Strong wind occurrence in Poland from the 13th to 16th centuries based on documentary evidence

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Abstract. A comprehensive database of strong winds up until AD 1600 was created based on documentary evidence ~~was created~~ for the area within the modern-day borders of Poland ~~until AD 1600~~. Three types of documentary sources were used: handwritten and unpublished, published, and "secondary" literature. The database contains detailed information about ~~the~~ occurrences of strong wind~~s~~ (the location/region, time, duration and indexation for intensity, extent and character of damage), as well as the exact textual content of the original weather note, the name of the source, and an evaluation of the source's quality. Five categories of strong winds were delimited: 1 – fresh and strong breeze (Beaufort scale 5–7), 2 – gale (8–9), 3 – storm (10–12), 4 – squall (i.e., gusty wind during a thunderstorm), and 5 – tornadoes. The intensity, extent, and character of damage were estimated based on the proposition given by Brázdil et al. (2004), which we slightly modified to include the Baltic Sea and its influence on coastal parts. In the database, 137 thus-defined strong winds were identified. A reliable estimate of some characteristics of the occurrence of strong winds in Poland seems possible from the mid-15th century onwards. The highest number of strong winds occurred in the second half of the 16th century, with a maximum in the 1570s. For each season, the greatest number of strong winds was found for the Baltic Coast and Pomerania region, and then for Silesia and Lesser Poland. Storms and gales were most common during the cold half-year (mainly in March, November, and December).

Keywords: historical climatology, documentary evidence, Poland, strong winds, database.

1. Introduction

Strong winds are among the most significant natural disasters, causing great damage around ~~in~~ the ~~entire~~ world and loss of human and animal lives. In Poland, for example, according to Lorenc (2012), they are the second ~~the~~ most dangerous natural phenomenon after floods. Results presented recently by the Statista Research Department (Apr 29 2024, https://www.statista.com/statistics/1269886/most-common-natural-disasters-in-europe) confirm that the same situation is observed in Europe. From 2001 to 2020, floods were most frequent (41%), followed by strong winds (27%). According to estimates by MunichRe (2011, 2020) ~~estimates~~, approximately ~~≃~~60% of all insured losses during 2000–18 were due to extreme meteorological events, foremost~~primarily~~ among which were extreme winds. Cusack (2023, see Figs 2 and 7) estimated ~~the~~ annual windstorm losses in Europe (12 countries) for the period ~~from~~ 1950 ~~to~~ –2022. The results showed that yearly losses usually (~80%) ranged~~oscillated~~ between 1 and 5 billion euros. Although no long-term trend is seen in the study period, the ~~greatest~~ losses were greatest ~~observed~~ in the 1980s.

Good and reliable knowledge about extreme winds is essential for many economic sectors, e.g., the design and construction of large and high buildings or the wind power sector (Outten and Sokolowski 2021). However, our knowledge about the different characteristics and impacts of extreme winds is still based mainly on results gathered for the instrumental period (for roughly ~~more or less for~~ the last 100–150 years), and most often only for the last few decades. Therefore, such knowledge is still insufficient and needs improving~~vements~~, which can be done by using a more extended series of data coming from the early- and pre-instrumental period. Many such data are still undiscovered, or they have been discovered and are stored in numerous archives worldwide but have not been digitised and exist only on paper ~~stored in numerous archives worldwide~~ (Hawkins et al. 2003). That is why data rescue activity is vital (for details, see e.g. Brönnimann et al. 2019; Lundstad et al. 2023). It can help improve our understanding of historical climate variations, including in strong winds. For example, Hawkins et al. (2019) demonstrated that the severe windstorm that occurred in February 1903 in England and Wales (which they reconstructed ~~by them~~ using documentary evidence) was characterised in some places by ~~stronger~~ winds that were stronger than those~~were~~ observed in the modern period (1950–2015). They thus suggest that ~~an~~ estimates of risk from severe windstorms based on contemporary data may need to be revised. A longer perspective on changes in intensity and impacts of extreme winds will ~~can~~ also be beneficial for ~~their future~~ simulations projecting future extreme winds, ~~and~~but also for ~~the~~ more reliable assessment of their associated risks ~~connected with them~~ to ~~for~~ societies. However, the mechanisms responsible for their changes and risks are often hard to identify because strong winds are highly changeable in terms of when and where they occur~~significant spatial-temporal changes of strong wind occurrences~~, as well as because they are ~~and also their~~ rar~~eity~~ and often local in character ~~significantly hinder the proper identification of the mechanisms responsible for their changes and risks~~.

According to Donat et al. (2011), in future climate simulations (investigated using multi-model simulations from global [GCM] and regional [RCM] climate models), increased~~enhanced~~ extreme wind speeds were projected~~found~~ over northern parts of Central and Western Europe in most simulations and in the ensemble mean (up to 5%). Consequently, they forecast that the potential losses will be higher in these regions, particularly in Central Europe. Conversely~~In turn~~, in Southern Europe, they ~~according to them, an~~ expect~~ed~~ a decrease in extreme wind speeds that will result in fewer ~~a reduction in loss~~ potential losses. More recent work (Outten and Sokolowski 2021) partly confirms the above findings. Using a 15-member ensemble of high-resolution Euro-CORDEX simulations (~12 km), they projected ~~found increases in the return period, i.e.~~ more frequent extreme episodes ~~projected~~ for Northern, Central and Southern Europe throughout the 21st century. At the same time, however, they underlined~~, however,~~ that ~~the~~ assessments of future changes in extreme wind ~~changes~~ remain fraught with uncertainty.

According to ~~As seen from~~ all the presented scenarios, strong winds ~~in Poland~~ will be more common in Poland. Thus, the associated economic and societal consequences may also be greater ~~more significant~~ than at present. Therefore, the investigation of all the characteristics of strong winds and their impacts should be intensified in Poland. ~~Although~~ Many ~~we have quite a large number of~~ works describe~~ing~~ strong winds in Poland in the contemporary period based on~~using~~ instrumental measurements (e.g., Stopa-Boryczka 1989; Paszyński and Niedźwiedź 1991; Krawczyk 1994; Adamczyk 1996; Lorenc 1996, 2012; Araźny et al. 2007; Tarnowska 2011; Ustrnul et al. 2014; Chojnacka-Ożga and Ożga 2018; Wibig 2021 and references therein). Nevertheless, they are largely~~all~~ restricted to ~~cover some~~ periods since the 1950s; they~~and~~ are also written mainly in Polish and are therefore ~~are~~ unknown to the international scientific community.

Only ~~in~~ a few works (e.g., Bartnicki 1930; Gumiński 1952; Piasecki 1952) contain~~is~~ analyse~~i~~s of winds (including strong winds) ~~available~~ for an instrumental period before 1950, with the earliest starting in ~~from~~ the late 19th century. Notably, however, ~~On the other hand,~~ there is a complete lack of such analyses ~~works~~ for historical periods, i.e. before 1800, based on~~using~~ documentary evidence, including~~and existing~~ data from~~visual~~ regular visual observations of winds.~~ For example,~~ Such evidence nevertheless exists. Two examples of regular visual ~~the latter kind of~~ observations with a quantitative estimation of wind ~~the~~ force ~~of the wind~~ are: one using a seven-degree scale (0–6) ~~exists~~ for Wrocław (formerly~~Orig.~~ *Breslau*, source: the newspaper *Oekonomische Nachrichten der Patriotischen Gesellschaft in Schlesien*) and one using a five-degree scale (0–4) for Żagań (formerly~~Orig.~~ *Saganenses*, source: *Ephemerides Societatis Meteorologicae Palatinae*, *1783–1795*, see also Przybylak et al. 2014 and Pappert et al. 2021). These examples relate to ~~for~~ the periods 1773–81 and 1781–92, respectively. In addition, similar detailed wind observations ~~of wind~~ that ~~reporting~~ quantitatively report on ~~force of~~ wind forces ~~also~~ exist for Gdańsk~~,~~. ~~where t~~The first regular meteorological observations in the city started in 1655 and were carried out by Bűthner, a professor of mathematics, who used to note daily observations of various weather phenomena including the occurrence of strong winds. Unfortunately, his manuscript was lost, probably irretrievably. It is possible to analyse only data for some selected years within his observations covering the years 1655–1701. The 18th century ~~(the Enlightenment)~~ brought to the coast a boom in interest in observing weather conditions and in their economic impacts ~~on the economy~~. This interest culminated on the 1st of January 1739 with ~~Its climax was~~ the beginning of regular instrumental meteorological measurements in Gdańsk by Hanov~~ on the 1st of January 1739~~. Wind observations were made in 1739–72 using a nine-degree scale (0–8) ~~in 1739–72~~ (see Table 5.1 in Przybylak 2010).

Knowledge about strong wind occurrences in Europe in the pre-instrumental period is also very limited, ~~al~~though it is significantly better than in other parts of the world. For example, for the period under study (13th–16th centuries), most of the works containing the most detailed climatic analyses regarding strong winds relate ~~are available~~ mainly ~~fo~~to~~r~~ the Czech Lands (e.g., Brázdil and Dobrovolný 2000, 2001; Dobrovolný and Brázdil 2003; Brázdil et al. 2004 and references therein). The last item cited is particularly valuable for its very detailed analysis of different aspects related to strong winds for the entire last millennium based on documentary evidence. However, even ~~in~~ that~~is~~ publication~~,~~ contains only~~some~~ limited information about strong winds for the pre-1500 period~~ is available~~, precisely because of the paucity ~~directly caused by the small number~~ of existing historical sources. For central Europe, information about strong winds is also contained in monographs analysing different kinds of extremes (Pfister 1999; Glaser 2001, 2013). For the Low Countries (the coastal areas of ~~the~~ south-western Netherlands and Flanders), a valuable paper is available presenting storminess changes in the period 1390–1725 (de Kraker 2013 and references therein). It is essential to add that de Kraker~~the author~~ also graded storm events using an eight-degree scale. Similar work~~,~~ as that~~as~~ mentioned for the Low Countries~~,~~ also exists for the North Sea, the British Isles, and Northwestern Europe (Lamb 1991 and references therein). For a smaller area in this European region (the Thames estuary), there are also works published by Galloway and Potts (2007) and Galloway (2009). Finally, we should also mention the work of Orme (2015), which analysed late-Holocene storminess in Europe using various proxies.

This short review shows that, although better than for other parts of the world, our knowledge about the occurrence of strong winds in Europe~~, although better than in other parts of the world,~~ is very limited. That is why there is an urgent need to improve and widen this knowledge. The main aim of the present paper is to partly fill this gap by presenting an analysis of strong wind occurrences in Poland for the period from the late 13th century (the first record of strong wind in Poland found in historical sources) to the end of the 16th century.

2. Area, data and methods

2.1. Area

The analysis of strong winds in the studied period is conducted for the area of Poland within its contemporary bor~~ders~~undaries~~. Poland is a Central European country stretching from the Baltic Sea in the north to~~and~~ the Sudetes and Carpathian Mountains in the south (Fig. 1). To more precisely estimate the spatial changes in strong wind~~s~~ occurrences, ~~the~~ analysis was also performed ~~made~~ for six historical-geographical regions: Baltic Coast and Pomerania, Masuria and Podlasie, Greater Poland, Masovia, Silesia, and Lesser Poland (Fig. 1). Data from the contemporary period representing all the mentioned regions were collected for 12 meteorological stations – two for each region.

Fig. 1. Geographical location of Poland, main historical-geographical regions and contemporary meteorological stations (red dots) (after Ghazi et al. 2024, modified)

At present (1966–2018), the average annual wind speed calculated based on 41 stations ~~wa~~is 3.6 ms^{-1} (Wibig 2021). Excluding mountainous areas, for which we have no historical data, ~~the largest~~ average wind speeds in Poland are largest~~noted~~ in the coastal part of the Baltic Sea (4–5 ms^{-1}) and slightly~~a little~~ smaller in the central part, e.g. in Warszawa (~~Eng.~~ Warsaw), at 4.0 ms^{-1}. The weakest winds in Poland are noted in the foothills of the Sudeten and Carpathian Mountains (less than 3 ms^{-1}). ~~The spatial distribution of E~~Extreme winds are ~~is~~ slightly differently distributed than ~~compared to the~~ average winds~~ones~~. Specifically, t~~T~~he greatest extreme winds occur in the southwestern~~SW part of~~ Poland and the next greatest~~n~~ along the ~~in the coastal part of the~~ Baltic Sea coast (Wibig 2021).

2.2. Sources and data

T~~he following t~~hree types of documentary sources were used~~: handwritten and unpublished, published, and "secondary" literature (e.g., articles, monographs)~~ to search for weather notes describing the occurrence of strong winds in Poland, namely handwritten and unpublished literature, published literature, and "secondary" literature (e.g., articles, monographs). The number of ~~used~~ historical sources for ~~in~~ the study period that were used correlates strongly with their availability, which is ~~the~~ greatest ~~in~~for the more recent~~less~~ ~~distant~~ centuries. For example, for the 16th century~~,~~ we used 85 sources, wh~~il~~ereas for the 13th and 14th centuries~~,~~ we used 1 and 27 sources, respectively. For every ~~event of~~ strong wind occurrence in Poland, a detailed reference to the source(s) is given; see https://doi.org/10.18150/W6PMBQ.

~~A quality assessment of e~~Each ~~used~~ source used was quality-assessed~~conducted~~ by historians using the method that the historical sciences call~~ed~~ "source criticism" ~~in the historical sciences~~. This method involves ~~allows for~~ examining the authenticity of specific human activities (historical source) and reading their meaning (historical event) in the light of the causes and conditions of their creation in the historical process. To support the selection of appropriate sources and weather note(s) describing strong winds, three quality categories were distinguished: 1 – weak, 2 – moderate, and 3 – high~~, to choose an appropriate source and weather note(s) describing strong winds~~. The following rules were used to stratify sources by ~~according to their~~ quality; 1 – weak, if the information was derived from secondary literature rather than the original source; 2 – moderate, if the information was written centuries after the strong wind occurrence; and 3 – high, if the information was written in a source in the same period that the strong wind event occurred and provides precise information. For the analysis, we used mainly the last category of sources, which provided the mo~~be~~st valuable data.

2.2.1. Database: historical period

This work represents ~~For~~ the first time~~,~~ that a comprehensive database of strong winds related to the period before the 19th century ~~is~~has been prepared for Poland ~~by a team of climatologists and historians~~ based on all documentary evidence. Reflecting the scientific subject matter and the historical nature of the source material, it involved a team combining climatologists and historians. At the time of publication, t~~T~~he database ~~at the present stage~~ has been completed for the period ~~is finished~~ until the end of the 16th century (see https://doi.org/10.18150/W6PMBQ). It contains detailed information about the occurrence of strong winds (the location/region, time, duration, and indexation for intensity, extent, and character of damage), as well as the exact textual content of the original weather note, the name of the source, and an evaluation of the source's quality. The source information is not complete for every case of strong wind. For example, s~~S~~ometimes~~,~~ only general information is available that ~~about the~~ strong winds occurred somewhere in Poland. In such ~~a~~ cases, there is no information about the place or region; therefore, to capture this information, we introduced an additional region category called “Poland”. Similarly, so too the i~~I~~nformation provided regarding ~~available for~~ the time of ~~the~~ strong wind occurrences ~~is also~~ varies in detail~~d~~. For some occurrences, we only have information about the year; for others, we only have information about both season and year. However, in most cases, we have information about the year, month and day(s) (and often about the start and end of the phenomenon). For this reason, it is essential to remember that the presented statistics~~,~~ (e.g., frequency of occurrence of strong winds in months, seasons and years)~~,~~ are based on different numbers of cases. In Table 1, we show~~ed~~ ~~some selected~~ examples of entries to the database ~~presenting~~ that vary~~ing~~ in degree~~s~~ of detail.

Table 1. Examples of entries in the strong wind database. „Explanation of abbreviations (A, B, C, D) below the table. Entire content of the table (numbers etc.) is described in a more comprehensive manner in the database and in the section Methods”.Explanation of abbreviations (A, B, C, D) below the table. Explanations of numbers and abbreviations in columns A, B, C, and D are provided in the database.

Region	Place	Date of occurrence	Description: original	Description: translation	Source	A*	B*	C*	D*
A complete record, including details of the exact date and place of occurrence of the phenomenon and associated damage									
Baltic Coast and Pomerania	Darłowo, Western Pomerania	11–13 Jan 1558	1558 Am Dienstag nach Maria Lichtmess (8. Februar) richtete der Wind in Stralsund grossen Schaden an den Brücken der Stadt an, die alle bis auf eine entzweibrachen. Auch Schiffe und Botte wurden zerstrümmert. Es war Nordwestwind, und zwar in der Nacht, sonst wären auch wohl Menschen ertunken. Auch auf dem Lande wurde den Häusern und Obstbäumen viel Schaden zugefügt. […] Auch in Rügenwalde richteten zwei grosse Stürme, die vom 11. bis 13. Januar und am 8. Februar wüteten, viele Verheerungen an. Das Wasser soll ellenhoch an der Stadtmauer gestanden heben, in die Speicher bei der Wipper gedrungen sein und auf de Münde 18 Wohngebäude zerstört haben, deren Einwohner sich nur dadurch retteten, dass sie auf Bäume kletterten.	1558 On the Tuesday after Candlemas (February 8th), the wind in Stralsund caused great damage to the city's bridges, all except one broke in two. Ships and boats were also wrecked. It was a north-westerly wind, and at night, otherwise people would probably have drowned. Much damage was also done to houses and fruit trees in the countryside. [...] Two big storms that raged from January 11th to 13th and February 8th also caused a lot of devastation in Rügenwalde. The water is said to have risen several metres above the city walls, infiltrated the granaries near the Wipper and destroyed 18 residential buildings on the estuary, whose residents only saved themselves by climbing trees.	Besch R., Strenge Winter in alter Zeit. Witterungsgeschichtliches aus Pommern, Unser Pommerland, Jg. 8 (1923), H. 1, p. 13.	1	3	2	DB DS DU DV DF
An Iinaccurate record – only fragmentary information on date of occurrence and associated damage									
Silesia	Nysa	autumn 1578	Ein heftiger Wind beschaedigte im Spaetherbst den obern Theil des Rathhauses, das schon durch fruehere Stuerme und Gewitter gelitten.	In late autumn, a strong wind damaged the upper part of the town hall, which had already suffered from early storms and thunderstorms.	Minsberg F., Geschichtliche Darstellung der merkwuerdigsten Ereignisse in der Fuerstenthums Stadt Neisse, Neisse	1	1	1	DS
A gGeneral record –— very fragmented information on the phenomenon									
Baltic Coast and Pomerania	Koszalin	1531	Anno 1531 — War ein grosser Sturm Wind, dass der Wind den grossen Wetter Hahn vom Kirchen Thurm abwarf und haben einige dieses vor eine Vorbedeutung gehalten, dass die Catholischen sollten untergehen, so auch kurtze Zeit darauf richtig erfolget, nemlich anno 1534, da das Pabsthum im gantzen Lande abgethan worden.	Anno 1531 – There was a great storm wind that threw the great clock from the church tower, and some thought that this was an omen that the Catholics would perish, which happened a short time later, namely in 1534, when the papacy was abolished in the entire country.	Wendtland J.D., Eine Sammlung unterschiedlicher die Historia der Stadt Cöslin betrffende Sachen	3	3	2	DB

* Explanations: A - Source quality, B - Type of strong wind, C - Extent of damage of strong wind, D - Character of damage of strong wind

~~Entire content of the t~~Table content (numbers, etc.) is described in full~~a more comprehensive manner~~ in the database and in the ~~section~~ Methods section.

The entire database contains 137 records documenting the occurrence of strong winds in Poland. The earliest~~first~~ weather note reporting the presence of strong wind was ~~found~~ for the year 1283. The number of weather notes (162) is not identical to the number of occurrences of strong wind ~~cases~~ because sometimes we have more than one weather note describing the same instance~~case~~ of strong wind. The statistics of weather notes documenting the occurrence of strong winds are presented in Fig. 2. ~~The greatest number of w~~Weather notes ~~we found~~ were most numerous for ~~for~~ the 16th (85 cases) and 15th (52) centuries and most scarce ~~less~~ for the 13th century (1).~~-~~ The most abundant seasons were ~~Most of them we found for~~ autumn (63) and winter (35). The vast majority of weather notes ~~exist~~ in the documentary evidence are accounted for by just ~~for~~ two regions, namely Baltic Coast and Pomerania (93) and Silesia (39), and the fewest are from ~~least for~~ the Masuria-Podlasie and Masovia regions, with 1 and 2 notes, respectively (Fig. 2).

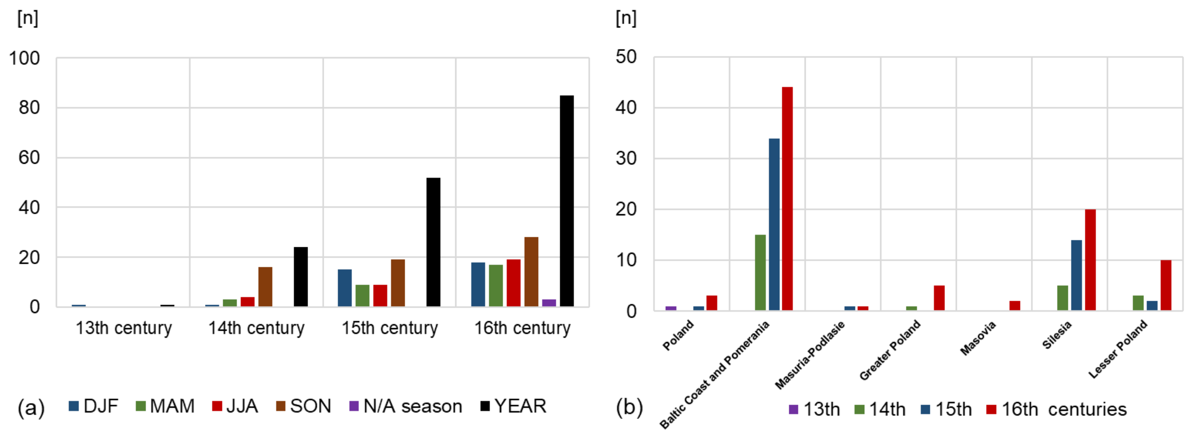

Fig. 2. Number ~~(~~[n]~~)~~ of weather notes for Poland for seasons (a) and regions (b), 1281–1600. Explanation: "N/A season" – specific season is not available (unknown)~~ season~~; the category "Poland" encompasses all notes for which ~~means that~~ the region is unknown.

~~There is strong coherence between t~~The number of available sources and the number of weather notes (i.e., ~~usually the number of~~ weather notes ~~is~~ usually exceed~~greater than the number of~~ sources in number) correlate strongly with ~~on the one hand and~~ the number of occurrences of strong winds~~ on the other~~. This pattern is similar to what we observed for flood records (Ghazi et al. 2023a, b, 2024, 2025) and drought records (Przybylak et al. 2020).

2.2.2. Database: contemporary period

Sub-daily data (every three hours) of wind speed for the period 1993–2022, for which the most homogeneous and complete series of wind values for Poland are available, were gathered for 12 meteorological stations (see Table 2, Fig. 1). As mentioned earlier, the~~y~~ stations ~~also~~ represent all six distinguished historical-geographical regions in the country. The wind data were downloaded from the website of the Institute of Meteorology and Water Management - National Research Institute (IMGW-

PIB) (https://danepubliczne.imgw.pl/). The two data types were collected as average wind speed every three hours and the highest gust of wind for 3-hour intervals.

Table 2. Geographical location of meteorological stations used in the work

No.	Name of meteorological station	H (m a.s.l.)	φ (N)	λ (E)
1.	Świnoujście	6	53°55’	14°14’
2.	Chojnice	164	53°43’	17°33’
3.	Olsztyn	133	53°46’	20°25’
4.	Suwałki	184	54°08’	22°57’
5.	Poznań	83	52°25’	16°51’
6.	Kalisz	138	51°47’	18°05’
7.	Warszawa	106	52°10’	20°58’
8.	Siedlce	152	52°11’	22°15’
9.	Wrocław	120	51°06’	16°53’
10.	Opole	165	50°38’	17°58’
11.	Kraków	237	50°05’	19°48’
12.	Rzeszów	200	50°06’	22°03’

2.3. Methods

2.3.1. Historical period

In our analysis, we distinguished four categories of strong winds, which are consistent with the proposition used by Brázdil et al. (2004, their types T1, T3–T5 in Table 6.1) for Czech Lands. ~~In addition, w~~We added one more category (tornadoes), which is treated separately:

a) Fresh and strong breeze (force according to Beaufort scale [BS] 5–7),

b) Gale (BS 8–9),

c) Storm (BS 10 and more),

d) Squall (i.e., gusty wind during a thunderstorm),

e) Tornado.

Using the final version of the database, each case of strong wind was analysed in detail. In the first stage, ~~an indexation of~~ its intensity was indexed~~done~~ by the author of ~~a~~the ~~particular~~ record being added ~~contributed~~ into the database. In the second stage, the proposed categories of wind intensities by individual contributors were discussed and finally accepted by the whole team of authors of this paper. To investigate the damage caused by strong winds, three categories of extent of damage were utilised (consistent with types E0–E2 in Brázdil et al. 2004, Table 6.2, modified):

a) E0 – no information about damage,

b) E1 – small damage, damage of lesser extent,

c) E2 – large damage, areally extensive damage.

The last category was slightly modified by us to include damage~~s~~ on the sea (destruction or sinking of ships) and losses caused by storm floods − reflecting the coastal location of Poland. Finally, if weather notes allowed, we also estimated the character of the damage~~d character~~, again using the proposition of Brázdil et al. (2004, Table 3).

Similarly as in the case of the extent of damage, we added two more categories to the list of types of ~~the~~ character of damage presented for the Czech Lands. The proposed new categories precisely describe the influence of the Baltic Sea on coastal parts. The "N/A" designation was used when the weather notes did not contain information about the character of damage. Thus, the following nine categories were distinguished to characterise damage~~s~~ and losses:

DO – casualties (lost lives),

DL – wind damage in forests,

DP – minor damage to buildings,

DB – considerable damage or destruction of buildings,

DS – uprooted fruit trees, damage to hop gardens and vineyards,

DU – damage to field crops, gardens and orchard harvests,

DV – considerable damage/destruction to vessels (including sunk), [newly added]

DJ – other damage (e.g., upturned carriages, vessels, injured persons, minor damage to property),

DF – considerable damage/destruction by storm flood or inland flood~~,~~ [newly added,]

N/A – information not available.

2.3.2. Contemporary period

Based on the ~~gathered~~ sub-daily wind data gathered, the following statistics were calculated:

1. Average daily, monthly, seasonal, and annual wind speed,
2. Highest gust of wind for every day, month, season, and year,
3. Frequency of gust winds of >17.0 ms^{-1} calculated for every month and year for each station,
4. Frequency of gust winds in the following speed intervals:

a) 8.0–17.1 ms^{-1} (BS 5-7) – quite strong, strong, and very strong wind,

b) 17.2–24.4 ms^{-1} (BS 8-9) – gale,

c) >24.4 ms^{-1} (BS 10-12) – very strong and violent storms, and hurricanes.

These three categories of strong winds listed in point 4 above, but particularly the categories described in points b and c, were used for comparison against~~with~~ the historical data. The analysis, however, is limited mainly to estimating differences and similarities in the study area's annual course and spatial distribution. We need to add that a reliable comparison of absolute values of the frequency of strong wind occurrences in both periods is impossible due to the undetectability of a probably large ~~a significant~~ number of events in the study's historical period, particularly those classified to the first category.

For many years, the IMGW-PIB did not maintain a separate database on squalls, land- and waterspouts and tornadoes, or~~and~~ the damage caused by the occurrence of such extreme events. In fact, this was a typical measure for many European national meteorological services – the duty to monitor damage caused by the aforementioned phenomena belonged to other state services. However, in 2015, the WMO decided to standard~~iz~~ise weather, water, and climate hazard information to allow more sophisticated analyses of data on the occurrence of such phenomena and the losses and damage associated with them. Then, many meteorological services, including IMGW-PIB, started to catalogue extreme weather, climate, and water phenomena and develop a dedicated database, but the material collected so far is too sparse for us to make a comprehensive analysis.

3. Results

3.1. Historical

According to Przybylak et al. (2023), in Poland, the Medieval Warm Period (MWP, recently also called the “Medieval Climate Anomaly”, MCA) started in the late 12th century and finished between the mid-14th and mid-15th centuries. Then, until the mid-16th century, the Transitional Period (TP) was distinguished (Niedźwiedź et al. 2015), followed by the Little Ice Age (LIA). Thus, our study period covers a large part of the MWP, the entire TP and the early decades of the LIA. As results from analysis conducted by Przybylak et al. (2023) and also from the database accompanying~~ied by~~ this paper, the available number of weather notes allow for a reliable estimate of the occurrence of strong winds, mainly from the 1450s onward. Two maxima of greatest storminess can be distinguished in this time: 1451–1520 and 1551–1600 (Fig. 3). The latter, however, reveals a greater number of occurrences of strong winds, especially ~~in particular~~ in the two decades~~:~~ 1571–80 (14 cases) and 1581–90 (12). In the pre-1450 period, we should underline the clear maximum of strong winds noted in the first half of the 14th century, followed by a less stormy period until the 1450s.

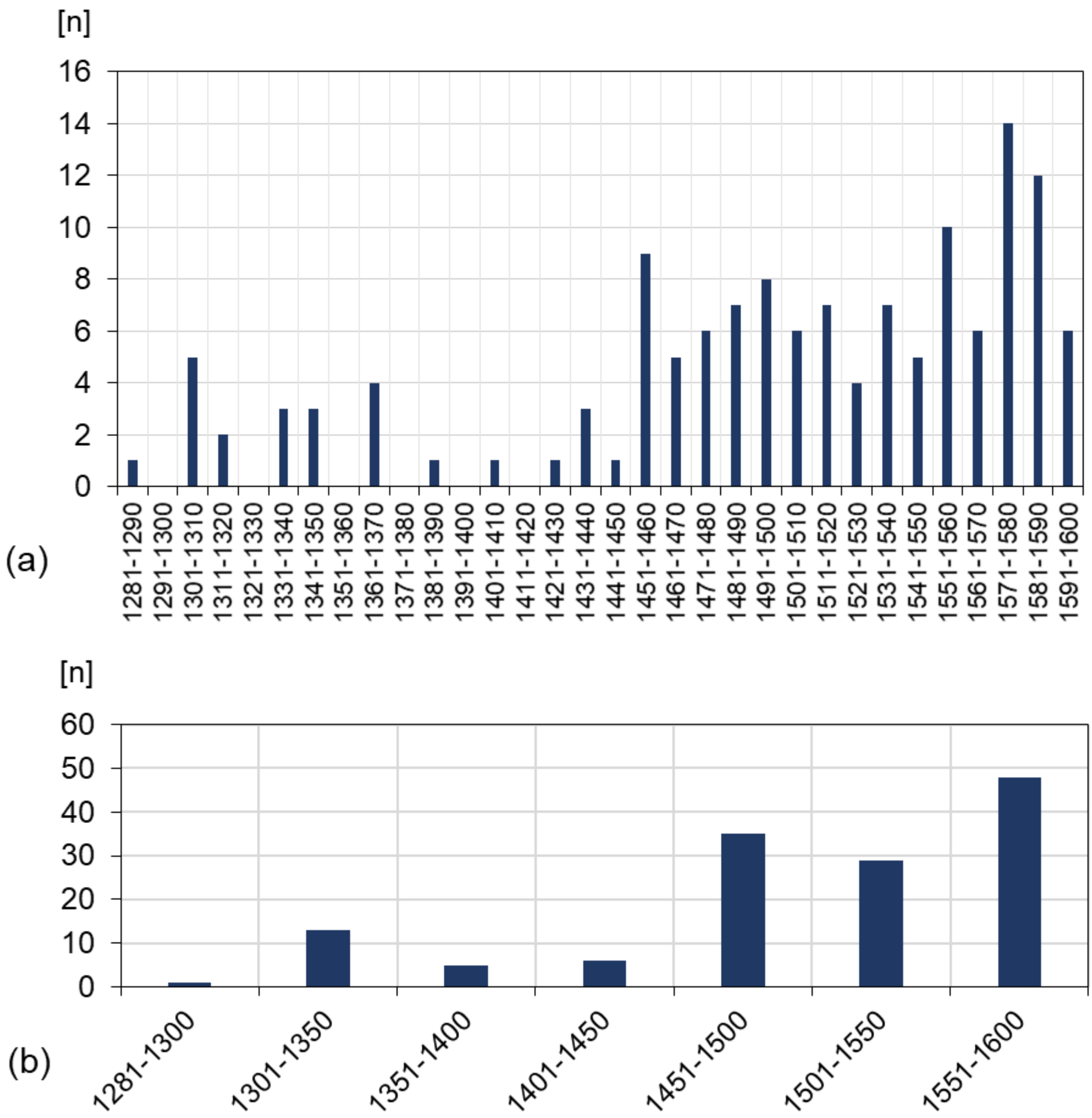

Fig. 3. Decadal (a) and 50-year (b) number (n) of occurrences [n] of all categories of strong winds of all categories in Poland, 1281–1600

Out of the six regions analysed, strong winds were noted most often in the Baltic Coast and Pomerania region (74 cases), and next most oftenthen in the Silesia region (34) (Fig. 4a, b). TQuite often, they were also registered also at moderate frequency in the Lesser Poland region (15). In other regions, their occurrence was sporadic, ranging from 1 to 6 cases (Fig. 4b). The annual cycle of strong winds occurrences can be estimated based on regions for which enough information exists. Strong winds were noted most often in autumn and in winter for Silesia and the Baltic Coast and Pomerania regions, and in summer and fall for the Lesser Poland region (Fig. 4b). August (13 cases) and March (12) were most abundant in strong wind occurrences in Poland, but the stormiest period of the year was from October to March, with at least ten cases in each month except February (Fig. 4a).

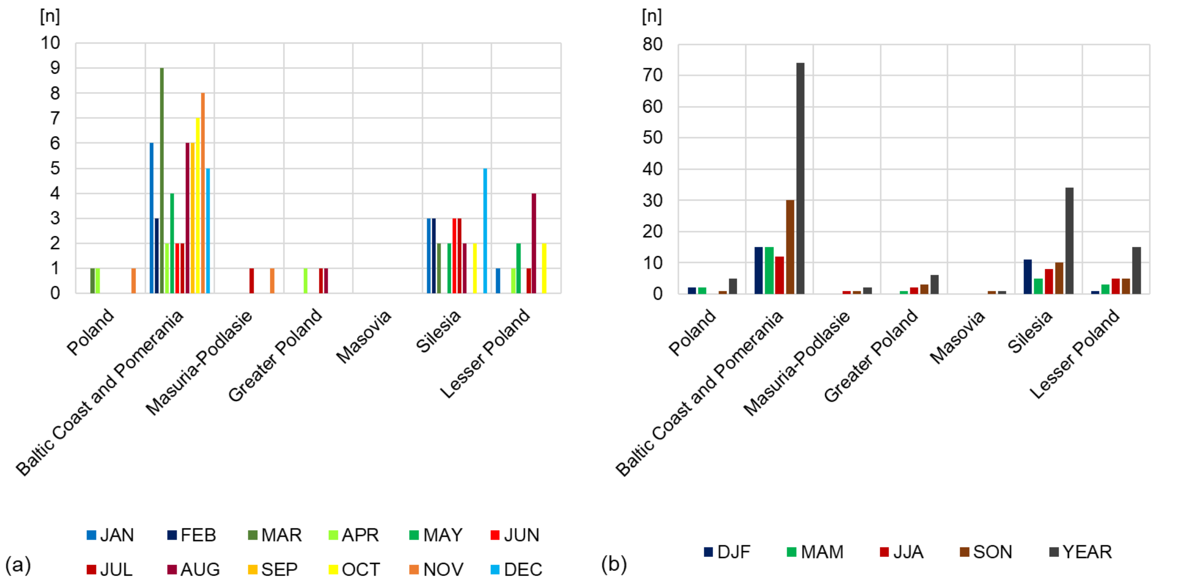

Fig. 4. Monthly (a) and seasonal (b) number ([n]) of all categories of strong winds of all categories byaccording to regions, 1281–1600.

Explanation: Please note that tThe total number of strong winds in seasons/years presented in Fig. 4b is greater than calculated based only on monthly statistics because, in some weather notes, there provide is information only about only the season or even only the year of the strong wind occurrence (see also text in 2.2.1. and Table 1).

In the entire study period (1281–1600) (Fig. 5), and also in two subperiods (1281–1500 and 1501–1600) (Fig. S1), the most frequent were storms and gales and the least frequent were fresh and strong breezes and, in particular, tornadoes (only one case). The sStorms and gales were most common in spring (mainly in March), autumn (particularly in November), and winter (mainly in December) (Fig. 5). It is worth noting a big change between the two studied two sub-periods infor August. In the period 1281–1500, in this month only storms were registered in this month, whereas for in the 16th century, all categories of strong winds were recorded (except tornadoes) (Fig. S1).

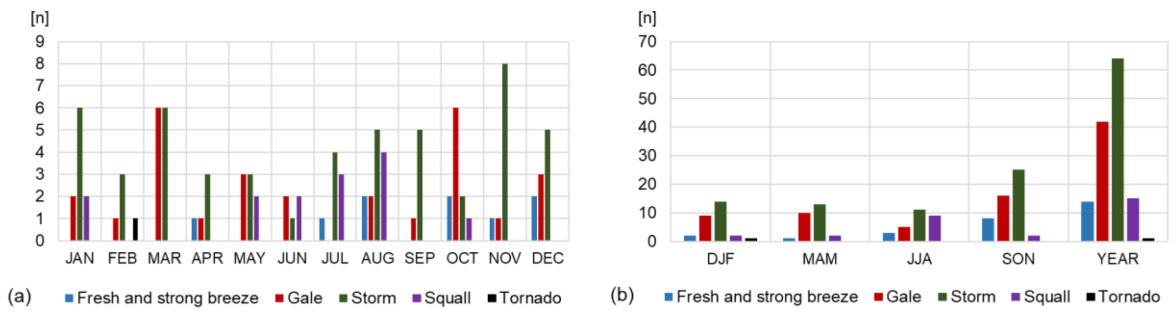

Fig. 5. Monthly (a) and seasonal (b) number (n) of occurrences [n] of different types of strong winds of different types in Poland, in the period 1281–1600

The spatial distribution of occurrences of strong winds (except tornadoes) is presented in Fig. 6 for the entire study period and in Fig. S2 for the two sub-periods. The most significant differences in spatial distribution between the two sub-periods are seen for two categories of strong winds, i.e. fresh and strong breezes and (particularly) for squalls (Fig. S2). In the latter case, the squalls were noted in the historical sources in the period 1281–1500 only for three regions: Silesia, the Baltic Coast and Pomerania, and Lesser Poland. In the 16th century, they were also found in Greater Poland. On average, for the entire study period, all categories of strong winds except squalls were most frequent in the Baltic Coast and Pomerania region (about 46–69%).~~,~~ ~~except the~~ ~~S~~Squalls ~~category, which~~ wereas noted most often in Silesia (40%). The region with the second greatest number~~amount~~ of strong winds (except squalls) was Silesia (14–27%) (Fig. 6).

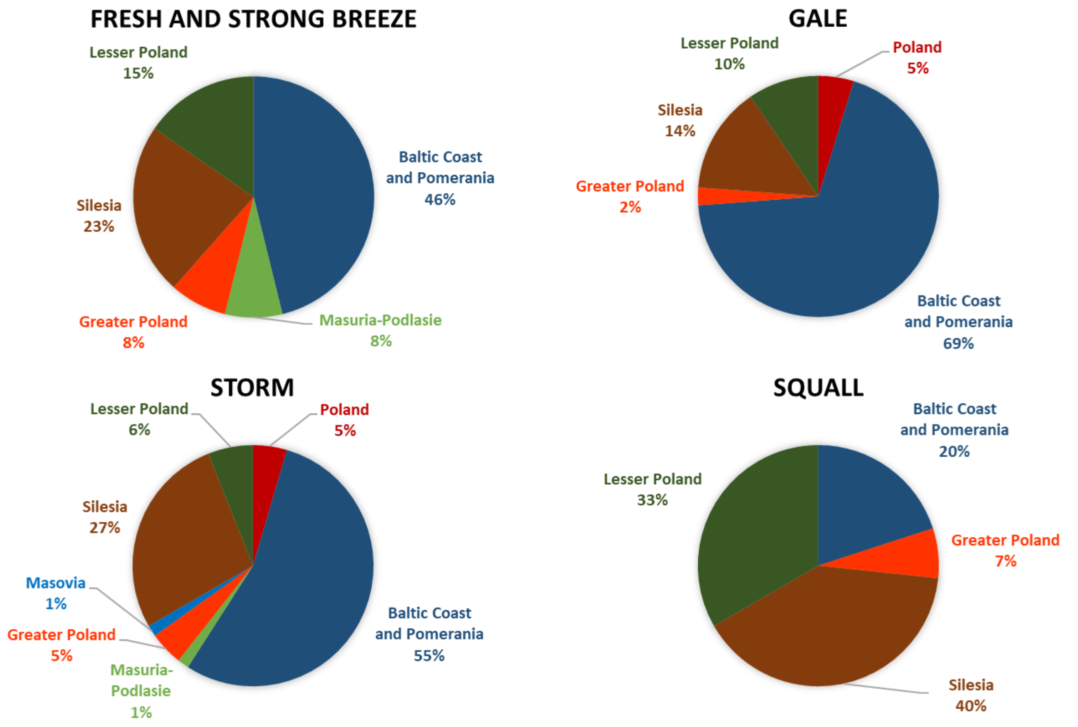

Fig. 6. Relative frequencies (%) of occurrence ~~of different types~~ of strong winds of different types (tornadoes excluded) in the studied regions of Poland, 1281–1600

The first category of strong winds (category 1) we proposed does not cause damage. The wind is chaotic in its flow, ~~causing the~~ moving ~~of~~ large tree branches and whole trees; it makes the use of umbrellas and walking against the wind difficult and causes snowstorms and blizzards during snowfall. According to Lorenc (2012), a gust wind speed above 17 ms^{-1} in climate conditions in Poland creates a threat to the population, economy, and environment. This~~It~~ means that all gales and storm winds (categories 2 and 3) classified by us based on documentary evidence have the potential to cause various kinds of damage, which we listed in the ~~m~~Methods section. However, when chroniclers mention these winds in historical materials, they rarely mention the devastating effects of their impact on the environment or humans. The absence~~lack~~ of information about ~~the~~ destruction probably reflects a lack of damage~~ates to the~~ in the immediate vicinity~~area~~ of their residence and does not rule out ~~possible~~ destruction having occurred elsewhere~~in other locations~~. Squalls, however, differ importantly from gales and storms, being ~~In the case of squall winds,~~ highly ~~due to their~~ localised ~~ly limited character~~ phenomena rather than the effect of m~~i~~acrocirculation. Accordingly, ~~and when there is~~ an absence~~no~~ of information about damage~~,~~ from a reported squall should be treated as strong evidence of a lack of damage ~~we cannot say the same, as in the case of gales and storms that are the effect of macrocirculation~~. The available weather notes describing the occurrence of strong winds allow us to classify damage according to its scale~~,~~ – small or large (see Fig. 7 and Fig. S3)~~ –~~.

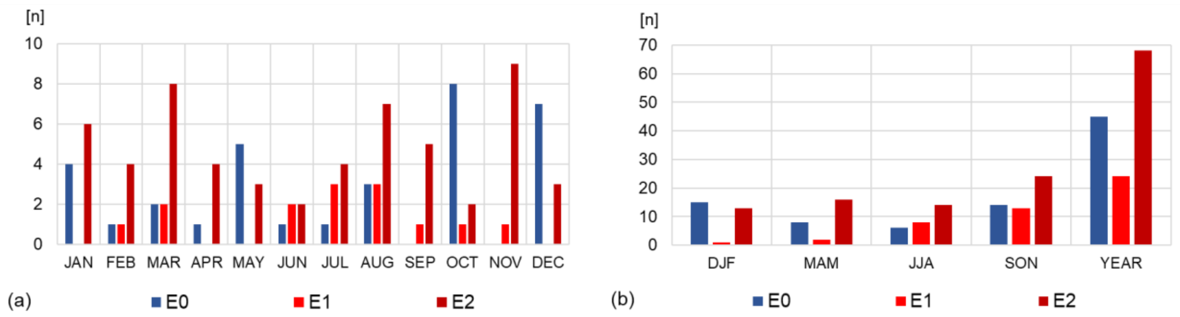

Fig. 7. Monthly (a) and seasonal (b) number ~~(n)~~ of occurrences [n] of strong winds in Poland, according to ~~the~~ extent of damage, 1281–1600

It is interesting to note that, for the study period, the E2 category ~~E2~~ of damage is most frequent, followed by ~~then~~ category E0, i.e. no information about damage. Category E2 prevails in all seasons (excluding winter) and in most of the months, excluding~~ept~~ December, October, June and May (Fig. 7). It is also worth noting that the frequency of category E0 ~~in~~ relative~~on~~ to E2 decreases from medieval times to the 16th century (see Fig. S3). This means that the 16th-century chroniclers were more precise than their predecessors in ~~inclined to~~ describing~~e~~ weather events~~,~~ (in this case, strong winds)~~,~~ and their effects ~~more precisely than their predecessors~~.

In the entire dataset, the largest share of ~~of~~reports of strong winds causing damage (categories E1 and E2) but containing ~~and in which there is~~ no information on damage (category E0) was ~~found, in line with expectations,~~ for the Baltic Coast and Pomerania (39–67%) and Silesia (16–35%). This was in line with expectations,~~;~~ these regions having yielded ~~for which~~ the most abundant datasets ~~exist~~ (Fig. 8). A similar situation is noted for both sub-periods, with the ~~one~~ only exception being the category E1 in the period 1281–1500 (Fig. S4). This category was a little more frequently reported for Lesser Poland (29%) and Silesia (29%) than for the Baltic Coast and Pomerania (28%) region.

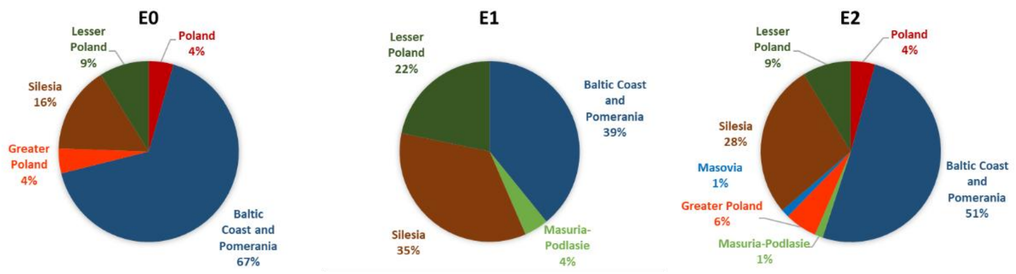

Fig. 8. Relative frequencies (%) of occurrences of strong wind~~s~~ in studied regions of Poland for different types of damage, 1281–1600~~.~~

For explanations of abbreviations, see Methods section.

The character of damage caused by the strong winds is shown in Fig. 9 for the entire study period and in Fig. S5 for the two analysed sub-periods. The two figures are roughly similar.

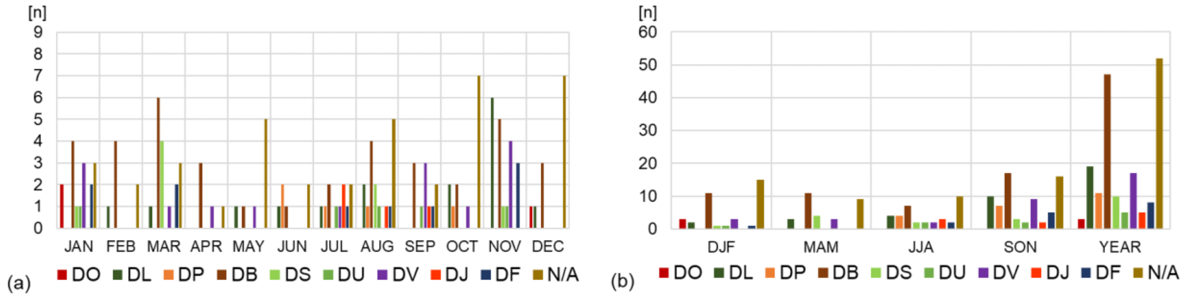

Fig. 9. Monthly (a)~~,~~ and seasonal and annual (b) number ~~(~~[n]~~)~~ of strong winds in Poland for which information about the character of damage exists (DO, DL, DP, DB, DS., DU, DV, DJ and DF) or does not exist (N/A), 1281–1600. ~~.~~

For explanations of abbreviations, see the Methods section.

On average, 28.7% of weather notes did not contain information about the damage caused by the strong winds (Fig. 9). Fewer such cases occurred in the 16th century (24.5%) than in medieval times (34.2%) (Fig. S5). O~~ut o~~f all distinguished damage categories, DB was the most frequent (26.0%), with ~~a~~its maximum occurring in the 16th century (28.4%). The next ~~following~~ most frequent categories of damage noted in the study period were DL (10.5%) and DV (9.4%), while the least frequent was DO (1.7%) (Fig. 9). About 60% of all mentions of damage~~s mentioned~~ in the weather notes were found for the cold half-year, but particularly for autumn (39.2%). The smallest number of weather notes about damages was noted for spring (16.6%). In the annual course, damage~~s~~ caused by strong winds in Poland was reported~~occurred~~ most often in November (20 cases, 14.0%), March and August (17, 11.9%), and least ~~with the smallest~~ often~~frequency~~ in April (5, 3.5%) (Fig. 9a).

The spatial distribution of distinguished categories of damage made by strong winds ~~in Poland~~ in the analysed regions of Poland is shown in Fig. 10 for 1281–1600 and in Fig. S6 for the two sub-periods~~:~~ 1281–1500 and 1501–1600. The analysis reveals that the most frequently noted categories of damage in Poland (DB, DL) were also present in all analysed regions, with a maximum in Silesia and Baltic Coast and Pomerania regions. ~~For t~~These two regions~~,~~ also exhibited the highest numbers of information items about other categories of damages caused by strong winds ~~was also the highest,~~ (except for the DJ category, which was noted most often for the Lesser Poland region) (Fig. 10). The greatest number of weather notes describing strong winds not informing about damages was found for the Baltic Coast and Pomerania region (67%) and then for the Silesia region (17%). The spatial distribution of reports of damages caused by strong winds presented for the entire study period was more similar to that noted in the 16th century than to that noted in the medieval period (cf. Figs 10 and S6).

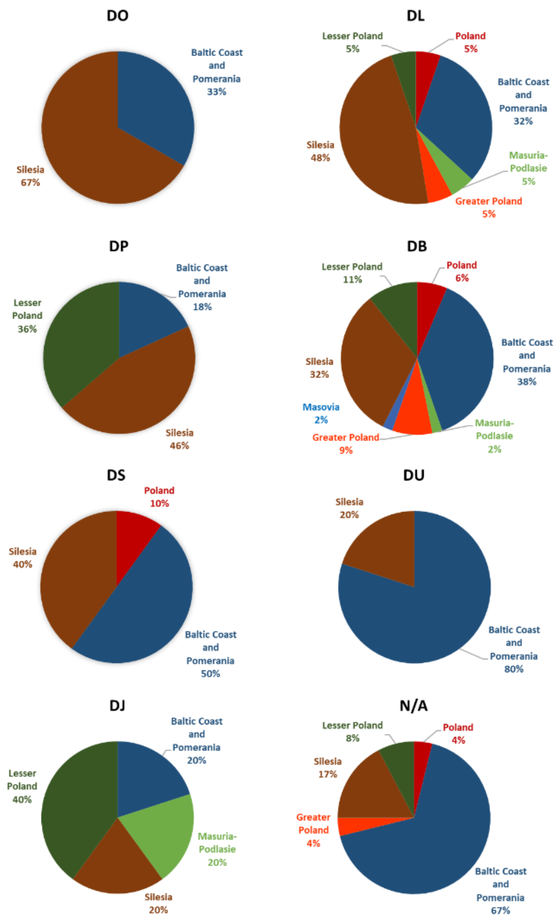

Fig. 10. The rRelative frequencies (%) of damage categories estimated for particular regions in Poland, in the period 1281–1600.

Explanations: Two categories (DV and DF) are not shown because they can occur only in the Baltic Coast and Pomerania region. For explanations of abbreviations, see the Methods section.

strong winds not informing about damages was found for the Baltic Coast and Pomerania region (67%) and then for the Silesia region (17%). The spatial distribution of damages caused by strong winds presented for the entire study period was more similar to that noted in the 16th century than that in the medieval period (cf. Figs 10 and S6).

3.2. Contemporary period

There follows a~~A~~ short analysis of the present occurrence of strong winds in Poland. This will support a ~~can be helpful for some~~ comparison against ~~purposes wi~~the historical results, mainly with regard to the spatial distribution and course ~~run~~ of ~~the~~ frequencies~~y~~ of strong winds in the annual cycle. It will a~~A~~lso~~,~~ be helpful to know~~ledge~~ ~~can be~~ about the ~~the values of the~~ greatest speeds of strong winds currently being observed ~~presently~~ in Poland.

The annual number of gust winds (>17 ms^{-1}~~–~~) in Poland in 1993–2022~~,~~ that~~which~~ can potentially cause damage~~,~~ usually does not exceed 20 cases (Fig. 11). However, ~~but~~ the 30-year average values are <10 at~~in~~ all stations ~~are <10,~~ except Rzeszów. The probability of occurrence of that kind of strong wind was ~~the~~ smallest in Masovia and Silesia (fewer than 16 cases). There are significant fluctuations in the annual number of gust winds from year to year, sometimes exceeding 10 cases. Also, the number of thus-defined strong winds has decreased since about 2010, particularly in the Masovia and Silesia regions.

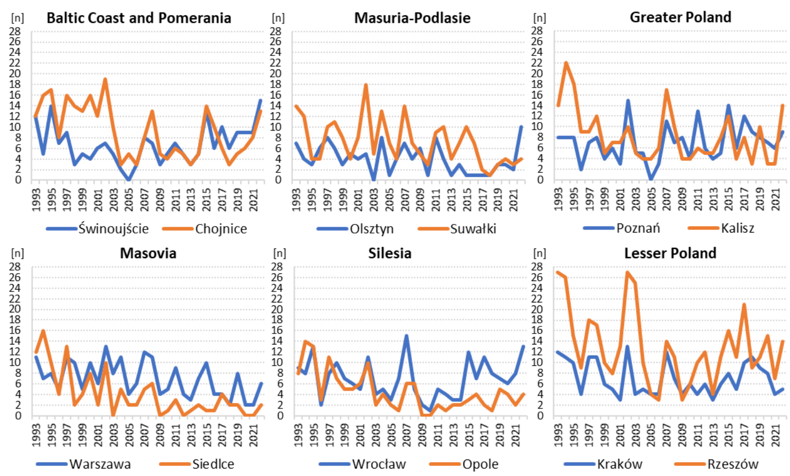

Fig. 11. Year-to-year course of the annual number ~~(~~[n]~~)~~ of gust winds of >17 ms^{-1} at selected stations representing six studied regions in Poland, 1993–2022

In the annual cycle, the average 30-year (1993–2022) monthly number of strong winds >17 ms^{-1} oscillated from below 0.4 in the warm half-year to more than 0.8–1.0 in Jan–Mar (Fig. 12). The first half of the cold season (Oct–Dec) has significantly fewer gust winds, rarely exceeding 0.8 cases in one month, except December in some stations.

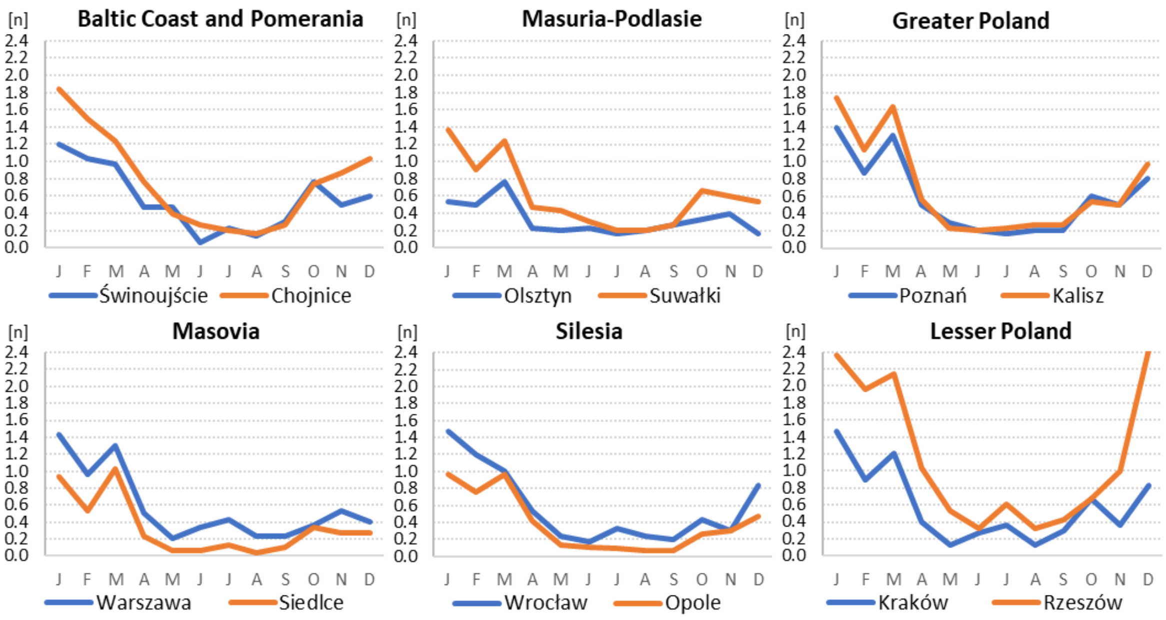

Fig. 12. Annual course based on the average monthly number {[n]} of gust winds of >17 ms^{-1} at selected stations representing the six studied regions in Poland, 1993–2022

In the studied period, the highest gust wind speed ~~in the majority of analysed stations~~ exceeded 30 ms^{-1} at the majority of analysed stations. It occurred most often in winter or summer months (Fig. 13). On the other hand, the lowest speeds, oscillating between 16 and 22 ms^{-1}, were measured only in the period from May to September. The highest strong wind speed (35 ms^{-1}) in Poland was measured in Wrocław (SW Poland) on July 23, 2017, while the lowest (18 ms^{-1}) was recorded in a few places (Świnoujście – June 18, 2012 and June 28, 2014; Siedlce – May 4, 1996 and May 3, 1997; Opole – August 28, 1994 and August 19, 2022). Gust winds of >17 ms^{-1} stratified into gales (8–9 BS) and storms (10 BS and more) do not show any important changes in the annual courses compared to annual courses based on all cases of strong winds >17 ms^{-1} (see Fig. 12 and Fig. S7). The main reason for this is the rare occurrence of storms in Poland. In the study period, storms were not observed in most of the years, and the maximum of them in one year reached three cases (not shown).

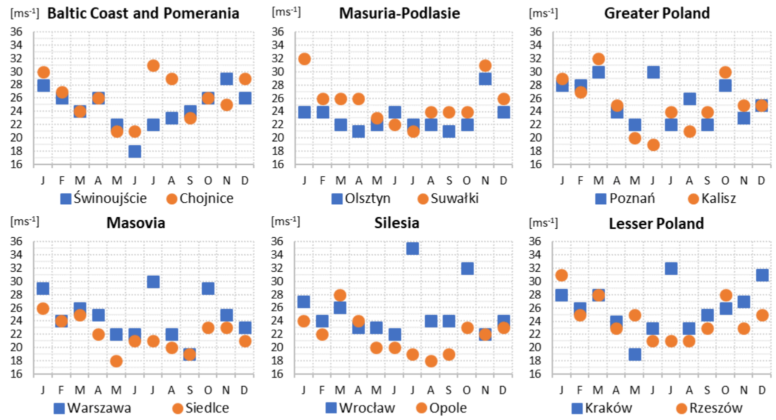

Fig. 13. Maximum monthly wind gust speeds (ms^{-1}) at selected stations in Poland representing the six studied regions, ~~in~~ 1993–2022

4. Discussion

Five categories of strong winds were distinguished in our database (https://doi.org/10.18150/W6PMBQ, see also Methods) and analysed in the present paper. The first three categories of strong winds (fresh and strong breezes, gales, and storms) in central Europe are connected with vigorous moving cyclones born near Iceland, and in particular with a passing cold front. Cyclonic activity is at its~~the~~ greatest in the cold half-year (October to March), and therefore, these categories of strong winds dominate in this part of the year. On the other hand, the last two categories (squalls and tornadoes) are typical for the warm half-year (April to September) and are related to thunderstorm clouds (Cumulonimbus) developing within ~~the~~ thermal turbulence occurring either in a single~~the one~~ air mass (sometimes called "isolated" or "local" thunderstorms) or within the zone of a passing cold front (multiple-cell storms, squall lines, or a supercell). As a result~~,~~ (especially for category 4 – squalls), the duration of these kinds of strong winds is short, and their spatial coverage is local~~, in particular in the case of the first category~~.

Recognising the types of strong winds based on the available descriptions of this weather element in historical sources is not always easy and unambiguous, due to the scarcity of information. Another difficulty in analysing changes in the frequency of occurrence of the phenomenon is the increasing number of sources as we move closer towards the present day. According to Brázdil et al. (2004), this is the main limiting factor for ~~the~~a climatological analysis of ~~investigating~~ changes in the occurrence of strong wind in historical times. Moreover, in older periods, attention was focused more on describing only extremely strong winds (see Fig. 5) and mostly those that caused serious material or human damage. On the other hand, at present, the occurrence of ~~strong winds of the 1st~~ category-1 strong winds (fresh and strong breezes) in all meteorological stations in Poland is about ten times more frequent than the sum of categories 2 and 3 (see Fig. S5). For this reason, time analysis of occurrences of most extreme wind categories seems most reliable, not only for the study of historical periods but also when we compare their frequencies in historical and contemporary periods. It is also not possible, based on the documentary evidence, to reconstruct strong winds for ~~the~~ individual places in Poland as ~~it~~ is normally done for ~~in the case of~~ systematic instrumental measurements. Therefore, all series of strong wind frequencies are presented here for the entire area of Poland.

The lower gust wind speed threshold, which was assumed for central Europe as potentially dangerous for the destruction of buildings, forests, gardens, etc.~~,~~ is 17 ms^{-1} (Brázdil and Dobrovolny 2001; Lorenc 2012). Therefore, it is possible to approximately compare the frequency of strong winds above this threshold obtained from contemporary instrumental observations with the summed frequency of historical winds assigned to categories 2–5. For ~~In the case of~~ category 4 (squall), only those cases for which damage was noted (8 cases) were taken. The results of the comparative analyses presented below must, however, be limited only to similarities and differences in the annual cycle and spatial distribution in the study area. A reliable comparison of absolute values of the frequency of strong winds is impossible due to the undetectability of probably numerous ~~a significant number of~~ events in the study's historical period. This will only be possible for some isolated periods for which daily weather records are available. For Poland, such series exist for selected periods in the 17th and 18th centuries (for details see Introduction) and will be the subject of our analysis in a separate article.

In Poland, the most frequent winds are from the western sector (from SW to NW), in particular from the NW direction, while the least frequent winds are from the sector from N to ESE (see Fig. 15.4 in Wibig 2021). According to investigations by~~of~~ Lorenc (2012), about 80% of strong winds of ≥17 ms^{-1} in Poland in the period 1991–2005 were associated with the occurrence of NWc circulation ~~type~~ (i.e., wind blowing from NW direction within cyclonic pattern) according to Lityński's (1969) classification. Also, ~~the~~ hurricane winds (>33 ms^{-1}) in Poland in the period 1971–2005 were mostly associated with NWc type and then with Wc type. As a result, both the greatest measured winds and the greatest frequency of them are characteristic for north-western, western and south-western Poland, in particular in the cold half-year (Lorenc 2012; Wibig 2021, see also Figs 10–12). Such spatial distribution of strong winds was also found for the study's historical period when the greatest frequencies were noted in the Baltic Coast and Pomerania and Silesia regions (see Fig. 4). In the Greater Poland region (central western Poland) this was not found, due to the ~~a very small~~ number of historical sources available being very small (see Fig. 2). It is worth also noting some similarity in annual cycles of strong wind occurrences in the historical and modern periods. In both periods, the greatest frequencies occurred in the cold half-year, and the lowest in summer. However, in the historical time, a greater frequency was observed in autumn than in winter, i.e. opposite to the modern time (cf. Figs 4 and 11). This can probably be interpreted as reflecting~~can be related to~~ ~~greater~~ the climate having been more continental~~ity of climate~~ in medieval times than it is now~~at present~~ (see Sadowski 1991; Przybylak 2016; Przybylak et al. 2023). The winters were clearly colder than today (see Przybylak et al. 2005, 2023) and were connected with negative values of the NAO (Przybylak et al. 2003). Such a circulation pattern in the Atlantic-European sector allowed more frequent advection of cold air masses to Poland from eastern and northern sectors within anticyclones coming from eastern Asia (Siberia) and the Arctic. On the other hand, positive NAO conditions often bring high storminess in Europe (Ommel 2015 and references therein).

~~From the mid-15th century, a~~The decadal number of sources (and thus~~, as a consequence,~~ the number of occurrences of strong winds) for the mid-15th century is~~seems~~ similar ~~comparable~~ to that for ~~with those found in~~ the 16th century (see Fig. 3). Therefore, for this period, it is possible to make a comparison with analogical investigations undertaken ~~made~~ for other parts of Europe. Unfortunately, the comparison is limited to only a few existing works presenting results, in particular for the 15th century (see Introduction). For Czech Lands, Brázdil et al. (2004) found only 24 cases of strong winds for this century, i.e. 40% fewer than we found for Poland (40). But the main difference is that, in the Czech Lands, the strong winds were connected with thunderstorms (convective storms), wh~~il~~ereas in Poland~~,~~ this category was noted only five times. A better and more reliable comparison is possible with ~~a~~the number of storm events occurring in the coastal area of Belgium and the south-west Netherlands. This number was provided by ~~De~~de Kraker (2013) using town accounts reporting on ~~informing about~~ the repairing of ~~the~~ damage to~~f~~ dikes, piers, groynes, and quay walls after storms. In the second half of the 15th century, in both areas (Poland and western Europe), the greatest numbers of strong winds were noted in the first and the last decades (cf. Graph 1 in ~~De~~de Kraker 2013 and Fig. 3 in this study). Similarly for the 16th century~~Also~~, a good agreement is found~~is seen in the 16th century~~. Specifically, b~~B~~oth in Poland and in coastal areas of Belgium and the Netherlands, strong winds were more common in the second half of the century than in the first. This finding is further confirmed by r~~R~~esults presented for the Czech Republic (Brázdil et al. 2004) and Germany (Glaser 2013) ~~also confirm this finding~~. In terms of ~~The greatest~~ differences in decadal totals among countries, the greatest is noted for the second decade of the 16th century, which was exceptionally rich in storm events in Belgium and the Netherlands in comparison to neighbouring decades. In Poland, the maximum ~~in this decade~~ is ~~also~~ seen in this decade as well, but it is not as great in absolute terms as the maximum~~in the case of~~ in Belgium and the Netherlands. On the other hand, in the Czech Republic, this maximum is not seen. In Germany, there was a steady increase in the number of strong winds until about 1575 and then a decrease by the end of the century. Such a tendency in the occurrence of strong winds in the last three decades of the 16th century was also noted in Poland (see Fig. 3). In both countries, the maximum of strong winds in the 16th century occurred in the 1570s.

Comparison of potential periods with strong winds (usually reconstructions of high/low storminess periods) against~~with~~ results obtained using other ~~different~~ natural proxies (e.g., sand dune development, windblown sand in peat bogs or marshes, etc.) allows for only ~~for~~ a very rough comparison. For example, ~~the~~ reconstructions have found the onset of ~~of the start of~~ a period of the great storminess ~~period~~ in the mid-16th century ~~(also seen in the documentary evidence from Poland, Czech Republic, Germany, and Belgium and the Netherlands) was found~~ for Scandinavia (De Jong et al. 2006; Clemmensen et al. 2008)~~,~~, the north-west Mediterranean (Sabatier et al. 2012) and Portugal (Costas et al. 2012). Importantly, this stormy period is also seen in the documentary evidence from Poland, Czech Republic, Germany, and Belgium and the Netherlands.

5. Conclusions and final remarks

There are numerous~~quite a few~~ mentions of strong winds in historical periods, but, as ~~can be seen from~~ the ~~presented~~ literature review shows, ~~this important element~~ there has been only very limited study~~i~~ of this important element ~~ed~~ in a long-term perspective ~~to only a small extent~~. This lack of research is ~~One of the most important reasons for this is~~ certainly due in large part to the great dynamics over time and spatial variability of the occurrence of strong winds in Europe, including Poland. These dynamics are ~~is last feature is~~ especially great for ~~important in the case of~~ convective storms, which are local in nature. Additionally, t~~T~~hese dynamics~~mentioned features of the occurrence of strong winds~~, together with the great diversity in ~~significantly changing~~ numbers of available historical sources~~,~~ (~~-~~especially before 1500), significantly hamper the proper recognition of this important element of the climate based on documentary evidence. As a result, reliable examination of changes in the occurrence of strong winds compared to the modern period is extremely difficult and limited, but it is nevertheless ~~still~~ possible.

Having stated ~~Taking into account~~ the preceding~~following~~ reservations, we present below the most important research results:

- ~~A reliable estimate of s~~Some characteristics of the occurrence of strong winds in Poland can be reliably estimated ~~seems possible~~ for ~~since~~ the mid-15th century onwards.~~;~~

- The highest numbers of strong winds occurred in the second half of the 15th century and (even more so) ~~particularly~~ in the second half of the 16th century. The decade with the greatest ~~most significant~~ number of strong winds was 1571–80 (14) (see Fig. 3).~~;~~

- For each season, the greatest numbers of strong winds were~~as~~ found for the Baltic Coast and Pomerania region, followed by ~~and then for~~ Silesia and then Lesser Poland (Fig. 4)~~;~~.

- Strong winds were noted most often in autumn and winter in Silesia and in the Baltic Coast and Pomerania regions (the two regions for which there is enough information to estimate the annual cycle), and in summer in the Lesser Poland region (Fig. 4b). August (13 cases) and March (12) were most abundant in strong wind occurrences in Poland, but the stormiest period of the year was from October to March, with at least ten cases in each month except February (Fig. 4a).~~;~~

- In the entire study period (1281–1600), and also in two subperiods (1281–1500 and 1501–1600), the most frequent were storms and gales and the least frequent were fresh and strong breezes (Fig. 5, Fig. S1), which were most common in autumn and in winter.~~;~~

- All categories of strong winds in the study period occurred with the greatest frequency in the Baltic Coast and Pomerania region, except squalls, which were most frequently noted in the Silesia region (Fig. 6). In the 16th century, however, squalls were most common in Lesser Poland (Fig. S2).~~;~~

- Damage of category E2 (areally extensive~~ded~~ damage) was more than three times more frequent than category E1 (~~damage of~~ lesser~~er~~ extensive damage~~t~~). About one third of the notes mentioned strong wind occurrence but~~and~~ did not contain information about the damage. The greatest and most frequent damage was noted for~~in~~ autumn (37.2%) and the smallest for~~in~~ spring (19.0%) (Fig. 7, Fig. S3).~~;~~

- O~~ut o~~f all distinguished categories of damage, DB (26.0%) and DL (10.5%) were most frequent, while the least frequent was DO (1.7%) (Fig. 9). About 60% of all ~~damages~~ mentions of damage~~ed~~ in the weather notes were found for the cold half-year, but particularly for autumn (39.2%). The analysis reveals that the most frequently noted categories of damage in Poland (DB, DL) were also noted in all analysed regions, with a maximum in Silesia and Baltic Coast and Pomerania regions.~~;~~

- ~~Spatial distribution of s~~Strong winds estimated for the studied historical period based on documentary evidence are similar to those of today in terms of spatial distribution, i.e. the greatest frequencies of strong wind occurrence in the Baltic Coast and Pomerania and Silesia regions (see Fig. 4) and in terms of distribution within ~~as well as~~ the annual cycle (Fig. 5) ~~are similar as today~~ (Lorenc 2012; Wibig 2021; see also Figs 10–12). These facts seem to confirm, to some extent, the reliability of the results obtained for the historical period.~~;~~

- The time changes in occurrences of strong winds in Poland in the period since the mid-15th century were found, using documentary evidence, to correspond well with those for other European countries (e.g., Czech Republic, Germany, and the Netherlands and Belgium)~~ using documentary evidence~~. Other proxy data used to reconstruct storminess changes in some parts of Europe in historical times (e.g., in Scandinavia, Portugal, and the south-west Mediterranean) also show~~s~~ a good correspondence with the presented results for central and western Europe.~~;~~

- The "fresh and strong breeze" category of strong winds ~~in historical times~~ was rarely noted by chroniclers in historical ~~, because~~times because winds of this category did not cause any material or human damage. On the other hand, this category of strong winds delimited using measurement data is, at present, about ten times more frequent than gales and storms taken together. Therefore, the sporadic records of this category of strong winds ~~recorded sporadically~~ during the historical period cannot be reliably used as a basis for ~~reliably~~ comparison against~~ed to~~ current conditions. Such comparison~~This~~ will probably only be possible for isolated periods for which daily weather observations are available.

The creation of databases on extreme phenomena and events in historical periods, as in this case of strong winds, is extremely important in order to be able to recognise the natural range of their temporal changes and to learn about spatial variability and their changes over time. The high variability, both in time and space, of the extreme phenomenon under study requires that significant temporal and spatial coverage be obtained for the correct and reliable identification of its features in Europe from a long-term perspective. The review of the state of knowledge on this subject made in this article clearly proves that it is very limited and, therefore, urgently requires intensified work, especially using documentary evidence, which is undoubtedly the most accurate source of information for the last millennium.

The same method of processing data on strong winds available in the documentary evidence of individual European and other non-European countries would significantly facilitate the recognition of this extreme phenomenon over a larger area and the comparison of results. For these reasons, in this article, we applied the proposal given in the work of Brázdil et al. (2004), which we only slightly modified to reflect the Baltic Sea's influence on the coastal part of Poland.

Competing interests. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements. The research work of RP, JF, PO and PW was supported by grant funded by the National Science Centre, Poland No 2020/37/B/ST10/00710). The work of AA was supported by funds from IDUB Research Group *Weather and Climate: Reconstructions and Future Scenarios*. We would like to thank Dr Babak Ghazi for preparing Fig. 1.

Author contributions. ~~Rajmund Przybylak~~RP: Conceptualisation, Methodology, Investigation, Data collection and selection, Database construction, Formal analysis, Literature review, Interpretation of results, Writing – original draft, Writing – review & editing, Funding acquisition, Project administration. ~~Andrzej Araźny~~AA: Conceptualisation, Methodology, Investigation, Data collection and selection, Formal analysis, Validation, Visualisation, Interpretation of results. ~~Janusz Filipiak~~JF**:** Conceptualisation, Methodology, Investigation, Data collection and selection, Database construction, Validation, Interpretation of results, Writing – original draft. ~~Piotr Oliński~~PO**:** Conceptualisation, Investigation, Data collection and selection, Database construction, Visualisation, Validation. ~~Przemysław Wyszyński~~PW: Software, Visualisation, Validation, Formal analysis. ~~Artur Szwaba~~AS**:** Database construction.

Financial support. The work was supported by the National Science Centre, Poland, project No. 2020/37/B/ST10/00710.

Data availability. Datasets for this research were derived from the following public domain resources:

1. Repository for Open Data (RepOD), Nicolaus Copernicus University Centre for Climate Change Research collection, as cited in Przybylak et al. (2025),
2. The Institute of Meteorology and Water Management (IMGW-PIB) website: https://danepubliczne.imgw.pl/

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