Climatic Change (2026) 179:248
https://doi.org/10.1007/s10584-026-04339-6

Reconstruction of extreme temperature events in medieval Poland (1001–1500 CE) from documentary evidence

Sajad Akbari Moghaddam Sani[1] · **Rajmund Przybylak**[1,3] · **Piotr Oliński**[2,3]

Received: 3 June 2026 / Accepted: 6 November 2026
© The Author(s) 2026

Abstract
Understanding the frequency, intensity, and societal impacts of extreme weather is essential for reconstructing past climate variability, yet systematic documentary-based reconstructions remain remarkably limited for medieval Poland. To address this gap in pre-instrumental data, this study reconstructs extreme temperature-related weather and climate events in Poland between 1001 and 1500 CE utilizing historical documentary evidence. A total of 299 extreme events were verified and synthesized from 452 primary weather notes. To mitigate duplication, overlapping accounts of the same anomaly were cross-referenced and merged. Validated events were categorized into severe frost; cold waves; river, lake, and sea ice events; snow and snowstorms; and heat and warm waves, with each classified by intensity, duration, and source reliability. The findings reveal a clear dominance of cold-related extremes, particularly severe frost and cold waves. A significant increase in the frequency and clustering of these events is observed during the fourteenth and fifteenth centuries, peaking specifically in the 1440s and 1450s. This pattern aligns with the broader Central European transition into the early phase of the Little Ice Age. Spatial analysis indicates a concentration of recorded events in the Baltic Coast, Pomerania, and Silesia, though this partly reflects uneven source preservation in prominent historical economic centers. Furthermore, cold extremes heavily disrupted transportation and caused environmental stress, whereas heat waves were strongly associated with agricultural damage. By integrating documentary evidence with quantitative analysis, this database provides crucial insights into historical climate variability and climate-society interactions.

Keywords Historical climatology · Extreme temperature events · Medieval Poland · Documentary evidence

✉ Sajad Akbari Moghaddam Sani
sajad.akbari@doktorant.umk.pl

[1] Department of Meteorology and Climatology, Faculty of Earth Sciences and Spatial Management, Nicolaus Copernicus University, Toruń, Poland

[2] Department of Medieval History and Auxiliary Sciences of History, Faculty of Historical Sciences, Nicolaus Copernicus University, Toruń, Poland

[3] Centre for Climate Change Research, Nicolaus Copernicus University, Toruń, Poland

Published online: 15 November 2026

1 Introduction

Extreme weather and climate events have played a crucial role in shaping human societies throughout history. Episodes of severe cold, prolonged frost, heavy snowfall, and extreme heat have repeatedly affected agricultural production, infrastructure, transportation, and public health, often triggering food shortages, economic disruption, and demographic crises. Understanding the frequency, intensity, and societal impacts of such extremes is therefore essential for reconstructing past climate variability and for placing recent anthropogenic climate change within a long-term historical context (Le Roy Ladurie 1971; Glaser and Riemann 2009; Field et al. 2012; Pfister and Wanner 2021; IPCC 2021, 2023).

The medieval centuries were characterized by substantial climatic variability across Europe. The period includes the Medieval Climate Anomaly (MCA), generally associated with relatively warm conditions in many regions, followed by the onset of the Little Ice Age (LIA), which brought increased climatic variability and more frequent cold extremes in parts of Europe. Numerous studies have documented severe winters, prolonged freezing of rivers and seas, and episodic summer heat extremes during this transitional period (Luterbacher et al. 2004; Büntgen et al. 2011; Camenisch et al. 2016; Przybylak et al. 2023). In northern and central Europe, documentary records frequently describe the freezing of major rivers and even parts of the Baltic Sea, indicating particularly severe winter conditions during certain decades. These events were often associated with large-scale atmospheric circulation anomalies, including persistent blocking patterns and variations in the North Atlantic Oscillation (Przybylak et al. 2003; Luterbacher et al. 2004; Trouet et al. 2009). Extreme climatic events during the medieval period also had profound societal consequences. Severe winters and prolonged cold spells could damage winter crops, cause livestock mortality, and disrupt transportation networks by freezing rivers and harbours (Kahle and Glaser 2025). Conversely, intense summer heat and drought could reduce crop yields and exacerbate food shortages. Documentary evidence from many parts of Europe links such climatic extremes with famine episodes, price fluctuations, and social instability (Jordan 1996; Slavin 2012; Campbell 2016; Bauch and Schenk, 2019; Oliński 2022).

Because instrumental meteorological observations in Europe extend back only a few centuries—with systematic measurements in Poland beginning primarily in the late eighteenth and nineteenth centuries—knowledge of earlier climate conditions relies on indirect evidence (Przybylak 2016; Opała-Owczarek et al. 2021 and references therein). In Poland, the vast majority of climatological literature is strictly limited to the period of instrumental observations, usually covering the last 200 to 250 years (Limanówka 2001; Przybylak et al. 2004; Lorenc 2005; Niedźwiedź 2010; Przybylak 2010 and references therein). To assess pre-instrumental climates, researchers have utilized natural proxies to establish low-frequency climate trends in Poland. These include dendroclimatological reconstructions using oak and pine chronologies (Krąpiec 1998; Przybylak et al. 2005; Zielski et al. 2010; Koprowski et al. 2012; Opała and Mendecki 2014; Opała-Owczarek et al. 2021) and analyses of lake sediments (Tylmann et al. 2013; Hernández-Almeida et al. 2015, 2017). However, such proxies frequently reflect average seasonal or annual climatic conditions and may not fully capture short-lived but high-impact weather extremes.

In contrast, documentary evidence preserved in chronicles, administrative records, correspondence, and early weather diaries often contains detailed descriptions of exceptional weather conditions and their societal consequences. Over the past several decades, histori-

cal climatology has developed standardized approaches for transforming these qualitative documentary descriptions into quantitative climate information (Bell and Ogilvie 1978; Pfister 1992; Brázdil et al. 2005, 2010; Nash et al. 2021). Such methods have been successfully applied in numerous European regions, including Poland (Przybylak et al. 2005, 2010, 2023; Przybylak 2011), the Czech Lands (Brázdil et al. 2019), Switzerland and the Alpine region (Camenisch et al. 2016), Germany (Glaser 2013), Hungary (Kiss 2019), and broader Central European syntheses (Dobrovolný et al. 2010), demonstrating the considerable value of documentary evidence for reconstructing pre-instrumental climate variability.

Despite these continental advances, systematic documentary-based reconstructions of extreme temperature events remain remarkably limited for Poland, particularly for the medieval period (11th–15th centuries). While historical documentary-based research in Poland has expanded recently, it has predominantly favored hydrological extremes, particularly the reconstruction of historical floods, ice-jams and droughts (Girguś et al. 1965; Grześ 1991; Cyberski et al. 2006; Pawłowski and Gorączko 2014; Przybylak et al. 2020; Ghazi et al. 2023). More recent work has synthesized proxy and documentary evidence to reassess general climate variability in Poland over the last millennium (Przybylak et al. 2023). Nevertheless, comprehensive, dedicated reconstructions of extreme temperature events—such as severe frosts, river and sea ice formation, snowstorms, cold waves, and heat waves—are still scarce. Most existing Polish lists of historical temperature extremes are highly fragmentary, rarely provide standardized intensity criteria, and often fail to cross-reference original historical archives with modern source-criticism methods. This represents a critical gap, as Poland possesses a rich repository of underutilized medieval documentary sources uniquely positioned to provide high-resolution data on historical climate extremes.

Reconstructing historical climate extremes in Poland is particularly important because the country lies in a transitional climatic zone between maritime and continental influences. Variability in atmospheric circulation patterns can produce pronounced temperature fluctuations, including severe winter cold events associated with continental and Arctic air masses, as well as summer heat waves linked to persistent anticyclonic circulation over Central and Eastern Europe (Niedźwiedź 1992; Luterbacher et al. 2010). These climatic characteristics make Poland a highly sensitive region for studying historical extreme temperature events and their spatial variability.

To address this research gap, the present study provides a systematic reconstruction of extreme temperature events in Poland during the period 1001–1500 CE based on documentary evidence. Using a comprehensive database compiled from historical sources, the study analyzes five categories of extreme events: (1) severe frost, (2) cold waves, (3) river, lake, and sea ice events, (4) snow and snowstorms, and (5) heat and warm waves. Each event is classified according to intensity, duration, and reliability of documentation. The main objectives of this study are threefold: first, to reconstruct the temporal variability of extreme temperature events in Poland during the medieval period; second, to examine their spatial distribution across different regions of the country using GIS-based analysis; and third, to evaluate the societal and environmental impacts of these events as recorded in historical sources. By integrating documentary evidence with quantitative analysis, this study contributes to a better understanding of climate variability in Central Europe prior to the instrumental period and provides new insights into climate–society interactions during the medieval centuries.

2 Study area

Poland is located in Central Europe between approximately 49° and 55° N latitude and 14° and 24° E longitude and covers an area of 312,679 km². The country lies within a transitional climatic zone between the maritime climate of Western Europe and the more continental climate of Eastern Europe (Szymanowski et al. 2013). This geographical position results in substantial variability in atmospheric circulation patterns and temperature conditions, making the region particularly sensitive to both cold and warm climate extremes (Araźny et al. 2021). The geographical location and major physical features of Poland, as well as historical regions for which analysis was conducted, are shown in Figure 1.

The topography of Poland is dominated by extensive lowland plains across the central and northern parts of the country, while uplands and mountain ranges occur in the south. The southern border is formed by the Carpathian and the Sudetes Mountains (1000–2500 m a.s.l.), which locally influence regional climate conditions through orographic effects. Northern Poland borders the Baltic Sea, which moderates winter temperatures along the coast but can also contribute to sea ice formation during particularly severe winters.

The hydrographic network of Poland is dominated by two major river systems: the Vistula (orig. Wisła) and the Oder (orig. Odra), both flowing northward into the Baltic Sea. Numerous historical documentary records describe the freezing of these rivers during severe winter conditions as well as the formation of ice cover on lakes and coastal waters.

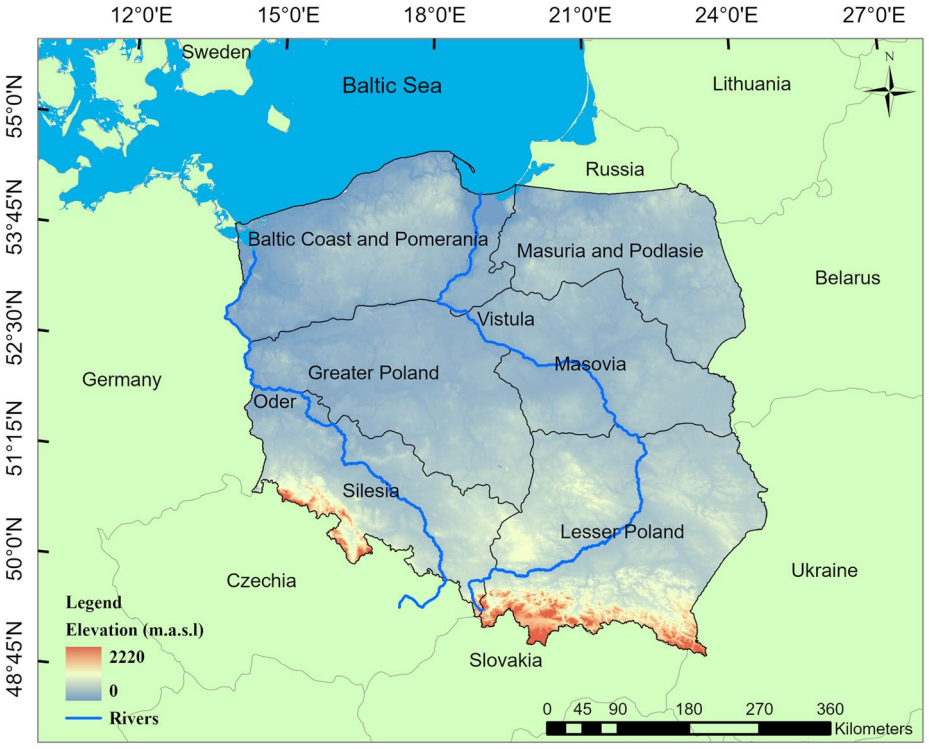


Fig. 1 Topographical map of Poland showing the study area, elevation gradients, major river systems (Vistula and Oder), and the boundaries of the six historical regions used for spatial classification

Such cryospheric phenomena provide valuable indicators of extreme cold events in historical climate reconstructions.

Climatically, Poland experiences relatively cold winters and moderately warm summers. In the period 1951–2018, mean winter temperatures range from approximately 0 °C along the Baltic coast and western border to below −3 °C in northeastern and mountainous regions, while mean summer temperatures range from around 15.5 °C in northern areas to more than 17.5 °C in south-western Poland (see Fig. 11.1 in Ustrnul et al. 2021). Winter conditions are strongly influenced by the advection of continental or Arctic air masses from eastern and northern Europe and Asia, which can produce prolonged frost periods and severe cold waves. Conversely, summer heat waves are typically associated with persistent high-pressure systems that transport warm air from southern or southeastern Europe, and sometimes even from North Africa.

Due to its transitional climatic setting, major river systems, and relatively rich historical documentation, Poland represents an important region for investigating historical temperature extremes in Central Europe. These geographical and climatic characteristics make the region particularly suitable for reconstructing past extreme weather and climate events prior to the instrumental period.

3 Data and methods

This study reconstructs extreme temperature events in Poland during the period 1001–1500 CE using documentary evidence derived from historical sources. The methodological framework follows established approaches in historical climatology that transform qualitative historical descriptions into structured datasets suitable for quantitative climate analysis (Pfister 1992; Brázdil et al. 2005, 2010; Nash et al. 2021).

3.1 Documentary sources

The reconstruction is based on a wide range of historical documentary sources describing weather conditions and their societal impacts. These include medieval chronicles, administrative records, ecclesiastical documents, historical compilations, and later scholarly syntheses of historical climate information. The core dataset primarily relies on newly undertaken archival research alongside foundational historical compilations of meteorological events derived from original texts. Most notable among these are the extensive collections of excerpts assembled by Girguś et al. (1965), as well as classic European catalogues such as Weikinn (1958). While these early compilations are foundational, they have been subject to valid methodological criticism regarding dating errors, ‘phantom’ events, and the uncritical reproduction of secondary sources (Alexandre 1987). To mitigate these known issues, entries extracted from older catalogues were never accepted at face value; rather, they served strictly as heuristic finding aids. Through collaboration with the historical expert on our author team, every flagged event was systematically traced back to its original primary narrative text to verify accurate dating, validate contextual translations, and eliminate duplicated accounts. These validated primary sources encompass key medieval texts and regional chronicles, including Caspar Weinreich’s Danziger Chronik (covering 1461–1496, published 1870), Johannes Lindau’s Geschichte des dreizehnjährigen Krieges (covering

1454–1466, published 1870), Simon Grunau's Preußische Chronik (compiled early 16th century, published 1889), and Sigismund Rosicz's Chronica (covering 1051–1470, published 1883).

Such sources frequently describe exceptional weather conditions, including severe winters, prolonged frost, frozen rivers and seas, heavy snowfall, and episodes of extreme summer heat. Documentary sources represent an important form of climate proxy data for the pre-instrumental period because they often describe short-lived but high-impact weather extremes that may not be fully captured by natural proxy records. However, to mitigate inherent biases related to selective reporting, regional differences in documentation, and variations in archival preservation, all documentary evidence was critically evaluated and cross-checked against independent accounts where possible to minimize duplication and potential misinterpretation of events (Bell and Ogilvie 1978; Brázdil et al. 2005).

To provide a comprehensive overview of the documentary foundation of this study without exceeding length limitations, a detailed inventory of the primary sources—including their archival origins, spatial and temporal coverage, and critical reliability assessments—is provided in the Electronic Supplemental Material (Supplementary Table S1). Generally, source availability increases significantly in the fourteenth and fifteenth centuries, with regional concentrations in prominent economic and administrative centers such as Gdańsk, Toruń, and Wrocław, reflecting the uneven spatial preservation of medieval Polish records.

3.2 Data extraction and database construction

Information on extreme weather and climate events was systematically extracted from historical documentary sources through detailed qualitative analysis of the texts. Each source was carefully examined for descriptions indicating exceptional or unusual weather conditions, particularly those associated with significant environmental or societal impacts. Only records describing clearly abnormal climatic phenomena—such as severe frost, unusually cold winters, frozen rivers, heavy snowfall, or extreme summer heat—were included in the dataset, while general seasonal descriptions without evidence of exceptional conditions were excluded.

It is important to clarify that unlike early modern weather diaries, which provide continuous daily meteorological observations, medieval Polish narrative sources are inherently discontinuous. Consequently, 'normal' weather conditions were implicitly defined by their absence in the historical record. Chroniclers selectively documented meteorological phenomena only when they deviated significantly enough from the norm to cause notable societal, economic, or environmental disruptions. Therefore, the filtering of baseline climate variability was largely performed by the original observers themselves.

During the data extraction process, a critical distinction was made between individual weather notes derived from the documentary sources and the verified extreme events that ultimately populate the database. Because significant climatic anomalies were frequently observed and recorded by multiple independent chroniclers, a single extreme event often generated several overlapping weather notes across different archives. To avoid duplicating data, all associated notes for a given anomaly were cross-referenced, and the event was logged only once based on the most reliable and detailed source description. In cases where independent historical sources provided conflicting reports of an event's intensity, the evaluation defaulted to the most contemporary account and was cross-validated against recorded

socio-economic or environmental impacts. Consequently, the total volume of raw weather notes significantly exceeds the final count of validated events. Figure 2 illustrates the spatiotemporal distribution of these raw weather notes by century, categorized by season and region, demonstrating the extensive primary source foundation of 452 weather notes from which the final 299 extreme events were synthesized.

For each identified event, the relevant information was entered into a structured database. Each event record includes the year of occurrence, the category of the event, geographic location (when available), intensity level, reported impacts, and the original documentary source. When possible, the approximate timing within the year and the duration of the event were also recorded. Event intensity was evaluated based on the severity of descriptions contained in the historical sources, combined with recorded societal and environmental impacts (e.g., crop damage, disruption of transportation due to frozen rivers, famine, or livestock losses). The database is available in the NCU repository (https://doi.org/10.18150/UHHLCN).

To mitigate the risk of subjective linguistic exaggeration by historical observers, the evaluation process did not rely solely on descriptive adjectives (e.g., 'terrible' or 'unprecedented' cold). Instead, the intensity classifications were strictly anchored to objective physical and socioeconomic proxies. For instance, severe winter extremes were verified through corroborating physical evidence such as the freezing of major navigable trade routes (the Vistula and Oder rivers), the formation of ice bridges on the Baltic Sea, or documented widespread mortality. This impact-driven approach effectively neutralizes narrative exaggeration and grounds the classifications in physical reality.

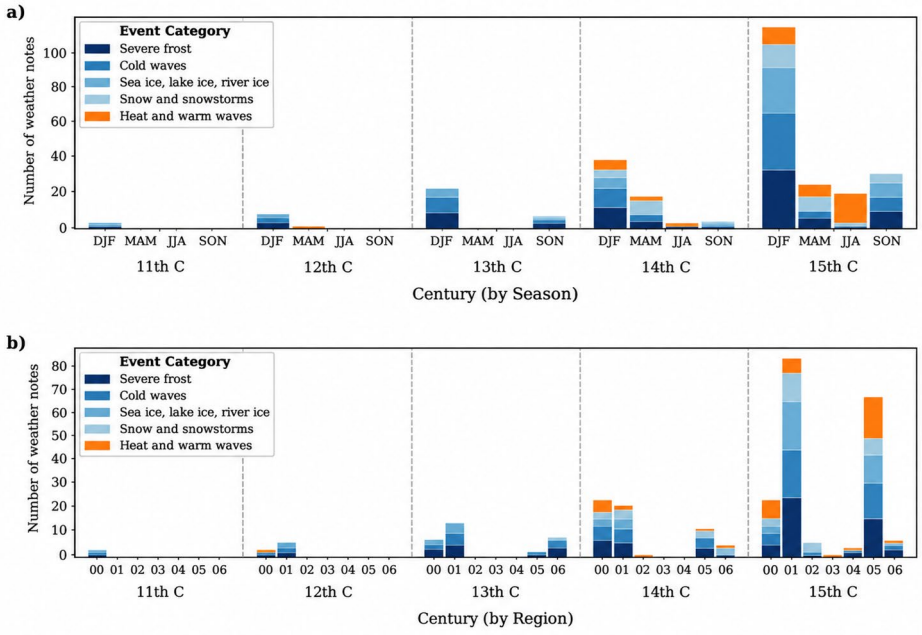


Fig. 2 Distribution of extreme weather notes extracted from documentary sources (1001–1500 CE). (**a**) Seasonal distribution (DJF: Winter, MAM: Spring, JJA: Summer, SON: Autumn). (**b**) Regional distribution. Region codes: 00–Poland (general/unspecified); 01–Baltic Coast and Pomerania; 02–Masuria-Podlasie; 03–Greater Poland; 04–Masovia; 05–Silesia; 06–Lesser Poland

3.3 Event classification

To facilitate systematic analysis, the documented events were classified into five categories representing different types of temperature-related extremes. These categories adhere to standard classifications utilized in historical climatology (Nash et al. 2021) and are defined as follows: (1) severe frost; (2) cold waves; (3) river, lake, and sea ice events; (4) snow and snowstorms; and (5) heat and warm waves. The explicit duration and intensity criteria (ranging from Level 1 [Mild-Moderate] to Level 3 [Very Strong/Catastrophic]) for these categories are summarized in Table 1.

Severe frost refers to prolonged periods of intense freezing conditions affecting soil, vegetation, and infrastructure. Cold waves represent short-term episodes of exceptionally low temperatures typically occurring during winter. River, lake, and sea ice events include reports describing the freezing of major rivers, lakes, and coastal waters such as the Baltic Sea. Snow and snowstorms encompass descriptions of heavy snowfall, blizzards, or

Table 1 Ordinal intensity classification criteria for extreme temperature-related events

Event type	Duration criteria	Intensity level 1 (Mild–Moderate)	Intensity level 2 (Strong)	Intensity level 3 (Very strong/Catastrophic)
Severe frost	Short: 1–5 days Long: 6–10 days Very long: >10 days	Frost mentioned without major impacts	Strong frost with agricultural or infrastructure impacts	Mortality of humans or animals, major rivers or Baltic Sea frozen, exceptional adjectives
Sea, river and lake Ice	Short: <1 month Long: 1–2 months Very long: >2 months	Thin ice or freezing of small rivers	Thick ice on rivers or lakes, limited transport	Baltic Sea or major rivers frozen, people/vehicles crossing ice
Snow and snowstorm	Short: <1 month Long: 1–2 months Very long: >2 months	Light/moderate snowfall	Heavy snowfall with disruptions	Collapsed structures, tree damage, animal mortality, exceptional descriptions
Cold wave	Short: 3–10 days Long: 11–20 days Very long: >20 days	Short cold spell	Prolonged cold spell with impacts	Very long cold waves with societal or environmental crises
Heat and warm wave	Short: 3–10 days Long: 11–20 days Very long: >20 days	Warm spell	Prolonged heat with agricultural stress	Drought, famine, mortality, extreme heat descriptions

unusually persistent snow cover. Heat and warm waves refer to periods of abnormally high summer temperatures, often associated with drought conditions or crop stress. This classification framework allows winter-related cryospheric phenomena to be distinguished from summer heat extremes and facilitates comparative analysis of different types of extreme events across time and space.

We acknowledge that societal vulnerability varies through time and space independently of climate. To ensure that high-intensity classifications (Levels 2 and 3) reflect true meteorological severity rather than merely social sensitivity, socio-economic impacts (such as famine or economic disruption) were strictly cross-evaluated alongside physical meteorological indicators that are independent of human vulnerability, such as the freezing of the Baltic Sea, the complete freezing of major rivers, or prolonged snow cover. Crucially, societal impacts were only factored into the intensity classification if the primary documentary source explicitly established a direct causal link between the specific weather extreme (e.g., severe frost) and the resulting consequence (e.g., crop failure leading to famine). In cases where documentary descriptions were vague, ambiguous, or lacked corroborating physical evidence, the events were conservatively assigned the lowest intensity class (Level 1). Furthermore, to ensure reproducibility and minimize subjective bias, an inter-observer consistency check was conducted. The extracted descriptions and their proposed classifications were independently evaluated by the interdisciplinary author team (comprising climatologists and a medieval historian). Discrepancies in intensity assignment were resolved through consensus, prioritizing contemporary accounts and physical environmental proxies.

To illustrate how qualitative historical descriptions from primary sources were systematically translated into these ordinal intensity levels, Table 2 presents the full classification progression (Levels 1–3) for severe frost, alongside a Level 3 (Very strong/Catastrophic) example for heat and warm waves. This highlights the methodological contrast between evaluating winter cryospheric phenomena and warm-season agricultural extremes.

3.4 Reliability assessment

Because documentary evidence varies in precision and credibility, each event record was evaluated using a reliability classification procedure commonly applied in historical climatology (Pfister et al. 1999). Crucially, the extraction, evaluation, and validation of the historical weather notes, mainly from the original Latin and German texts were conducted in collaboration with historians to ensure accurate contextual and linguistic interpretation. The reliability of individual reports was assessed based on the proximity of the source to the event (contemporary vs. retrospective), the level of detail provided, and the availability of corroborating information from independent sources.

To systematically evaluate the dataset, events were classified into three reliability tiers. High-confidence events are those corroborated by multiple independent contemporary sources or direct contemporary observations with detailed physical descriptions. Moderate-confidence events rely on reliable but second-hand accounts or possess partial independent corroboration. Low-confidence events depend on a single, often non-contemporary source with limited descriptive detail. This tiered approach ensures transparency regarding the documentary foundation of the reconstruction.

Table 2 Examples of documentary descriptions illustrating the intensity classification scale for winter extremes and a representative catastrophic summer extreme

Event Category and Intensity Level	Year	Description	Translation	Source
Severe Frost Level 1 (Moderate)	1431	War ein grosses Winter, Frost und Schnee	It was a great winter, with frost and snow	Archiwum Państwowe w Gdańsku, 492/250 - Johann Jacob Convent, Chronick der Stadt Elbing von 1237 bis 1454, p. 519.
Severe Frost Level 2 (Strong)	1458	Item feria tertia ante Thome apostoli nocte sequenti fluvius. Odere congelatus fuit nive et glacie per totum, stetique glacies usque ad feriam tertiam post letare, ubi per ventum tempestatis glacies dissoluta fuit	On the Tuesday before St. Thomas the Apostle's feast, the Oder River froze entirely with snow and ice. The ice lasted until Tuesday after Laetare Sunday, when it was broken up by stormy winds	Sigismundi Rosiczii Chronica, in: Scriptores rerum Silesiacarum, Breslau 1883, V. 12, p. 73; Pol N., Jahrbücher der Stadt Breslau, ed. J. G. Büsching, V. 2, Breslau 1815, p. 20.
Severe Frost Level 3 (Catastrophic)	1322	1322 reisete man auf der gefrornen Ostsee bis Luebeck und in entlegene Laender mit Schlitten, und waren hie und da fuer die Reisenden Herbergen auf dem Eise angeleget. In Litthauen und an den preussischen Grenzen erfroren viele Menschen und alle fruchttragende Baeume.	In 1322, people traveled across the frozen sea to Lübeck and distant lands on sleds, and shelters were established here and there on the ice. In Lithuania and near the Prussian borders, many people froze to death, and all fruit-bearing trees perished.	Bock F. S., Versuch einer wirtschaftlichen Naturgeschichte, V. 1, Dessau 1782, p. 691.
Heat and Warm Waves Level 3 (Catastrophic)	1473	R. 1473 w Polszczę, w Prusiech, wielka suchość panowała, thak iż Niemen … u Ragnety na koniu brodem przejeżdżano, u Torunia także Wisłę y pieszki przechodzono: A zboża, iarzyny, lasy, na koniec y bory z wielkiey suszy poschły y wygorzały: ogniem też Miast wiele wygorzało	In the year 1473, there was a great drought in Poland and Prussia, so much so that the Niemen River… could be crossed on horseback at Ragnety, and the Vistula River near Toruń could be crossed on foot. Crops, vegetables, forests, and even woods dried up and burned due to the severe drought, and many cities were also destroyed by fire.	Murinius, Marcin. Kronika albo krótkie z kronik rozmaitych zebranie, spraw potocznych ziemie z dawna sławney pruskiey przez … Wyd. K.W. Wójcicki. Warszawa 1844. [Biblioteka starożytna pisarzy polskich, IV]. p. 185.

3.5 Statistical and spatial analysis

Temporal variability in the occurrence of extreme temperature events was examined through descriptive statistical analyses of the compiled database. Annual and decadal frequencies of each event category were calculated to identify long-term patterns, clustering, and fluctuations during the medieval period. Because documentary records represent discrete event occurrences rather than continuous meteorological measurements, the analysis focuses on

changes in event frequency rather than absolute temperature anomalies. All statistical data processing, cross-tabulation of societal and environmental consequences, and the generation of graphical visualizations (including stacked bar charts and spatiotemporal heatmaps) were conducted using the Python programming language within the PyCharm 2025.2.3 integrated development environment.

Where geographical information was available, event locations were georeferenced and aggregated into six predefined historical-geographical regions. The base topographical map and regional boundaries (Fig. 1) were generated and rendered using ArcMap 10.8.2. This integrated spatial and statistical approach established distinct regional concentrations and vulnerability profiles for cold-season versus warm-season extremes across the study area.

4 Results

A total of 299 extreme temperature events were identified in Poland during the period 1001–1500 CE based on documentary evidence (Fig. 3 and for more details see also the database https://doi.org/10.18150/UHHLCN). The distribution across event categories ind icates a clear dominance of cold-related extremes. Severe frost (87 events) and cold waves (75 events) represent the largest proportions of the dataset, followed by river, lake, and sea ice events (51), heat and warm waves (45), and snow and snowstorms (41). This structure highlights the predominance of winter-related climatic hazards in the reconstructed series.

The temporal evolution of all recorded events reveals a pronounced increase in frequency toward the late medieval period, particularly after the thirteenth century (Fig. 3). While the early centuries (eleventh and twelfth) are characterized by sporadic and isolated records, a substantial intensification is evident during the fourteenth and especially the fifteenth centuries, when both the frequency and clustering of events increase markedly. Within this trend of intensification, the annual data highlights significant spikes emerging in the mid-to-late fourteenth century (e.g., 1353 and 1378), while the absolute single-year maximum occurs later, in 1443, reaching a peak of 16 events. While the figure encompasses all event types, these exceptional years and the broader decadal clustering observed in the 1440s and 1450s were overwhelmingly driven by the four cold-related categories, marking periods of intensely cold and frosty conditions (Figs. 3 and 4).

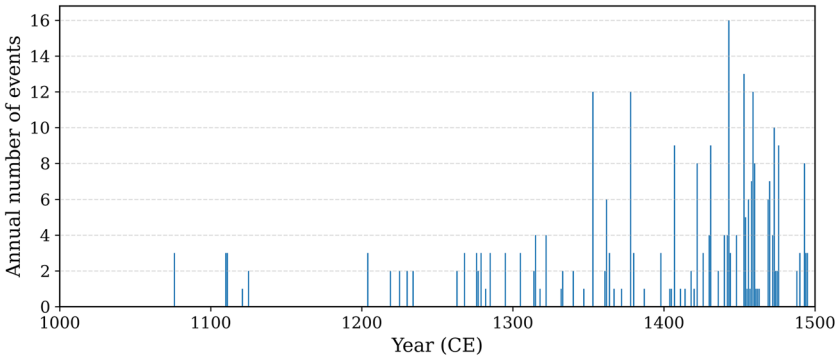


Fig. 3 Annual frequency of all documented extreme temperature-related events in Poland (1001–1500 CE)

To ensure that the observed late-medieval surge in climate extremes is not exclusively an artifact of increasing literacy, urban expansion, and improved chronicle preservation, it is necessary to contextualize these frequencies against historical source availability. While the overall volume of surviving administrative and narrative texts indeed multiplies during the fourteenth and, most notably, the fifteenth centuries, the clustering of cold-related extremes does not scale linearly with source production. Specifically, the intense concentration of severe winter events in the 1440s and 1450s disproportionately exceeds the background rate of documentary expansion. This non-linear increase suggests that while improved data coverage plays a role, the observed spikes represent a genuine climatic signal reflecting heightened variability.

To better understand the drivers of this intensification, the temporal distribution was aggregated by decade and categorized by event type (Fig. 4). The decadal stacked bar chart reveals that the late-medieval surge in climate extremes was not uniform across all phenomena but was overwhelmingly driven by severe frosts, cold waves, and ice-related events. Notable early clustering of these cold extremes began in the mid-to-late fourteenth century, particularly during the 1350s and 1370s. Subsequently, the mid-fifteenth century emerges as a period of intensely concentrated anomalies, with the 1450s marking the highest decadal peak of recorded events in the dataset. Heat and warm waves, although less frequent overall, also show a noticeable rise during the fifteenth century, indicating an increase in warm-season extremes alongside the dominant cold-season variability. Conversely, snow and snowstorms display a more irregular temporal pattern without a clear long-term trend.

It is crucial to note that the near-total absence of recorded heat and warm waves between 1000 and 1300 (Fig. 4) does not imply a strictly cold background climate during this period. Rather, it reflects a severe recording bias inherent to sparse early medieval documentation, where chroniclers disproportionately prioritized catastrophic winter shocks over warm-season anomalies.

The seasonal distribution of extreme temperature events is strongly asymmetric, reflecting the internal consistency of the classification scheme. Severe frost, cold waves, and ice events are overwhelmingly concentrated in the winter months (December to February), accounting for roughly 70% of all cold-related records. Conversely, heat and warm waves are strictly confined to the summer season (June to August), with practically no excep-

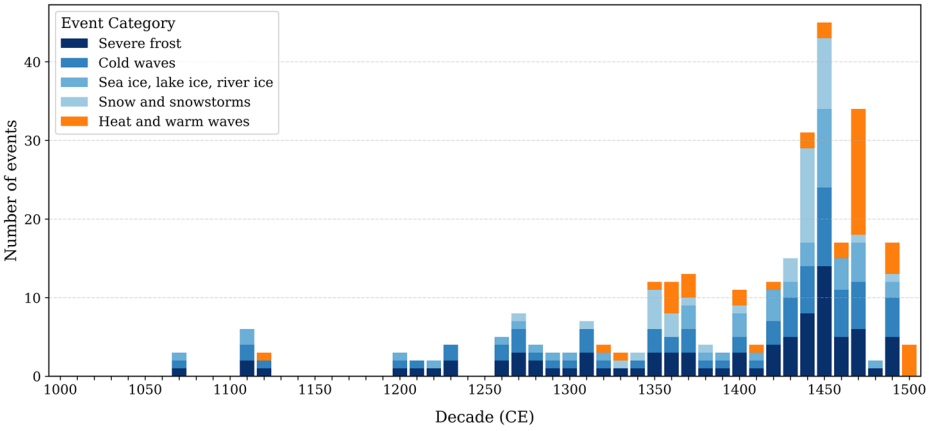


Fig. 4 Decadal frequency of extreme temperature events categorized by type (1001–1500 CE)

tional warm anomalies recorded in the transitional seasons, particularly in autumn. Snow and snowstorms exhibit a slightly broader temporal spread, primarily distributed between winter and early spring (March to April). Occurrences in autumn were less than half as frequent. It is important to underline that cold-related extremes were also observed in summer, though very rarely (Fig. 5).

The classification of event intensity reveals a strong predominance of high-severity occurrences across all categories (Fig. 6). The dataset is heavily skewed toward the highest intensity class (Level 3: very strong or catastrophic), which comprises approximately 70% of the total reconstructed events. Moderate or mild events (Level 1) are comparatively rare, representing only a minor fraction of the database. This skewed distribution is particularly evident for severe frost, where Level 3 events outnumber lower-intensity events by a ratio of nearly 3 to 1.

This strong predominance of high-severity occurrences is a well-documented characteristic of historical documentary evidence. Medieval chroniclers and analysts did not maintain continuous meteorological records; rather, they selectively documented phenomena that triggered significant socioeconomic, agricultural, or environmental impacts. Consequently, mild or moderate anomalies (Level 1) often passed unrecorded as part of normal seasonal variability, whereas catastrophic extremes (Level 3)—such as prolonged deep freezes causing human mortality, crop destruction, or the freezing of major navigable trade routes—were systematically documented and preserved. Therefore, this distribution reflects the inherent impact-driven recording bias of pre-instrumental narrative sources rather than the absolute meteorological frequency of all historical anomalies.

Spatially, the distribution of extreme events across Poland shows pronounced regional variability. As illustrated in the regional distribution by event category (Fig. 7), the highest concentration of recorded events occurs in the Baltic Coast and Pomerania, as well as in Silesia. Other regions, including Masovia, Greater Poland, Lesser Poland, and Masuria-Podlasie, exhibit considerably fewer records. This regional pattern becomes increasingly distinct over time (Fig. 8), with the density of events rising sharply in the northwestern and southwestern parts of the country during the fourteenth and fifteenth centuries. While this

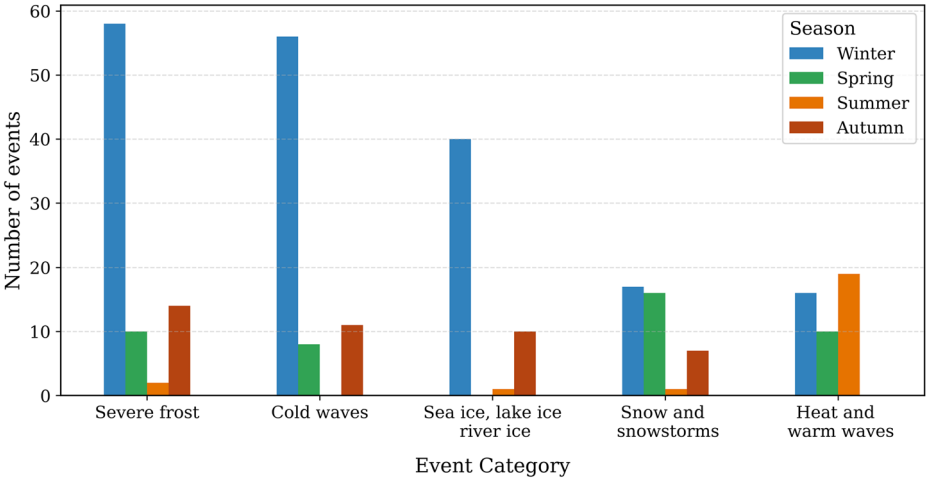


Fig. 5 Seasonal distribution of recorded extreme events by category

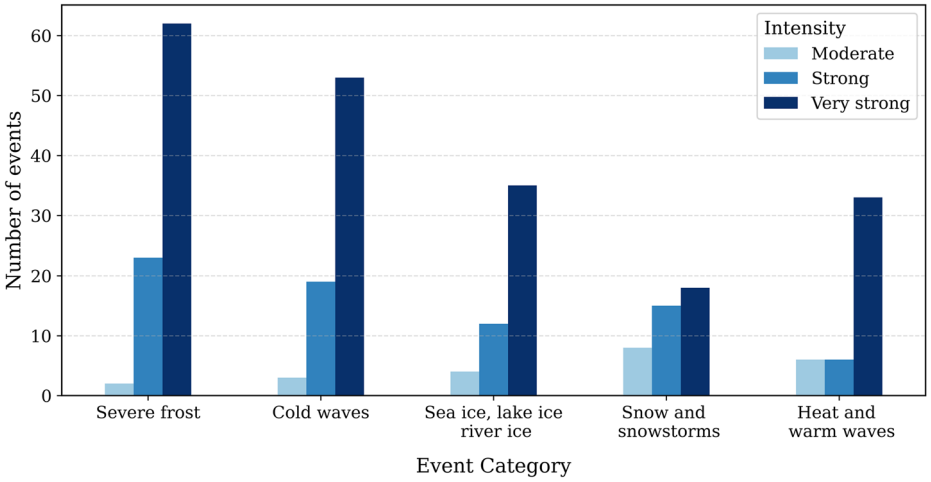


Fig. 6 Classification of event intensity across the five temperature-related categories

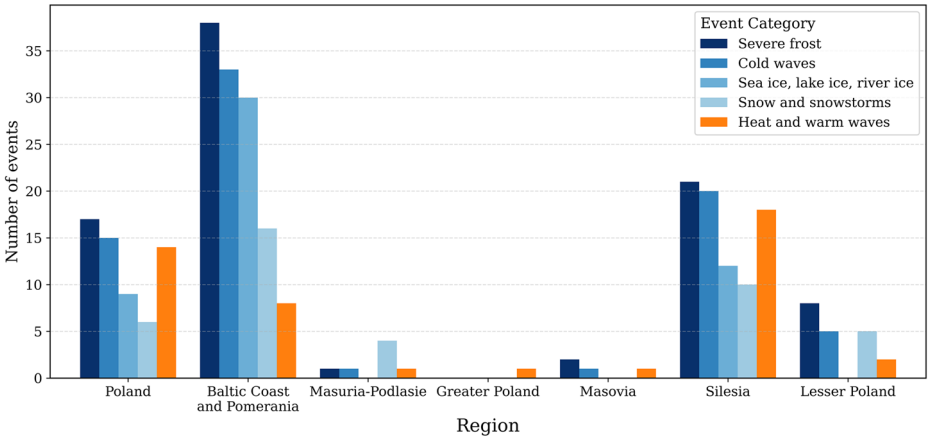


Fig. 7 Regional distribution of extreme events grouped by category

spatial structure partly reflects a genuine climatic signal, it is fundamentally intertwined with the distribution of medieval population and administrative centers. Regions exhibiting the highest event densities—such as the Baltic Coast and Silesia—coincide directly with major economic and ecclesiastical hubs (e.g., Gdańsk, Toruń, and Wrocław) where chronicles were most systematically produced and preserved. Because quantitative demographic data for medieval Poland is insufficient to mathematically 'control' or weight for this recording bias, these regional frequencies must be explicitly interpreted as a combined reflection of both localized climatic vulnerability and administrative source availability.

The societal and environmental consequences of these extremes are synthesized in the impacts matrix (Fig. 9), which demonstrates distinct vulnerability profiles for different event types. Cold-related extremes—particularly severe frost, cold waves, and ice phenomena—are most heavily linked to transport disruptions (due to the freezing of navigable rivers and

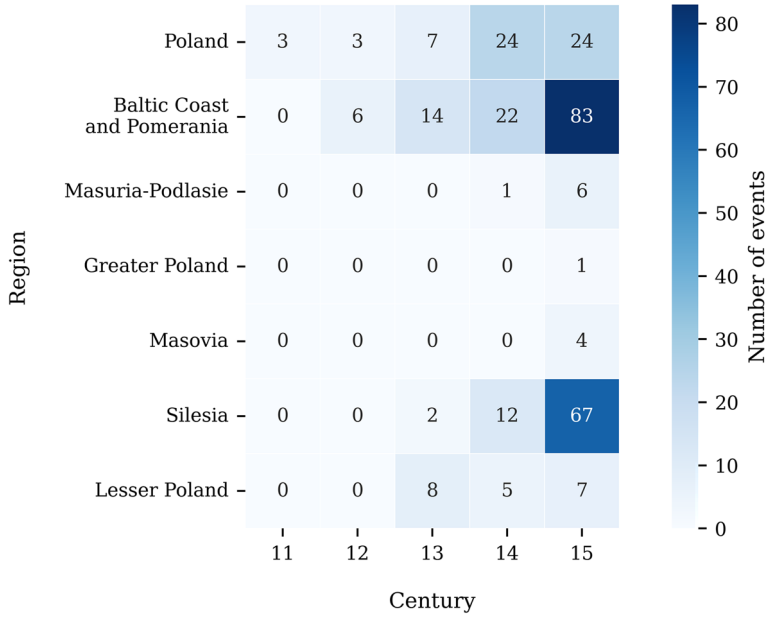


Fig. 8 Spatiotemporal heatmap of recorded events across the six analytical regions by century

coastal waters) and broader environmental stress. In contrast, heat and warm waves possess a different impact signature, being most strongly associated with agricultural damage and environmental stress, reflecting the sensitivity of pre-industrial agriculture to prolonged warm and dry conditions. Less frequent but notable impacts across the matrix include famine, economic disruption, and livestock mortality, indicating that both winter and summer temperature extremes could trigger cascading socio-economic consequences for medieval society.

Taken together, the temporal, seasonal, spatial, and impact-based analyses reveal a coherent pattern of increasing variability in extreme temperature events across medieval Poland. The progressive rise in event frequency from the late fourteenth century onward, combined with distinct regional clustering and differentiated societal impacts, indicates that climatic extremes were not randomly distributed but followed identifiable temporal trajectories and spatial structures.

Regarding the reliability of the reconstructed dataset, 56.3% of the extreme events were classified as high-confidence, 18.6% as moderate-confidence, and 25.1% as low-confidence (relying primarily on single sources). To ensure the robustness of the observed climatic trends, a sensitivity analysis was conducted utilizing exclusively the high-confidence records. The analysis confirms that the temporal clustering of extreme cold events in the mid-fifteenth century, as well as the spatial concentration along the Baltic Coast and Silesia, remain statistically robust even when single-source and non-contemporary accounts are excluded. This indicates that the long-term patterns identified are genuine climatic phenomena rather than artifacts of low-reliability documentation.

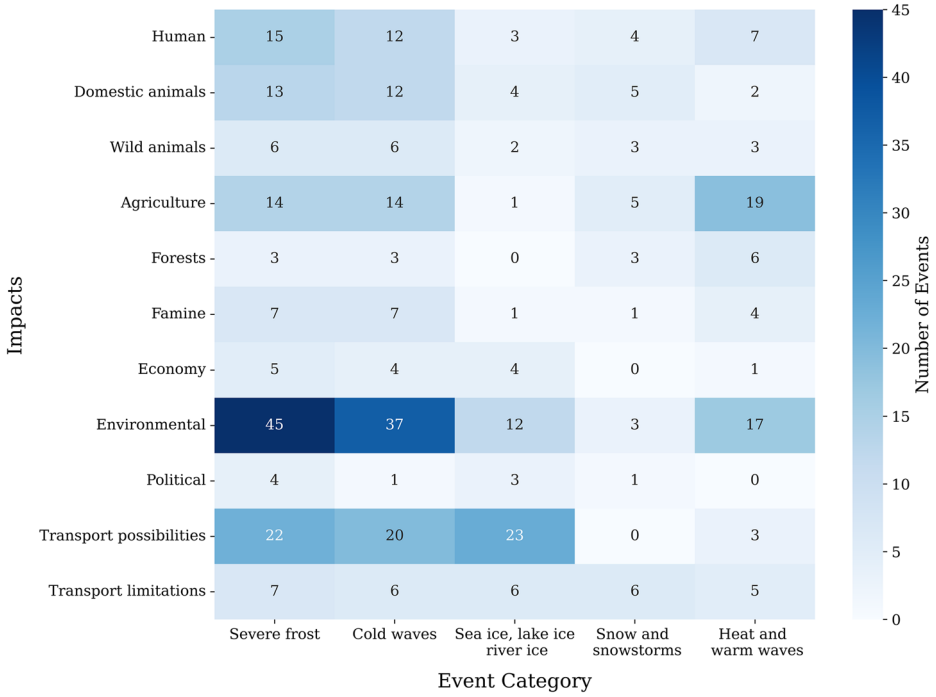


Fig. 9 Matrix of societal and environmental impacts associated with each extreme event category

5 Discussion

Our reconstruction of extreme temperature events in medieval Poland (1001–1500 CE) reveals a pronounced, progressive increase in climatic variability, particularly during the fourteenth and fifteenth centuries. This interval is marked by a severe surge in cold events—including frost, cold waves, and extensive ice formation on rivers, lakes, and parts of the Baltic Sea—which is highly consistent with the broader Central European transition from the Medieval Climate Anomaly to the early phases of the Little Ice Age (Luterbacher et al. 2004; Büntgen et al. 2011; Brázdil et al. 2005; Niedźwiedź et al. 2015; Camenisch et al. 2016).

The clustering of cold extremes in our dataset, notably peaking in the 1430s and 1440s (Fig. 4), exhibits a strong, explicit temporal correlation with independent climate reconstructions from neighboring regions. Specifically, the extraordinary frequency of severe winter events we identified during the 1430s directly matches the continental-scale cold phase associated with the early Spörer Minimum, as detailed for north-western and central Europe by Camenisch et al. (2016). Furthermore, the absolute single-year maximum of extremes in our dataset, occurring in 1443, perfectly mirrors the extreme winter severity indices recorded in both the Czech Lands (Brázdil et al. 2010) and Germany (Glaser 2013). Regionally, the abundance of sea-ice events and documented 'ice bridges' along the Polish Baltic Coast in our database aligns precisely with the severe ice winter chronologies developed for the broader Baltic Sea by Koslowski and Glaser (1999) and Jevrejeva (2001). This direct chronological agreement confirms that our decadal event frequencies do not merely

reflect local archival survival, but accurately capture large-scale atmospheric circulation anomalies, such as persistent continental blocking anticyclones, across Central Europe.

While cold extremes overwhelmingly dominate the record, episodes of heat and warm waves are also evident, especially during the late fifteenth century. This suggests that the medieval climate in Poland was not uniformly cold, but rather characterized by heightened interannual and decadal variability, corroborating recent regional reconstructions utilizing both proxies and documentaries (Przybylak et al. 2023). Such variability likely reflects underlying dynamical drivers. The observed extremes can be linked to shifts in atmospheric circulation, including an increased frequency of blocking patterns and negative phases of the North Atlantic Oscillation, which favored cold air advection during winter, alongside persistent high-pressure systems that contributed to summer heat extremes (Przybylak et al. 2003; Luterbacher et al. 2004; Trouet et al. 2009; Niedźwiedź 2010).

This inherent reporting bias directly explains the apparent contradiction emerging in the early centuries of our dataset (Fig. 4). While proxy-based reconstructions demonstrate that Central Europe experienced generally warmer baseline conditions during the Medieval Climate Anomaly (MCA) between the 11th and 13th centuries (Büntgen et al. 2011; Przybylak et al. 2023), our documentary database is heavily dominated by cold extremes during this exact period. This should not be misinterpreted as a substantive macro-regional climatic contrast. Medieval chroniclers selectively documented weather only when it triggered acute societal distress. Anomalous severe winters during the MCA caused immediate infrastructural paralysis and agricultural crises worth recording. Conversely, warmer-than-average summers often benefited agriculture in Poland's transitional climate and therefore passed unrecorded as 'favorable' rather than 'extreme'. Consequently, the early dominance of cold records is an artifact of source vulnerability and early documentary scarcity, whereas the true climatic shift toward the Little Ice Age is evidenced by the absolute multiplication and unprecedented clustering of severe winters in the 15th century.

This study provides one of the first comprehensive and spatially explicit inventories of extreme temperature events for medieval Poland, integrating timing, intensity, spatial distribution, and societal impacts. Previous studies were often limited to isolated phenomena, individual years, or partial datasets without systematic classification. The concordance of our temporal patterns with the wider Central European historical climate network suggests large-scale climatic forcing rather than local or archival artifacts.

Crucially, the analysis of societal impacts emphasizes the acute vulnerability of medieval communities to extreme temperatures (Fig. 9). Transport disruption, environmental stress, and agricultural damage are the most frequently reported consequences. Cold-related extremes routinely paralyzed transport and communication via the freezing of navigable waterways, while sudden thaws following severe snow accumulation frequently triggered catastrophic ice-jam floods, a cascading hazard well-documented in Polish historical hydrology (Grześ 1991; Cyberski et al. 2006; Ghazi et al. 2023). Conversely, the heat waves and summer droughts identified in this dataset were direct drivers of agricultural failure. Such agricultural shocks were not isolated phenomena; documentary evidence extensively links these warm-season extremes to grain shortages, price spikes, livestock mortality, and demographic crises, corroborating broader European historiography on pre-industrial climate-society interactions, such as the catastrophic Great Famine of 1315–1317 (Jordan 1996; Slavin 2012; Campbell 2016; Bauch, 2019).

Several limitations of the study must be acknowledged. Documentary sources are inherently selective and unevenly distributed; they tend to record only those events associated with significant environmental or societal disruptions. This results in a skewed distribution where moderate events appear comparatively rare, highlighting an inherent selective bias. Moreover, this reporting bias was likely amplified by perceptual factors, particularly during the relatively warmer baseline of the Medieval Climate Anomaly (1000–1300 CE). During a generally mild climatic phase, sudden and severe cold shocks were perceived as highly anomalous and devastating, prompting chroniclers to disproportionately depict extreme winter events over summer heat. Thus, the early prevalence of cold extremes represents a complex interplay between genuine human perceptual sensitivity to cold anomalies and the aforementioned documentary source artifacts. Furthermore, the uneven survival of historical sources and their spatial concentration in politically and economically important areas—particularly along the Baltic coast, Pomerania, and Silesia (Figs. 7 and 8)—introduces potential biases in event density, which must be considered when interpreting spatial patterns (Brázdil et al. 2005). Finally, as is common in historical climatology, the apparent increase in event frequency over time partly reflects the expansion of urban centers, increasing literacy, and improved administrative documentation in the late Middle Ages. However, because the frequency of recorded extremes in the mid-fifteenth century—particularly severe frosts and Baltic Sea ice events—far outpaces the general regional increase in manuscript production, we conclude that this period represents a robust climatic anomaly associated with the onset of the Little Ice Age, superimposed upon a baseline of improving source coverage.

Nevertheless, the relatively large number of systematically categorized events and the spatially explicit framework provide a robust basis for analyzing long-term variability and impacts. Future research should integrate documentary evidence with high-resolution proxy records, such as tree rings and lake sediments, and with climate model simulations to better constrain the magnitude, drivers, and spatial patterns of extreme events. Extending the analysis into the sixteenth century and beyond would allow direct comparison with early instrumental records, enhancing our understanding of long-term climate variability and risk in Central Europe.

6 Conclusion

The reconstruction of extreme temperature events in medieval Poland from 1001 to 1500 CE provides a vital long-term context for understanding regional climate dynamics prior to the instrumental period. By systematically analyzing historical documentary sources, this study identified 299 distinct events, highlighting a pronounced dominance of cold-season extremes such as severe frost and cold waves.

A central finding of this research is the distinct surge in recorded climatic variability and extreme events during the fourteenth and fifteenth centuries. This intensification aligns with the broader Central European transition into the early Little Ice Age, which brought more frequent cold extremes interspersed with episodic heat events. Spatially, these historical records are clustered primarily in the Baltic Coast, Pomerania, and Silesia. Rather than representing solely a robust regional climatic signal, this distribution heavily reflects

the uneven preservation of documentary sources in politically and economically important historical centers.

The recorded impacts of these phenomena emphasize the profound vulnerability of medieval societies to climatic shocks. Winter extremes—most notably the freezing of coastal waters and the Baltic Sea—routinely paralyzed regional mobility and commercial transportation networks (Kahle and Glaser 2025, 2026), triggering broad environmental stress, while prolonged summer heat directly caused severe agricultural damage and exacerbated food shortages. The dominance of catastrophic (Level 3) extremes in the dataset highlights the impact-driven recording bias of medieval chroniclers. Despite these inherent limitations in historical documentation, the strong temporal correlation with broader Central European datasets validates the usefulness of this reconstruction. Future investigations should integrate this documentary framework with high-resolution natural proxy records, such as tree rings and lake sediments, to better constrain the magnitude and spatial patterns of extreme pre-industrial climate events.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10584-026-04339-6.

Acknowledgements The authors would like to acknowledge the National Science Centre, Poland, for providing a grant (no. 2020/37/B/ST10/00710) to finance the preparation of this article.

Author contributions Sajad Akbari Moghaddam Sani: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Software, Visualization, Validation, Writing – original draft, Writing – review & editing. Rajmund Przybylak: Conceptualization, Methodology, Investigation, Data curation, Funding acquisition, Project administration, Validation, Supervision, Writing – review & editing. Piotr Oliński: Conceptualization, Methodology, Investigation, Data curation, Validation.

Funding This research was funded by a grant obtained from the National Science Centre, Poland, project (no: 2020/37/B/ST10/00710).

Data availability The dataset of Extreme Temperature Events in Medieval Poland (1001–1500 CE) is available at (https://doi.org/10.18150/UHHLCN). Other data used in this research are available from the corresp onding author, upon reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

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.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

Alexandre P (1987) Le climat en Europe au Moyen Âge: contribution à l'histoire des variations climatiques de 1000 à 1425, d'après les sources narratives de l'Europe occidentale. École des hautes études en sciences sociales

Araźny A, Bartczak A, Maszewski R, Krzemiński M (2021) The influence of atmospheric circulation on the occurrence of dry and wet periods in Central Poland in 1954–2018. Theoret Appl Climatol 146(3–4):1079–1095. https://doi.org/10.1007/s00704-021-03780-0

Bauch M, Schenk GJ (eds) (2019) The crisis of the 14th century: teleconnections between environmental and societal change? De Gruyter. https://doi.org/10.1515/9783110660784

Bell WT, Ogilvie AEJ (1978) Weather compilations as a source of data for the reconstruction of european climate during the medieval period. Clim Change 1(4):331–342. https://doi.org/10.1007/BF00135154

Brázdil R, Pfister C, Wanner H, von Storch H, Luterbacher J (2005) Historical climatology in Europe – The state of the art. Clim Change 70(3):363–430. https://doi.org/10.1007/s10584-005-5924-1

Brázdil R, Dobrovolný P, Luterbacher J, Moberg A, Pfister C, Wheeler D, Zorita E (2010) European climate of the past 500 years: new challenges for historical climatology. Clim Change 101(1–2):7–40. https://doi.org/10.1007/s10584-009-9783-z

Brázdil R, Dobrovolný P, Trnka M, Řezníčková L, Dolák L, Kotyza O (2019) Extreme droughts and human responses to them: the Czech Lands in the pre-instrumental period. Clim Past 15(1):1–24. https://doi.org/10.5194/cp-15-1-2019

Büntgen U, Tegel W, Nicolussi K, McCormick M, Frank D, Trouet V, Esper J (2011) 2500 years of European climate variability and human susceptibility. Science 331(6018):578–582. https://doi.org/10.1126/science.1197175

Camenisch C, Keller KM, Salvisberg M, Amann B, Bauch M, Blumer S, Wetter O (2016) The 1430s: a cold period of extraordinary internal climate variability during the early Spörer Minimum with social and economic impacts in north-western and central Europe. Clim Past 12(11):2107–2126. https://doi.org/10.5194/cp-12-2107-2016

Campbell BMS (2016) The great transition: climate, disease and society in the late-medieval world. Cambridge University Press. https://doi.org/10.1017/CBO9781139031110

Cyberski J, Grześ M, Gutry-Korycka M, Nachlik E, Kundzewicz ZW (2006) History of floods on the River Vistula. Hydrol Sci J 51(5):799–817. https://doi.org/10.1623/hysj.51.5.799

Dobrovolný P, Moberg A, Brázdil R, Pfister C, Glaser R, Wilson R, Zorita E (2010) Monthly, seasonal and annual temperature reconstructions for Central Europe derived from documentary evidence and instrumental records since AD 1500. Clim Change 101(1–2):69–107. https://doi.org/10.1007/s10584-009-9724-x

Field CB, Barros V, Stocker TF, Dahe Q (eds) (2012) Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the Intergovernmental Panel on Climate Change. Cambridge University Press

Ghazi B, Przybylak R, Oliński P, Bogdańska K, Pospieszyńska A (2023) The frequency, intensity, and origin of floods in Poland in the 11th–15th centuries based on documentary evidence. J Hydrol 623:129778. https://doi.org/10.1016/j.jhydrol.2023.129778

Glaser R (2013) Klimageschichte Mitteleuropas: 1200 Jahre Wetter, Klima, Katastrophen. Wissenschaftliche Buchgesellschaft (WBG). ISBN: 978-3-534-26154-2

Girguś R, Strupczewski W, Rojecki A (1965) Wyjątki ze źródeł historycznych o nadzwyczajnych zjawiskach hydrologiczno-meteorologicznych na ziemiach polskich w wiekach od X do XVI. Wydawnictwa Komunikacji i Łączności, Warszawa, Poland.

Glaser R, Riemann D (2009) A thousand-year record of temperature variations for Germany and Central Europe based on documentary data. J Quat Sci 24(5):437–449. https://doi.org/10.1002/jqs.1302

Grześ M (1991) Zatory i powodzie zatorowe na dolnej Wiśle: mechanizmy i warunki. Polska Akademia Nauk, Instytut Geografii i Przestrzennego Zagospodarowania, Warszawa. https://rcin.org.pl/dlibra/doccontent?id=19480

Hernández-Almeida I, Grosjean M, Przybylak R, Tylmann W (2015) A chrysophyte-based quantitative reconstruction of winter severity from varved lake sediments in NE Poland during the past millennium and its relationship to natural climate variability. Q Sci Rev 122:74–88. https://doi.org/10.1016/j.quascirev.2015.05.029

Hernández-Almeida I, Grosjean M, Gómez-Navarro JJ, Larocque-Tobler I, Bonk A, Enters D, Ustrzycka A, Piotrowska N, Przybylak R, Wacnik A, Witak M, Tylmann W (2017) Resilience, rapid transitions and regime shifts: Fingerprinting the responses of Lake Zabińskie (NE Poland) to climate variability and human disturbance since AD1000. Holocene 27(2):258–270. https://doi.org/10.1177/0959683616658529

IPCC (2021) Climate change 2021 – the physical science basis. Cambridge University Press. https://doi.org/10.1017/9781009157896
IPCC (2023) Climate Change 2023 – Synthesis Report. IPCC, Geneva, Switzerland. https://doi.org/10.59327/IPCC/AR6-9789291691647
Jevrejeva S (2001) Severity of winter seasons in the northern Baltic Sea between 1529 and 1990: reconstruction and analysis. Climate Res 17(1):55–62. https://doi.org/10.3354/cr017055
Jordan WC (1996) The great famine: northern Europe in the early fourteenth century. Princeton University Press. ISBN: 978-0-691-05891-7
Kahle M, Glaser R (2025) Climatic conditions and mobility from 1000 to 1500. Hermeneutic and statistical approaches. In: Mobility in the early Middle Ages, and beyond – Mobilität im Frühmittelalter und darüber hinaus. De Gruyter, pp 161–186. https://doi.org/10.1515/9783111166698-009
Kahle M, Glaser R (2026) Monthly temperature indices for Central Europe from AD 1000 to AD 1500 [Dataset]. https://doi.org/10.6094/UNIFR/283310
Kiss A (2019) Droughts, Dry Spells and Low Water Levels in Late Medieval Hungary (and Slavonia) III: Potential Dry Spells and the Drought of (1516-)1517. J Environ Geogr 12(3–4):53–67. https://doi.org/10.2478/jengeo-2019-0012
Koprowski M, Przybylak R, Zielski A, Pospieszyńska A (2012) Tree rings of Scots pine (Pinus sylvestris L.) as a source of information on past climate in northern Poland. Int J Biometeorol 56(1):1–10. https://doi.org/10.1007/s00484-010-0390-5
Koslowski G, Glaser R (1999) Variations in reconstructed ice winter severity in the western Baltic from 1501 to 1995, and their implications for the North Atlantic Oscillation. Clim Change 41(2):175–191. https://doi.org/10.1023/A:1005466226797
Krąpiec M (1998) Oak dendrochronology of the Neoholocene in Poland. Folia Quaternaria 69:5–134
Le Roy Ladurie E (1971) Times of feast, times of famine: a history of climate since the year 1000. London, ISBN 978-0-04-551020-7
Limanówka D (2001) Rekonstrukcja warunków klimatycznych Krakowa w pierwszej połowie XIX wieku. Instytut Meteorologii i Gospodarki Wodnej, Warszawa
Lorenc H (2005) In: Atlas klimatu Polski. Instytut Meteorologii i Gospodarki Wodnej, Warszawa. ISBN: 83-88897-43-8
Luterbacher J et al (2004) European seasonal and annual temperature variability, trends, and extremes since 1500. Science 303(5663):1499–1503. https://doi.org/10.1126/science.1093877
Luterbacher J, Xoplaki E, Kilttel M, Zorita E, González-Rouco JF, Jones PD, Stossel M, Rutishauser T, Wanner H, Wibig J, Przybylak R (2010) Climate change in Poland in the Past centuries and its relationship to European climate: evidence from reconstructions and coupled climate models. In: Przybylak R, Majorowicz J, Brázdil R, Kejna M (eds) The Polish climate in the European context: an historical overview. Springer, Berlin, Heidelberg, New York, pp 3–39. https://doi.org/10.1007/978-90-481-3167-9
Nash DJ, Adamson GCD, Ashcroft L, Bauch M, White S (2021) Climate indices in historical climate reconstructions: a global state of the art. Clim Past 17(3):1273–1314. https://doi.org/10.5194/cp-17-1273-2021
Niedźwiedź T (1992) Climate of the Tatra Mountains. Mt Res Dev 12(2):131–146. https://doi.org/10.2307/3673787
Niedźwiedź T (2010) Wieloletnia zmienność wskaźników cyrkulacji atmosferycznej nad Polską Południową. Uniwersytet Śląski, Katowice
Niedźwiedź T, Glaser R, Hansson D, Helama S, Klimenko V, Łupikasza E, Małarzewski Ł, Nordli Ø, Przybylak R, Riemann D, Solomina O (2015) The historical time frame (past 1000 years), w: The BACC II Author Team, Second assessment of climate change for the Baltic Sea Basin, regional climate studies. Springer Open, pp 51–65
Oliński P (2022) Pogoda i klimat regionów południowobałtyckich od końca XIV do początków XVI w. w źródłach narracyjnych. Wydawnictwo Naukowe Uniwersytetu Mikołaja Kopernika, 300 pp. https://doi.org/10.12775/978-83-231-4936-1
Opała M, Mendecki MJ (2014) Zastosowanie metod dendroklimatologicznych w badaniach zmian środowiska. Prace Geograficzne 136:65–80
Opała-Owczarek M, Niedźwiedź T, Przybylak R, Tylmann W (2021) Climate change before instrumental measurements. In: Falarz M (ed) Climate change in Poland. Springer, pp 71–119. https://doi.org/10.1007/978-3-030-70328-8_5
Pawłowski B, Gorączko M (2014) Z badań nad znakami powodziowymi w dolinie Wisły. Gospodarka Wodna 2:57–63
Pfister C (1992) Monthly temperature and precipitation patterns in Central Europe from 1525 to the present. A methodology for quantifying man-made evidence on weather and climate. In: Climate since A.D. 1500. Routledge, pp 118–142. ISBN: 978-0415120302
Pfister C, Wanner H (2021) Klima und Gesellschaft in Europa. Die letzten tausend Jahre. Haupt, Bern. ISBN 978-3-258-08182-3

Pfister C, Brázdil R, Glaser R, Barriendos M, Camuffo D, Deutsch M, Rodrigo FS (1999) Documentary evidence on climate in sixteenth-century Europe. Clim Change 43(1):55–110. https://doi.org/10.1023/A:1005540707792

Przybylak R (2010) The climate of Poland in recent centuries: a synthesis of current knowledge: instrumental observations. In Przybylak R, Majorowicz J, Brázdil R, Kejna M (eds) The Polish climate in the European context: an historical overview. Springer, pp 129–166. https://doi.org/10.1007/978-90-481-3167-9_5

Przybylak R (2011) Changes in Poland's climate over the last millennium. Czasopismo Geograficzne 82(1–2):23–48

Przybylak R (2016) Poland's climate in the last millennium. Oxford research encyclopedia of climate science. Oxford University Press. https://doi.org/10.1093/acrefore/9780190228620.013.2

Przybylak R, Wójcik G, Marciniak K (2003) Wpływ Oscylacji Północnoatlantyckiej oraz Arktycznej na warunki termiczne chłodnej pory roku w Polsce w XVI-XX wiekach. Przegląd Geofizyczny 1–2:61–74

Przybylak R, Wójcik G, Marciniak K, Chorążyczewski W, Nowosad W, Oliński P, Syta K (2004) Zmienność warunków termiczno-opadowych w Polsce w okresie 1501-1840 w świetle danych historycznych. Przegląd Geograficzny 76(1):5–31

Przybylak R, Majorowicz J, Wójcik G, Zielski A, Chorążyczewski W, Marciniak K, Nowosad W, Oliński P, Syta K (2005) Temperature changes in Poland from the 16th to the 20th centuries. Int J Climatol 25(6):773–791. https://doi.org/10.1002/joc.1149

Przybylak R, Oliński P, Chorążyczewski W, Nowosad W, Syta K (2010) The climate of Poland in recent centuries: a synthesis of current knowledge: documentary evidence. In Przybylak R, Majorowicz J, Brázdil R, Kejna M (eds) The Polish climate in the European context: an historical overview. Springer, pp 167–190

Przybylak R, Oliński P, Koprowski M, Filipiak J, Pospieszyńska A, Chorążyczewski W, Puchałka R, Dąbrowski HP (2020) Droughts in the area of Poland in recent centuries in the light of multi-proxy data. Clim Past 16(2):627–661. https://doi.org/10.5194/cp-16-627-2020

Przybylak R, Oliński P, Koprowski M, Szychowska-Krąpiec E, Krąpiec M, Pospieszyńska A, Puchałka R (2023) The climate in Poland (central Europe) in the first half of the last millennium, revisited. Clim Past 19(12):2389–2408. https://doi.org/10.5194/cp-19-2389-2023

Slavin P (2012) The Great Bovine Pestilence and economic crisis in England. Economic History Rev 65(4):1318–1322. https://doi.org/10.1111/j.1468-0289.2011.00625.x

Szymanowski M, Kryza M, Spallek W (2013) Regression-based air temperature spatial prediction models: an example from Poland. Meteorol Z 22(5):577–585. https://doi.org/10.1127/0941-2948/2013/0440

Trouet V, Esper J, Graham NE, Baker A, Scourse JD, Frank DC (2009) Persistent positive North Atlantic Oscillation mode dominated the Medieval Climate Anomaly. Science 324(5923):78–80. https://doi.org/10.1126/science.1166349

Tylmann W, Zolitschka B, Enters D et al (2013) Laminated lake sediments in northeast Poland: distribution, preconditions for formation and potential for paleoenvironmental investigation. J Paleolimnol 50(4):487–503. https://doi.org/10.1007/s10933-013-9741-7

Ustrnul Z, Wypych A, Czekierda D (2021) Climate change before instrumental measurements. In Falarz M (ed) Climate change in Poland. Springer, pp 275–330. https://doi.org/10.1007/978-3-030-70328-8_11

Zielski A, Krąpiec M, Koprowski M (2010) Dendrochronological data. In Przybylak R, Majorowicz J, Brázdil R, Kejna M (eds) The Polish climate in the European context: an historical overview. Springer, pp 191–217. https://doi.org/10.1007/978-90-481-3167-9

Weikinn C (1958) Quellentexte zur Witterungsgeschichte Europas von der Zeitwende bis zum Jahre 1850: Hydrographie, Teil 1 (Zeitwende–1500). Akademie-Verlag, Berlin. https://doi.org/10.1515/9783112564028

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.