the NAO index to explain storminess across Europe varies in space and with the considered period.

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1 Introduction

Severe storms can do widespread damage to ecosystems, property and society. Inland areas are affected by windthrow uprooting trees, soil erosion and damage to construction. Coastal regions are not only exposed to the wind force but to storm surges and wind waves in the wake of storms as well. Due to its impact on socioeconomic structures storm-climate naturally attracts public attention. In the North–East Atlantic and the North Sea a roughening storminess was perceived and public concern was raised in the early 1990s.

About that time the European research project WASA (Waves and Storms in the North Atlantic) was launched to clarify whether the storm and wave climate has actually worsened or not. WASA concluded that there are: considerable variations in storminess on a decadal timescale; a positive trend in storminess from the 1960s to the 1990s and storm intensities of the mid 1990s are comparable to those of the early twentieth century (WASA 1998). As for the later twentieth century these conclusions are supported by Wang and Swail (2001). Alexander et al. (2005) also found an increase of severe storm events over the UK during the later part of the twentieth century and Alexandersson et al. (2000) pointed out that this positive trend in

storminess seems to have been broken by the middle of the 1990s.

The fact that on a timescale of 100 years or more Bärring and von Storch (2004) detected no consistent trend, highlights the importance of employing data that reach far back in time before any judgment about storminess can be made. Long-term daily wind measurements, which may appear as first choice data, are characterized by spatial sparseness and inhomogeneities, caused by instrumentation changes, site moves and environmental changes (Peterson and Hasse 1987). Quality assessment and adjustment (if applicable at all) are fraught with problems. Figure 1 shows the number of gales or still fiercer storms for Vienna from direct wind measurements. Aside from a number of obstacles, two major inhomogeneities are documented (Auer et al. 2001): 1909, relocation of the wind recorder from 27 to 35 m above ground; 1911, the year that features 10 events, a switch from a mechanical anemometer (Beckley-Adie) to a pressure tube anemograph (Dines). As direct wind measurements are no alternative it may appear reasonable to assess changes in cyclone activity by evaluating historical weather maps. However, the amount of information contained in weather maps has changed over time along with the improvements in observing the lower troposphere and thus the use of weather maps is problematic too (WASA 1998). Schmidt and von Storch (1993) used the geostrophic wind, calculated from triangles of local pressure readings, as proxy for storminess. Kaas et al. (1996) demonstrated that changes in the geostrophic wind's percentiles actually reflect changes in wind conditions. Kaas et al. (1996) also suggested other proxies that are based on local pressure observations such as the rapid fall of pressure at single sites. Such proxies have already been used to describe Northern European storminess over the past 200 years (Bärring and von Storch 2004) and for the later twentieth century (Alexander et al. 2005).

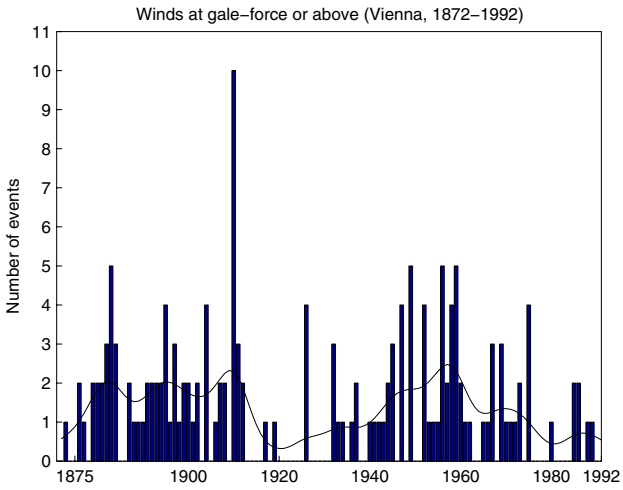

Fig. 1 Number of storm events (November–February) at or above Beaufort 8 and the Gaussian low-pass (21 years) filtered curve

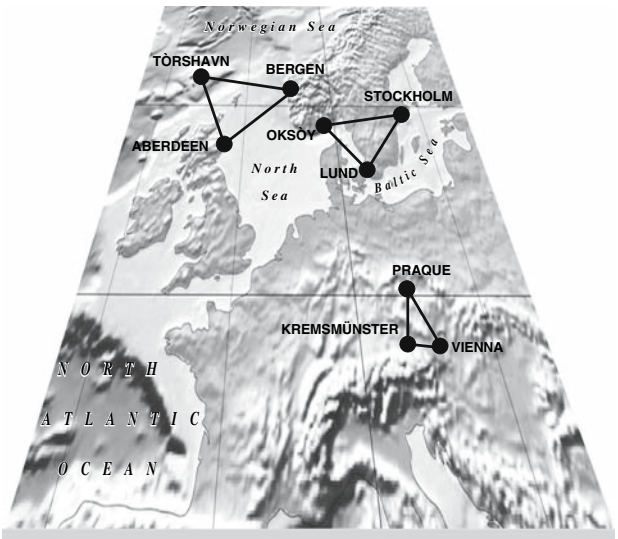

Fig. 2 Location of employed stations and assembled *triangles*

2 Data

Pressure data from Northern Europe and their quality are detailed in Alexandersson et al. (1998) and the update to 2005 is processed accordingly. High wind speeds across Europe are generally associated with extratropical cyclones, which occur in North or North-Western Europe all year but in Central Europe almost entirely from November to February. Figure 2 shows the locations of the stations and the formed triangles. Thus, to capture storminess in Northern Europe readings across the whole year are needed whereas in Central Europe the focus is on November–February.

In Central Europe we have pressure readings at four stations. These are Kremsmünster (1874–2005) and Vienna (Hohe Warte, 1872–2005) in Austria, and Klementinum (1874–2001) plus Karlov (1921–2005) in Prague, Czech Republic. Apart from Prague–Klementinum where readings are taken at noon only, all stations provide three readings per day. In Prague readings are at 7 am, 2 pm and 9 pm throughout the whole period. Until 1970 Austrian measurements were taken at 7 am, 2 pm and 9 pm and from 1971 onward the 9 pm readings are switched to 7 pm. For all years 1971 onward Prague (Karlov) data were linearly interpolated between readings at 2 pm and 9 pm to obtain an estimate of the 7 pm pressure. This procedure yields smoothed values of the potential true pressure that can cause errors of several hPa in unfortunate cases (Schmith et al. 1997). We estimated pressure readings in the evening a second time by transferring the 7 pm

readings at the two Austrian stations to 9 pm and compared it to the first approach that involves interpolation at Karlov only. This introduces further smoothing and may serve as a hint about the extent of the error introduced by the interpolation. The filtered estimates are highly correlated ($r > 0.99$) and largest absolute differences are about 5% of the range spanned by them, making the run of the curves almost identical.

Homogeneity is always an issue if long-term time series are analyzed (e.g. Auer et al. 2001). The applicability of homogenization methods generally depends on the time spacing between readings, the availability of nearby stations and the meteorological element under consideration. Due to its spatial smoothness, air pressure shows an expedient signal to noise ratio (Auer et al. 2007), that qualifies for a straightforward adaptation of relative homogeneity tests, being available from earlier applications to monthly values (Auer et al. 2001).

We used the monthly adjustments for the daily series of Vienna and Kremsmünster to remove non-climatic inhomogeneities. If possible, dates of inhomogeneities were checked against meta-data. Finally, we utilized cumulative inter-station differences to assess the quality of the homogenized series. This is a simple, qualitative method (Bosshard and Baudenbacher 1996) that identifies breaks via changes in the slope of pressure differences between two sites.

Since no homogenization on a monthly base has been done for Prague, we utilized the homogenized daily series of Vienna and Kremsmünster for comparison. Again, cumulative series of pressure differences between stations were used for break detection. Shifts in the average of such differences prior to and after breaks were used to adjust the data.

Moreover, temporal differences at all stations are computed for outlier-detection. Differences of two consecutive readings exceeding 20 hPa were flagged and compared to preceding and subsequent differences. If flagged values were prior to or after differences of similar magnitude but opposite sign, readings were set to missing.

3 Results

The derivation of the geostrophic wind is done as in Alexandersson et al. (1998). Wind force is assessed via the length of the geostrophic wind vector and heavy wind events through annual or seasonal high percentiles (here: 95th and 99th). Stations and assembled triangles are shown in the right panel of Fig. 2. Figure 3 shows the filtered 95th and 99th percentiles of the geostrophic wind as score variables.

North-Western European storminess (Fig. 3) starts at rather high levels in the 1880s, decreases below average conditions around 1930 and remains declining till the 1960s. From then until the mid 1990s a pronounced rise occurs and values similar to those of the early century are reached. Since the mid 1990s storminess is around average or below. This picture—a decline that lasts several decades followed by an increase from the 1960s to the 1990s and a return to calm conditions recently, is to be found for the North European triangle as well. The increase, however, is far less pronounced. Central Europe features high-level storminess peaking around the turn from the nineteenth to the twentieth century which is followed by a rapid decrease. Since then a gradual increase prevails until the 1990s and most recent values show a return to average or calm conditions.

Next to this broad agreement between Central and Northern Europe storminess the link between the regions seems feeble and not dominated by anti-correlations which could be expected from a physical reasoning. Close to the end of the nineteenth century storminess increases in Central Europe while it decreases in North-Western and Northern Europe and the transition to low levels of storminess in the early twentieth century takes place rather

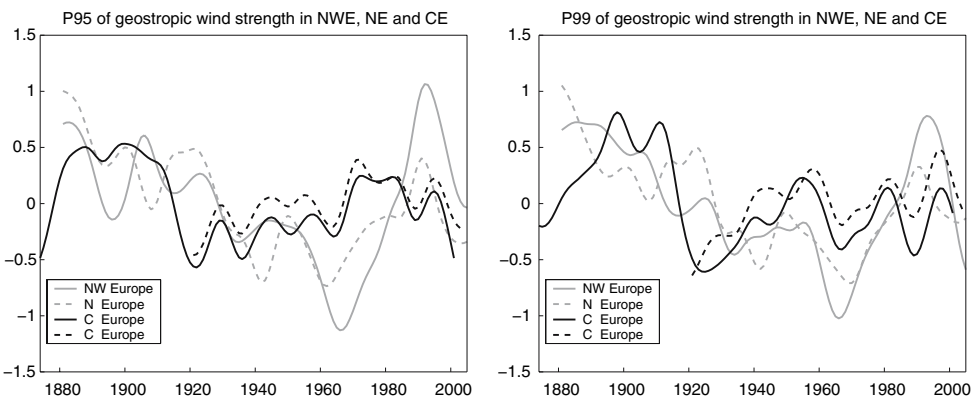

Fig. 3 Gaussian low-pass filtered (21 years) curves for the 95th (*left*) and 99th (*right*) percentiles of the geostrophic wind throughout Europe. The heavy curve is made up by Kremsmünster, Vienna and Prague–Klementinum while the heavy dashed curve by Kremsmünster, Vienna and Prague–Karlov (note that tails are based on less data than the rest)

suddenly in Central Europe but over several decades in Northern Europe. Different from North-Western Europe the succeeding increase happens at a slow rate in Central Europe and values reached in the 1990s appear unremarkable.

Figure 4 depicts the 95th percentiles of absolute pressure changes per 24 h. Stations which have been used to form triangles show fairly similar behavior. Stations across Nothern Europe show an overall decrease in storminess from the 1880s to the middle of the twentieth century followed by an increase afterwards. Most recent years are marked by a return to average values, which may be either the beginning of a long-term decline or the downward phase of quasi-decadal oscillation. Values of the early twentieth century fit those of the latest maximum. Hence, the broad chronology of the twentieth century at the northern stations is a decrease followed by an increase and a return to average values most recently. A related evolution can be found at the Central European stations as well. However, the rise from the 1880s onwards and the following decrease are much steeper in Central Europe and levels of storminess are particularly low in the early 1880s in Central Europe but high in Northern Europe. In the late 1950s, early 1960s and somewhat prior to 1980 storminess is higher in Central Europe whereas in the late 1960s and the 1990s Northern European storminess is more pronounced. This indicates opposite behavior during the second half of the twentieth century, which could be expected from physical reasoning. However, there is no obvious reason for the rather similar evolution during the preceding period.

An empirical orthogonal analysis (von Storch and Zwiers 1999) of the 95th percentiles of the absolute pressure changes per 24 h reveals two dominant patterns explaining more than 60 and 20% of the temporal variability among the stations (see Fig. 5, left panel). The leading EOF reflects the overall agreement across the stations and its time coefficient traces the aforementioned chronology of the twentieth century. The second EOF highlights the differences between Northern and Central European storminess. Relatively low values of the second EOF's time coefficient at the beginning 1880s and around 1990 show the simultaneous occurrence of high-level storminess in Northern Europe and calm conditions in Central Europe (Fig. 5, middle panel). The local maxima reached in the late 1950s and prior to 1980 show high storminess in Central Europe and less storminess in Northern Europe.

When distributing the variability onto two rotated EOFs the rotated EOFs identify two groups of stations, which are those in Northern Europe and the stations in Central Europe (Fig. 5, right panel). This remains unaltered no matter whether the rotation is carried out in three, four or five dimensions. A hierarchical Cluster Analysis using the Euclidean norm as the similarity measure and the "complete linkage" technique as aggregation criterion leads to similar results (not shown).

NAO indices may be used as potential candidates to explain phases of enhanced and reduced storminess. Positive values of NAO indices can be generally associated with more storms approaching Northern Europe while stormy conditions in Central Europe would be attributed to negative NAO index values. This would cause an inverse relationship between Northern and Central Europe storminess. However, Alexandersson et al. (1998) demonstrated that the NAO index defined by the mean pressure difference between Ponta Delgada on the Azores and Stykkisholmur on Iceland has a rather limited capacity to explain variability in Northern European storminess for the past 130 years. We utilized the NAO index of Luterbacher et al. (2002), who define it as a standardized difference between SLP averages of four grid-points on a 5° × 5° longitude–latitude grid over the Acores and Iceland.

Considering the whole period, the 95th percentiles and unfiltered curves, we found a weak positive albeit significant ($\alpha = 0.05$) link for Northern Europe (correlation

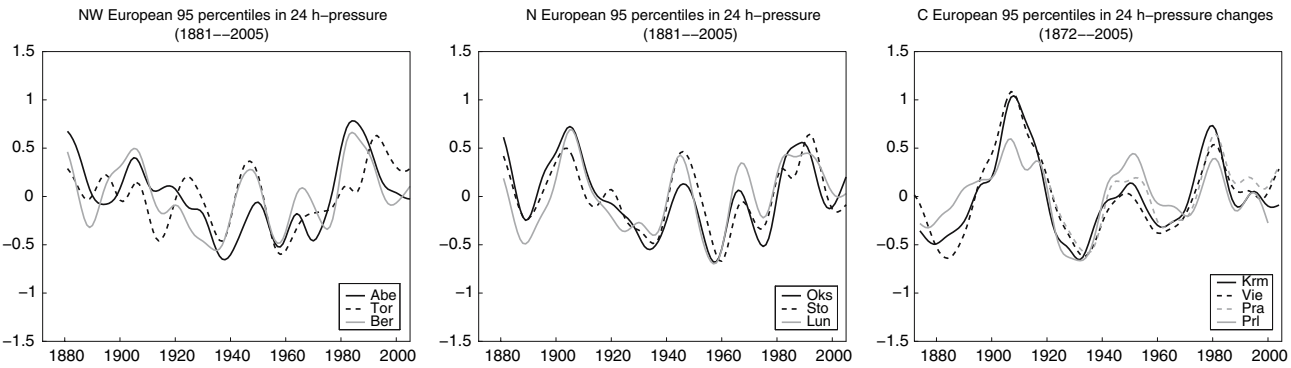

Fig. 4 Temporal evolution of the filtered 24 h pressure changes 95th percentiles. *Left to right* stations in North-Western, Northern and Central Europe

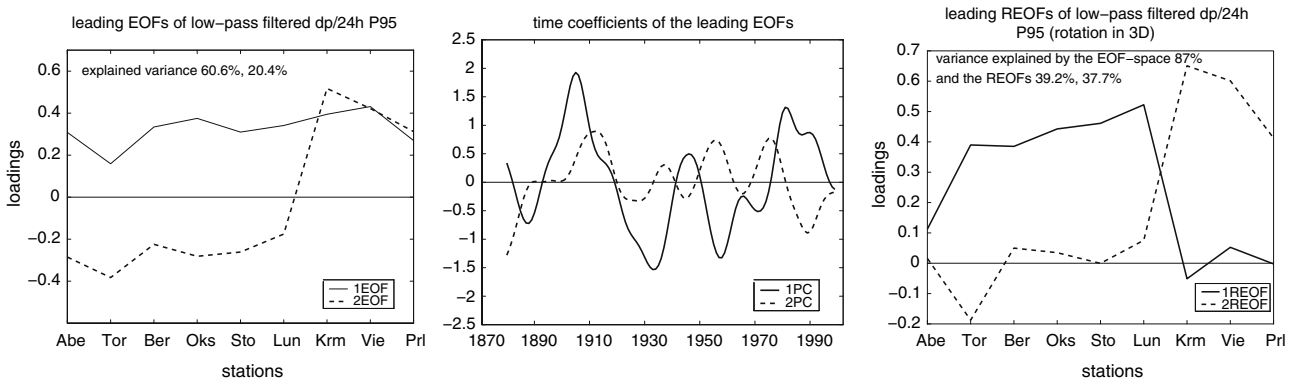

Fig. 5 The two leading EOFs across the stations (*left*) their corresponding time coefficients (*middle*) and the two rotated EOFs. Abbreviations on the *x*-axis of the pattern-panels stand (from *left* to *right*) for Aberdeen, Torshavn, Bergen, Oksoy, Stockholm, Lund, Kremsmünster, Vienna and Prague (Klementinum)

coefficient of approximately 0.4) and an even weaker, insignificant negative relationship for Central Europe (about −0.15). Values of correlation decrease when the 99th percentiles are regarded or Gaussian filtering is applied. Thus, the above described statistical link between the NAO and European storminess is found, but it seems rather loose. Moreover, the general resemblance between storminess in Northern and Central Europe suggests no strong influence of the NAO index on storminess on long timescales as well, which is in line with Alexandersson et al. (1998). During the later twentieth century a significant link between North–West European storminess during the JFM season and the NAO index was detected by Alexander et al. (2005) who relate changes in the NAO to the number of severe storms events across the UK and Iceland. All findings together indicate that the NAO index's ability to explain storminess varies with time and across regions.

4 Conclusions

The present study significantly extends the explored regions (e.g. Alexandersson et al. 1998; Alexander et al. 2005) into Central Europe. Thereby it allows for an assessment of European storminess on a more general scope. The increase in storms throughout Northern Europe from the 1960s to the 1990s raised public concern. This diminished once storm levels decreased in the mid 1990s (Alexandersson et al. 1998).

This study provides updated information relevant in determining whether storminess is once again on the incline or has settled to more calm conditions. Major findings are listed as follows in italics:

The storm climate in Europe has undergone considerable changes throughout the past 130 years and shows significant variation on a quasi-decadal timescale

The bulk chronology since the 1880s may be described as residing at high levels of storminess around the early twentieth century, followed by a decline to rather calm conditions and a rise afterwards. The decline appears suddenly in Central Europe and over several decades in Northern Europe. Findings for Northern Europe are in accordance with WASA (1998), Alexandersson et al. (1998) and Bärring and von Storch (2004). Alexander et al. (2005) showed that the later part of the twentieth century is marked by increasing storminess, which is in line with our findings. However, the much longer period used here reveals that this increase from the 1960s to the 1990s starts from particularly calm conditions and ends at levels of storminess, which are comparable to those of the turn from the nineteenth to the twentieth century. Recent years have brought no substantial change for Northern Europe and are hence collaborating claims raised by Alexandersson et al. (2000). For Central Europe we are not aware of any comparable assessment of storminess yet, so findings appear new. Highest levels of Central European storminess are reached after a steep incline from the 1880s at the beginning of the twentieth century. After a rapid fall to below average values storminess slowly inclines to average conditions towards the end of the century.

Most recent years are characterized by a return to average or calm conditions

Alexandersson et al. (2000) regarded a breakdown of the increase in Northern Europe storminess since the mid 1990s as likely, though their claim referred to data that only ranged till 1998. Thus it is advantageous to update the analysis and to determine if the claim can be adapted to the most recent years as well. We found it applies. In Central Europe the geostrophic wind indicates some years of enhanced storminess in the late 1990s, but more recent years were calm too.

Storminess in Northern and Central Europe share their main characteristics

The aforementioned bulk run of storminess through the past 130 years is to be found in Northern Europe and Central Europe. An EOF analysis reveals the leading EOF as being representative of the commonness among the investigated stations and its time coefficient tracks the broad evolution. A rotated EOF analysis and a cluster analysis show that stations in Central Europe can still be separated from those in Northern Europe. Together that means similarities amongst the stations are an important feature, but Central European stations can still be distinguished from those in Northern Europe.

The ability of the NAO index to explain storminess across Europe depends on the region and period under consideration

The NAO index is capable of explaining some variability in North-Western Europe throughout the last decades (Alexander et al. 2005), but fails to explain earlier storminess (Alexandersson et al. 1998). In Central Europe the link over the past 130 years is looser still. So, even though the sign of the correlation between the NAO index and storminess attributes negative NAO index values to higher storminess in Central Europe while positive values come along with enhanced storminess in Northern Europe, the NAO index is not very helpful to describe storminess over the past 130 years. This highlights the importance of long-term, high-quality climatological datasets for statistical analysis in climate assessment. Datasets used in this study put the perceived increase in Northern Europe's storminess during the later part of the twentieth century into perspective, showing that levels of storminess in the 1990s fit those of the late nineteenth, early twentieth century. This is in line with Bärring and von Storch (2004), who showed for Lund and Stockholm that storminess has not significantly changed over the past 200 years.

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