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EDITED BY
Yaoping Wang,
The University of Tennessee, Knoxville, United States

REVIEWED BY
Eric Samakinwa,
University of Bern, Switzerland
Yachen Liu,
Xi'an University, China

*CORRESPONDENCE
Tudor Caciora
✉ tudor.caciora@yahoo.com

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Reconstruction of climatic events from the 16th century in Transylvania: interdisciplinary analysis based on historical sources

Ovidiu Răzvan Gaceu[1], Tudor Caciora[1]*, Ștefan Baias[1], Cezar Morar[1], Mihai Dudaș[2], Marius Stupariu[1] and Maria Maxim[1]

[1]Department of Geography, Tourism and Territorial Planning, Faculty of Geography, Tourism and Sport, University of Oradea, Oradea, Romania, [2]Jimbolia Technology Highschool, Jimbolia, Romania

Introduction: Understanding past climate variability is essential for interpreting current and future climate trends, particularly during defining climate periods for the past two millennia, such as the Little Ice Age, which had significant socio-economic impacts.

Methods: The present study uses an interdisciplinary approach, analyzing written documents such as chronicles, diaries, and official records to extract data related to climate events in the 16th century in Transylvania (on the current territory of Romania). The obtained results were processed using statistical techniques to reconstruct the evolution of the weather during the respective period.

Results and discussion: The study identifies multiple pieces of evidence associated with extreme weather events, including 40 unusually warm summers and several years of excess precipitation or drought. In particular, the period 1,527–1544 was marked by intense heat and droughts, severely affecting agriculture and causing famine. In contrast, the second half of the century is defined by increased rainfall, with numerous reports of flooding and excessive rain, particularly in the 1590s. These extreme climatic events profoundly affected society, contributing to food shortages and increased mortality from starvation and diseases (especially the plague). At the same time, compared to the territory of Western Europe, in Transylvania, heat waves and droughts were more frequent in the first half of the 16th century, while in Western Europe, these climatic phenomena were more sporadic and less intense. Finally, the manuscript emphasizes the significant role of the climate in shaping the historical and socio-economic landscape of Transylvania in the 16th century, offering perspectives on the complex interactions between the climate and the human component.

KEYWORDS

historical climatology, 16th century, extreme climatic events, Transylvania, historical sources, climatic variability

1 Introduction

Knowledge of past climate fluctuations is essential for a better understanding of current and future climate variability. Thus, any approach to the present and the future in this matter is not possible outside of the long-time of history (Jones and Mann, 2004; Tierney et al., 2020). This is an interdisciplinary field, which requires continuous research to determine exactly how the climate evolved and the various effects it had on the social and economic components (Pfister, 2010; Pribyl, 2014). The study of climate and climatic events in the past is the prerogative of historical climatology. In recent decades, the field has seen a significant expansion, both in terms of the regions studied, the methods and techniques used, and the extensive interdisciplinary collaborations (White et al., 2022). An essential aspect of historical climatology is the types of sources it uses because the information related to the climate from the historical past is contained in two archives, namely the archive of nature and the archive of society. Both are proxy data sources, but they can be processed in time series and calibrated using statistical methods for the main climatic elements (temperature, precipitation, atmospheric pressure, etc.) (Glaser and Stangl, 2004; Adamson et al., 2018).

In nature's archive, information can be found in the isotopes of various chemical elements in glaciers (especially those of O_2), terrestrial and marine sediments, pollen, or tree rings (Zheng et al., 2014; Tierney et al., 2020). Thus, Waller et al. (2024) use an extensive set of proxy data from natural sources (such as tree growth rings, corals, and ice cores), documentary data, and early instrumental measurements to reconstruct global climate variations, including temperature, precipitation, atmospheric pressure and other variables, for the period 1421–2008. The study is based on an advanced data assimilation model, which combines historical observations with climate simulations, providing a detailed picture of intra-annual and multidecadal climate variability. Samakinwa et al. (2021) focus their analysis on the reconstruction of sea surface temperature and sea ice concentration for the period 1000–1859, using a combination of proxy data and climate models. This reconstruction contributes significantly to the understanding of climate interactions between the oceans and the atmosphere in the past. Reichen et al. (2022) explore seasonal climate variability through a cold-season temperature reconstruction for the period 1701–1905 based on phenological data from the northern midlatitude region. The study focuses on the use of phenological indices, such as dates of flowering or crop maturity, to provide a detailed insight into seasonal climate trends in the Northern Hemisphere. These papers highlight the various methods and sources used to reconstruct climate variability on a global scale and regional, over extended time intervals, contributing to a better understanding of past climate dynamics.

On the other side, the data from the society archive are of two types, direct and indirect. The direct ones are observations on the climate in the form of written documents or information transmitted orally, recorded in parish or monastery registers, in cult or lay books of chroniclers, in the travel notes of diplomats, missionaries, and monks, in calendars, diaries, archives, etc. In most of them, meteorological records can be identified, although very disparate, but which can be ordered, with the rigor approximation, into coherent series (Carey, 2012; Ingram et al., 1978). The indirect ones refer to observations regarding the state of the water, snowfall, and snow cover, the phenophases of wild and cultivated plants, the starting dates of the vine picking, the blooming dates of the cherries, the value and price of the grains, the quantity and sugar content of the must, markings of water level on buildings or stones, sculptures, paintings showing frozen or dry rivers, historical images, and maps, records of religious processions to remove dangerous meteorological phenomena such as drought, excess precipitation or cold (Pfister, 1999, Pfister, 2010; Lunt et al., 2013).

The use of written historical documents in climate research offers several advantages over natural proxy data, but it also presents certain challenges. Among the advantages is that written records often reflect the direct, personal experiences of the authors, providing truthful accounts (apart from potential political biases). These documents typically offer high spatial and temporal resolution, with precise details about when and where climatic events occurred, and clarity regarding their significance (Zheng et al., 2014; Chen et al., 2020). Additionally, such sources provide insights not only into the weather but also into how societies responded to climatic changes, offering a more comprehensive understanding of climate's influence on historical events (Pfister et al., 2008). However, there are notable disadvantages. Some writings may be incomplete, focusing primarily on exceptional events rather than providing a consistent record, making them less useful for reconstructing average climatic values. These accounts can also be subjective and limited in scope or duration (Chen et al., 2020). Furthermore, many historical records are concentrated in regions like Asia and Europe, where documentation occurred earlier due to longer histories of social and economic development. This leaves large parts of the world with relatively recent climate records, hindering the reconstruction of older climatic events (Pfister et al., 2008).

These fundamental aspects of historical climatology have laid a strong foundation for researchers to investigate the effects of climate variability on different historical periods. The 16th century stands out as a pivotal moment in climate history, representing a period of significant transition during the intensification of the Little Ice Age (LIA), a global cooling event that spanned from the 14th to the 19th century. This shift from the warmer conditions of the early middle ages to cooler climates had profound impacts on agriculture, food resources, and the social and economic stability of societies (Mann et al., 2009; Luterbacher et al., 2016). The century saw the effects of the LIA intensify across Europe, with average temperatures dropping by about 0.5°C after 1560 compared to earlier periods (Teodoreanu, 2017; Le Roy Ladurie, 1983; Le Roy Ladurie, 2004). This cooling led to colder and longer winters and summers that were either cold and rainy or dry, which resulted in poor harvests, famines, and epidemics. However, there were occasional intervals where conditions improved, with warmer winters and normal summers yielding better harvests, offering some relief amid the general trend of climate deterioration (Pfister and Brázdil, 1999; Pfister et al., 1999).

Based on the previously indicated, the present study aims to evaluate the climate evolution in the 16th century on the territory of Transylvania (western and central Romania) using data from the society's archive. In this sense, the research focuses on the analysis of written documents and other relevant historical sources, which provide direct and indirect testimonies on the climatic phenomena of this region. In the present case, the written documents represent a valuable resource for reconstructing the evolution of the climate because an extremely high spatial and temporal resolution is needed, the place where the data was recorded and the year (if not the day and month) being extremely important. Thus, the study aims to investigate short and long-term climate variations, with a particular emphasis on identifying extreme climate events, such as particularly cold winters, cold or particularly hot summers, or conversely, intervals of favorable weather conditions. In addition, it will follow how these climatic variations have influenced the economic and social aspects of the Transylvanian communities, including the impact on agriculture and the population's health. Integrating climate data with socio-economic records provides a holistic perspective on how 16th century climate shaped regional development. Using a wide range of historical sources and applying rigorous analytical methods will contribute to a detailed reconstruction of the Transylvanian climate of this period, highlighting not only general trends, but also specific seasonal and annual fluctuations.

Besides the general European context in the full intensification of the LIA from the 16th century, Transylvania presents regional particularities that make it an interesting case study for illustrating how the former determined the climatic variability in a region of significant strategic importance. Thus, the present study contributes to a better understanding of how past climate variations shaped not only the natural environment but also the socio-economic development of the analyzed region, providing, at the same time, valuable information for the management of current and future climate variability.

2 Study area

In the 16th century, unlike today, the territory of Romania was not part of a unitary state, being divided into three distinct principalities (Wallachia, Moldova, and Transylvania). However, politically separated, they had a common culture and linguistic identity, which was consolidated over the centuries, culminating in the union of the principalities of Wallachia and Moldova in the 19th century (1859) and the creation of modern Romania at the beginning of the 20th century (1918) (Figure 1; Hitchins, 1996).

The political-military events of this complicated 16th century will significantly shape Europe's political and social map, influencing the balance of power between the great empires and kingdoms. In this turbulent context, although the Romanian principalities had a marginal role in the significant European conflicts, they were subjected to constant pressure from powerful neighbors, such as the Ottoman Empire, the Kingdom of Hungary, and later the Habsburg Empire (Georgescu, 1991).

Wallachia and Moldova frequently found themselves balancing between loyalty to the Ottoman Empire and efforts to maintain autonomy through alliances with regional powers like the Kingdom of Poland or the Habsburg Empire. Internal struggles for the throne, conflicts, and external invasions weakened their ability to significantly influence European politics. In contrast, Transylvania became an autonomous principality under Ottoman suzerainty after the fall of the Kingdom of Hungary after the Battle of Mohács in 1526, acting as a strategic buffer between the Habsburgs and the Ottomans (Böhm, 1867; Köpeczi et al., 1985; Haţegan et al., 2006).

Economically, Transylvania was more integrated into the Central European system, connected to Western Europe's trade routes, and had a more developed urban infrastructure, with cities like Sibiu, Braşov, and Cluj serving as important commercial and cultural centers. This contrasted sharply with Wallachia and Moldova, which were more isolated and focused on agriculture, with less-developed urban areas and economies tied to the Ottoman Empire. Additionally, Transylvania's ethnically diverse population, including Romanians, Hungarians, Saxons, and Szeklers, facilitated cultural exchange and

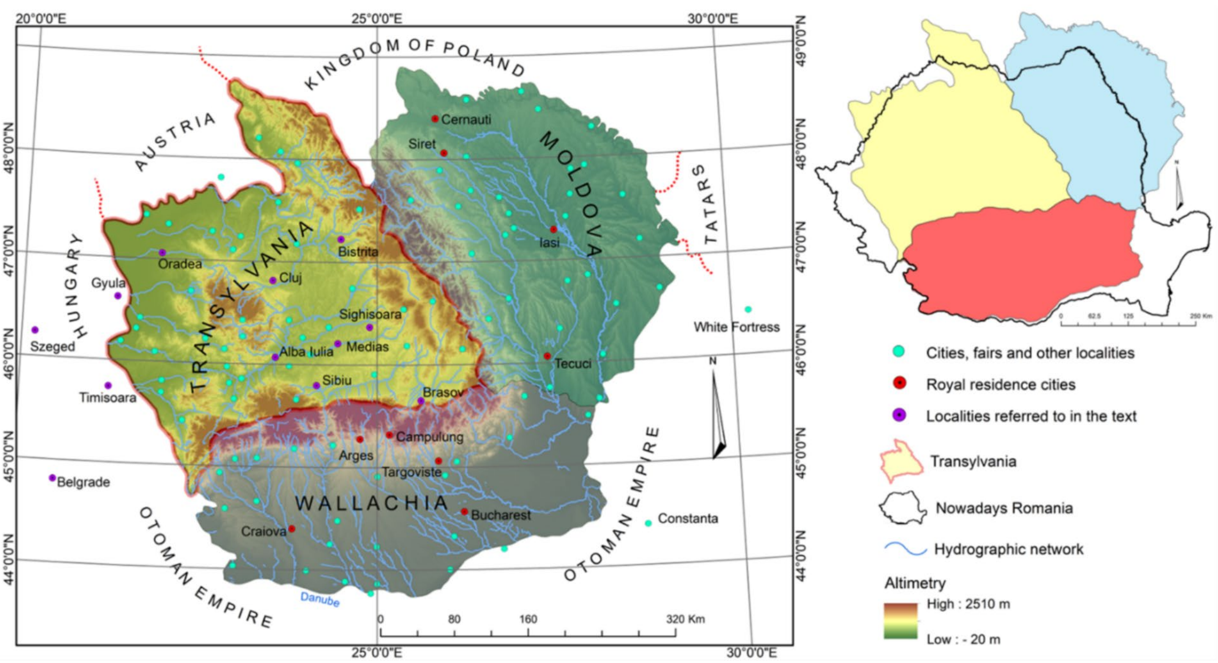

FIGURE 1
Territorial expansion of the Romanian principalities at the end of the 16th century, the main localities of the time and the main settlements referred to in the manuscript.

innovation, contributing to its socio-economic progress. Despite Ottoman suzerainty, Transylvania enjoyed greater autonomy in managing internal affairs and economic development, while Wallachia and Moldova faced more direct Ottoman control, paying tribute and with limited autonomy, restricting their growth (Giurescu, 1976; Borsa, 1996; Treptow and Popa, 1997). The advance that Transylvania had in relation to the other Romanian principalities is also reflected in the quantity and quality of information sources (implicitly those related to climatic events), in this sense the larger volume of information sources coming from Transylvania is easily observable. This is also individualized against the background of the use of the printing press starting from the third decade of the 16th century (more than 40 religious books were printed in Brasov in the period 1557–1582), as well as the appearance of numerous schools and colleges in the second half of the century (Borsa, 1996; David, 2019).

The quantity and quality of information sources available for the territory of Transylvania was the basis of the decision to focus on this case study. In contrast, in Wallachia and Moldova, the sources of information are much less and often very fragmented, which limits the ability to accurately reconstruct the climate evolution in these regions (at least for the 16th century; in the following centuries, the database grows significantly for the respective principalities as well). This imbalance in the availability of historical data justifies the choice of Transylvania as the focal point for our study, allowing us to build a more robust and accurate picture of the climate in the 16th century on the current territory of Romania. This selection ensures that our conclusions are based on a complete and more reliable corpus of data, properly reflecting the complexity of climate dynamics and their impact on human society.

3 Materials and methods

The present paper considers the reconstruction of the evolution of the climate in the 16th century based on the information available in the society's archive. Being on the border between geography and history, it uses an interdisciplinary working methodology, the database being the works and historical documents available in different categories of bibliographic sources (chronicles, journals, letters, reports, scientific articles, history books, other written documents, and different databases).

Because most of the time, the facts described in the analyzed database were lived by the authors, there is also a high degree of subjectivity, but this does not make them less relevant for climate studies. On the contrary, such documents provide valuable information, especially when corroborating with other independent sources or climate data obtained through modern reconstruction methods. Such an approach is more inclined to analyze how the people of those times felt the climatic variations and their effect and less to the reconstruction of specific values of the main components of the climate. This approach is essential because it offers a direct perspective on the social and cultural effects of the past's variability and special climatic events. At the same time, in addition to a complete and relevant understanding of the climate impact and its implications, it creates a more nuanced and richer narrative of the interaction between man and the environment over time.

Each type of database consulted has specific characteristics, but they act complementary to recreate the climate evolution in the 16th century on the territory of Transylvania. Thus, chronicles, diaries, letters, and reports describe climatic events well, but meteorological phenomena are mainly located relatively in time and space and do not capture the entire spatial–temporal extension. A disadvantage is also the fact that it is necessary to go through a massive volume of written information to identify some meteorological events of interest and the fact that they are in foreign documents, handwritten in the old form of the respective languages (most often Hungarian and Turkish). Historical documents are made up of court decisions, royal, voivodeship decrees, etc., which are more objective than the previous ones, but describe very few meteorological events (Figure 2).

History articles and books have the advantage of narrowing down the research area to the one of interest and locating meteorological events well in time and space. However, they require traversing a huge

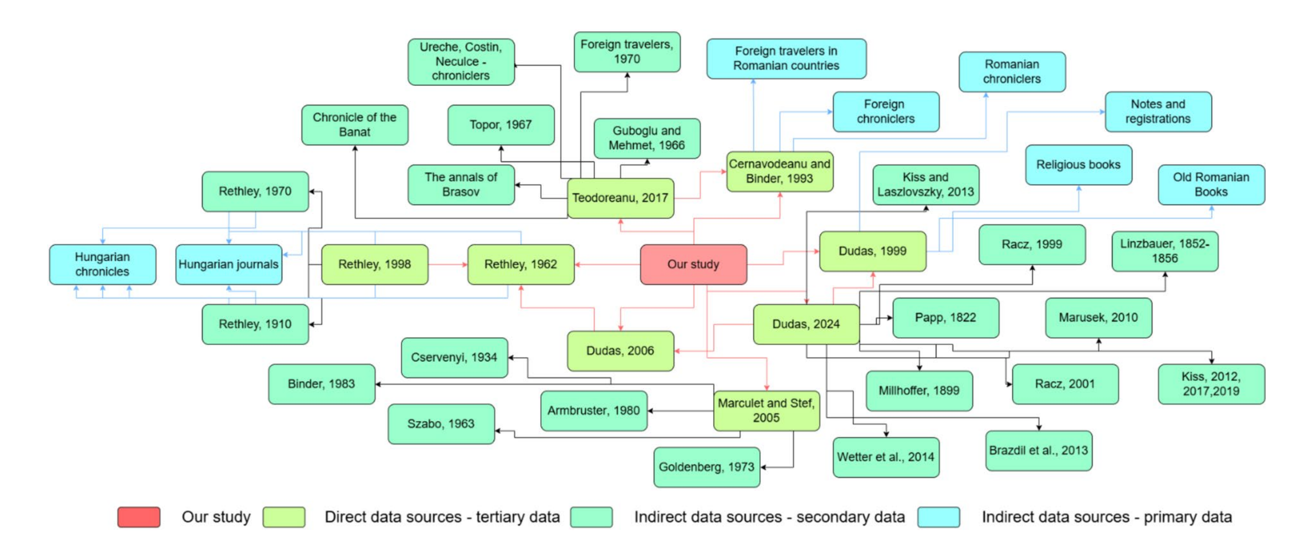

FIGURE 2
The sources used in the reconstruction of climatic events from the 16th century on the territory of Transylvania.

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volume of information to identify meteorological phenomena. This is because meteorological events are usually neglected in these sources, and their research object is always different (social, economic, political events, etc.).

The data sources used in the analysis are classified on three levels, according to the age and nature of the writings, to ensure a systematic and rigorous approach to the information. Tertiary sources include works consulted in detail, which provide a synthesis of historical events, with particular emphasis on climatic aspects. These sources do not add new information to the literature, but are based on the analysis and interpretation of primary and secondary sources, providing context and an integrated perspective. Secondary sources mainly consist of old writings, which either directly document meteorological phenomena or, indirectly, provide valuable information about historical climatic events, thus contributing to the reconstruction of the climatic context of the era. As for primary sources, they are original documents such as religious books, chronicles, travelogs and other historical writings that record events in a direct manner. Many of these documents are preserved in Romanian and Hungarian archives, either in their original form or republished, thus constituting the essential factual basis for detailed analysis of the historical climate (Figure 2). Among the cited sources, the works of Teodoreanu (2017) and Cernovodeanu and Binder (1993) focus on the presentation of meteorological information covering the entire territory of Romania, offering a broad perspective on climate variations. In contrast, the studies carried out by Mărculeț and Ștef (2005), as well as those by (Dudaș, 1999, 2006, 2024), focus the analysis exclusively on the current territory of Transylvania, bringing valuable details regarding regional climate phenomena. A significant contribution is also made by the works of Réthly (1962) and Réthly (1998), who, in the specific political and administrative context of the 16th century, provide a detailed compilation of climatic events and natural disasters documented on the territory of Hungary. His work should be based especially on the notes made by Hungarian chroniclers such as Gyulafy Lestár, Bruckner, Istvánffy Miklós, Farkas Bethlen, medieval documents of the Hungarian National Archives, historical works (Bánlaky, Bártfai, Kubinyi, etc.) or travel diaries.

The data obtained from historical sources can be considered quantitative, as they are extracted from subjective observations and descriptions made by the authors in the context of their era. The process of extracting this data involves two distinct situations. In the first situation, the authors accurately recorded the climate development or event, for example, statements such as "*all summer it was hot, and there was a great drought*" or "*this year there was a lot of snow and a hard winter*." These records facilitate the interpretation of the data, as they leave no room for ambiguity regarding the climatic characteristics of the respective season or year. In the second situation, climate information must be inferred based on indirect descriptions of the events. For example, statements such as "*strawberries were picked in October*" indicate unusually warm weather, "*the Danube froze*" suggests a very cold period, and "*the rivers dried up*" denotes a hot and dry period. These deductions require careful interpretation and correlation with other sources to validate the hypotheses.

An aspect that complicates the scientific analysis is the existence of inconsistencies between the information from different sources, especially between the documents from Hungary and those from Transylvania. However, given the spatial distribution of climate phenomena, these discrepancies may sometimes be plausible. Other difficulties include the lack of information for certain periods and the language barriers associated with the age of the sources. The documents are written in various languages, such as Hungarian, Slavonic with the Cyrillic alphabet, Latin (for nobility or Catholic ecclesiastical institutions) and Turkish (for the administrative context of Wallachia and Moldova). These particularities require an interdisciplinary effort to translate, interpret and validate the data so that they are integrated into a coherent scientific analysis.

The process of extracting climate data from the original sources also involves an intervention by the author. To determine whether a year can be classified as a "hot year," there must be explicit descriptions of extreme heat events, such as prolonged droughts, rivers that dried up, or crops compromised by high temperatures. To systematically quantify qualitative descriptions, as Butzer and Pfister (1987) also indicate, for example, a "hot year" can be defined by the existence of several independent reports of heat and its socio-economic impacts, such as food shortages or an increase in mortality. At the same time, it is very difficult to eliminate subjectivism from such sources, considering that it is an own experience of the person recording, being by its nature a subjective one. But a conservative approach must be kept in cases of ambiguity, of unclear records (which are classified separately) or that are not expressive enough to draw a well-documented conclusion.

Databases containing meteorological events in Transylvania, Hungary, or other parts of the continent can bring the necessary (but never sufficient) information. However, these are few and sometimes erroneous, especially in older works that deal with larger areas. These databases (especially proxies) can also serve as an element of comparison between those drawn up by different historical sources and what modern methods of reconstructing the climate of the past indicate, to obtain a more objective and comprehensive overview. In the present study, the comparative databases used are mainly represented by the Old World Drought Atlas (OWDA) maps, which use the self-calibrating Palmer Drought Severity Index (scPDSI) to determine the degree of aridity of the climate of European territory and north Africa between the year 0 AD and until now (Cook et al., 2015).

Based on the previously mentioned bibliographic sources, the notes on the climate from the 16th century on the territory of Transylvania were divided, according to the climate component, into three categories: cold and warm years, dry and rainy years, and respectively, calamities associated with the climate. Cold and warm years are based on information about the thermal regime, with particular emphasis on hot years (HY) and hot summers (HS), as well as on hot winters (HW) and cold winters (CW). The purpose of dry and rainy years is to obtain information about the precipitation in that period, representing them through a number of four components: dry year (DY), rainy summer (RS), floods (FD), and rainy year (RY). Finally, climate-related calamities cover a wide range of events, from hail (H), famine (FA), plaque epidemic (PE), locust invasion (LI), weak harvests (WH), strong storms (SS), thunderstorms (TS), fires (FI), and even earthquakes (EQ) (Figure 3). Some of these are difficult to associate with the effects induced by the climate; they belong more to the social, cultural, geological, or biological spectrum, but they indeed represent only a link in a much more complex chain, within which the climate undoubtedly played an important role. This perspective can be best illustrated by the analysis of epidemics (PE in the case of the present work), which, in addition to the fundamental biological causes, are influenced by many other factors. A significant

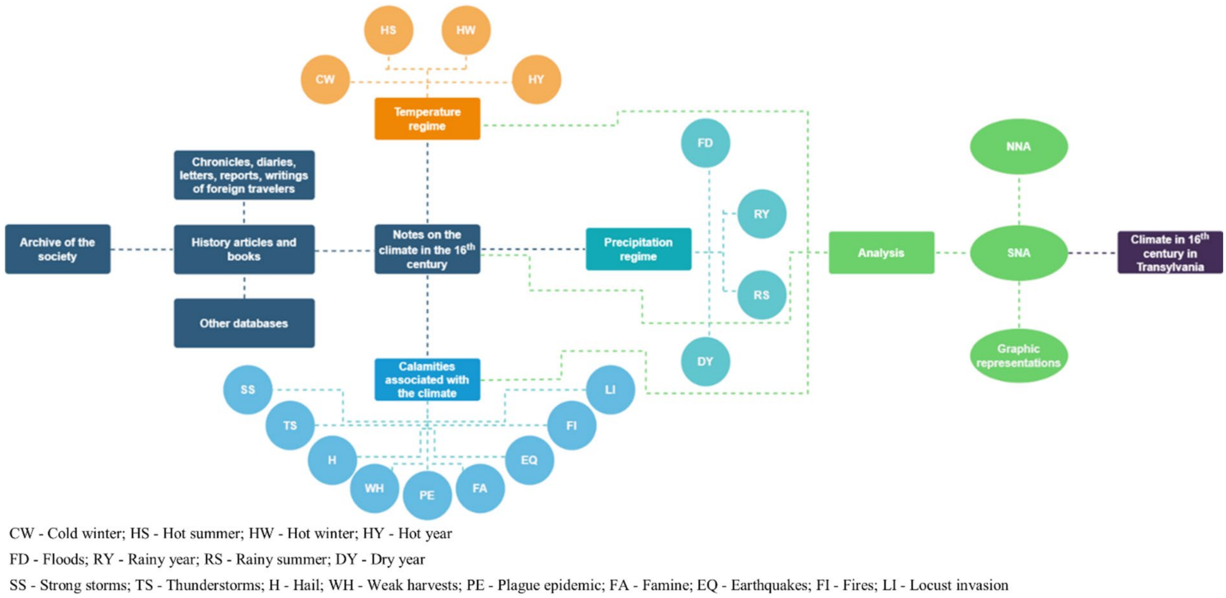

FIGURE 3
The integrative reconstruction and analysis methodology of historical climatic events in Transylvania from the 16th century.

factor is the climate, which contributed to the spread of epidemics in the past, although it was not their only determinant. Climate has particularly influenced through its effects on agriculture, such as FA caused by climate disturbances, including droughts, floods and LI. These extreme climatic events weakened the nutritional status of populations, making them more vulnerable to disease and favoring the spread of epidemics. Thus, climate played an indirect but crucial role in amplifying the impact of historical epidemics, and a one-sided relationship between cause (microbe) and effect (epidemic) is all the less feasible as causality is, most of the time, so complex (Pillatt, 2012; Boia, 2020).

The data were processed and interpreted using advanced statistical and visualization tools to comprehensively and rigorously analyze the collected information. Specifically, the software R 4.4.1 and MathLab R2024a were used to create graphical and heatmap representations, which allowed a clear visualization of the evolution of climate events throughout the 16th century. These visualizations were essential for identifying temporal and spatial patterns and highlighting significant climate anomalies. To centralize and present the data in an accessible and easy-to-interpret way, Neural Network Analysis (NNA) and Social Network Analysis (SNA) were implemented. These analyses were conducted using Gephi 0.10.1 and VennMaker 2.03 software, which facilitated the creation and visualization of complex interaction networks between different climate phenomena. NNA was employed to model the evolution of climate elements and their impact, emphasizing the non-linear interactions between various climate variables. SNA was crucial in examining and visualizing the connections between climate events and their societal impacts, identifying critical nodes and key routes for influence propagation. Additionally, to ensure a nuanced interpretation of the historical and climatic data, direct quotations from the consulted literature were included to provide authentic context and maintain informational accuracy, especially when classifying certain complex data (Figure 3).

For years in which no evidence of climatic conditions was identified, they were classified as WI (without information) within the models used. The lack of data can have many causes, but most often it is explained by the tendency of the people of that time to record only special or extreme climatic events. Therefore, a WI year may indicate a relatively stable and favorable climate without notable events. However, other possibilities must be considered, like the fact that there could be unusual climatic conditions that were either not observed or not recorded by contemporary authors for various reasons, such as neglect or prioritization of other subjects. On the other hand, documents containing such records may have been damaged, lost or destroyed over time, thus limiting access to complete information. At the same time, in the context of Transylvania from the 16th century, the available data are less compared to those in Western Europe, but significantly more numerous than those from the other two Romanian principalities. This difference largely reflects the social and economic context of the period, which influenced both the frequency and detail of historical records.

To reconstruct the evolution of climatic conditions, descriptions of weather from various historical sources were compared to identify recurring themes. The frequency of congruent records was used as an indicator of data accuracy. In cases of conflicting information, a mapping of source locations was carried out to identify local differences and variations caused by microclimates. Irreconcilable information was excluded, but for the 16th century in Transylvania, the sources proved generally homogeneous, providing a solid basis for climate analysis. This approach allowed a rigorous integration of historical data, reducing uncertainties.

4 Results

4.1 Cold and warm years

Historical documents mention that there were 40 HS, seven HY, eight CW, and one HW in this century. If the available information has

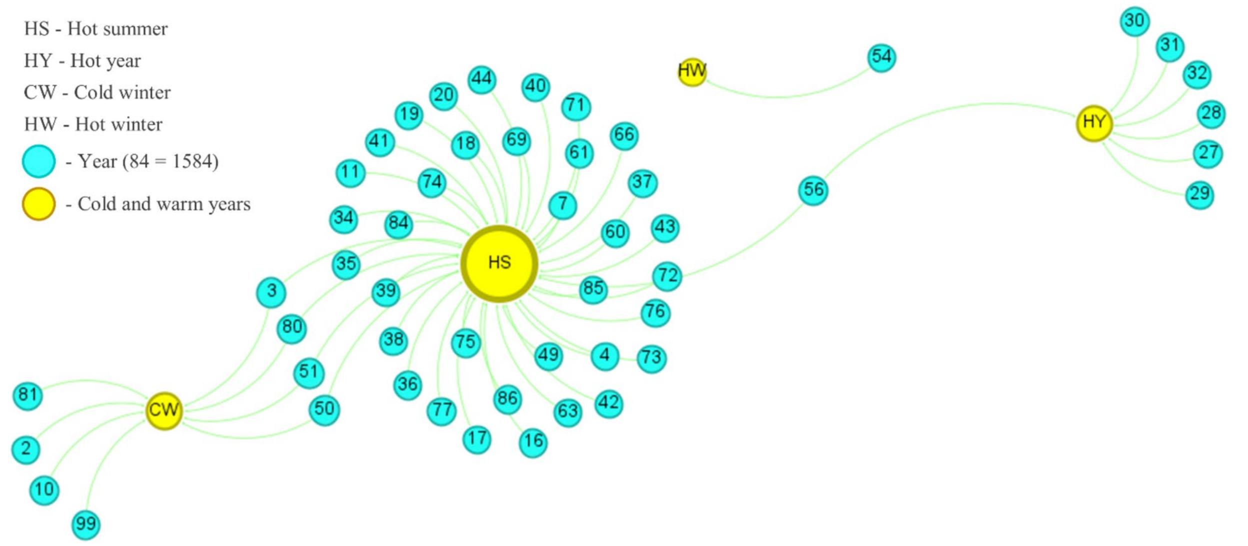

FIGURE 4
The temporal network of the thermal regime in the 16th century. Correlations between years and climatic events associated with temperature.

been unilateral and single for most years, some exceptions exist. Thus, in 1503, 1550, 1551, and 1580, particularly hot weather was reported during the summer, doubled by very cold weather in the winter. At the same time, the year 1556 is characterized by HS and HY, indicating its extreme potential in terms of high temperatures (Figure 4).

CW were recorded at the beginning, respectively, at the end of the century (Figure 4). The first CW is assigned to the year 1502 when "*after December 6, the frosts started and it snowed a lot*" (Teodoreanu, 2017); in 1510 when, due to the harsh winter, the reserves of hay for animals dried up, leading to a series of thefts, reported in Timis county (Kiss, 2019; Dudaş and Urdea, 2021); in 1550, when the winter was very harsh and so long that it lasted until March on the shores of the Adriatic Sea and until May in Transylvania (Réthly, 1962). The latter was followed by a short HS and again by cold starting at the end of September in Transylvania, the abandonment of the siege of the Timişoara fortress on October 25, 1551, being attributed by some chroniclers to the cold and rains (Réthly, 1962; Guboglu and Mehmet, 1966; Guboglu, 1974; Dudaş, 2006; Haţegan et al., 2006). After these CW, the reporting of particularly cold weather episodes decreased until the end of the century, when some authors mention the years 1570, 1580, 1581, and 1599 as having CW with blizzards, sleet, and frost (Teodoreanu, 2017). Atypical for this period was the HW reporting, which was mentioned only once, namely in 1554, when "*the poor harvests of the rainy years and the atypical weather from the fall of 1553 and the winter towards 1554, sunny as if it were spring, caused the malnutrition that facilitated the terrible plague epidemic of 1553–1554, especially in the south of Transylvania*" (Mărculeţ and Ştef, 2005).

Much more often, there were episodes of particularly hot weather and heat waves, which affected the Pannonian Plain or Central Europe, with the possibility that some also affected Transylvania. Figure 5 indicates that hot weather was recorded with a much higher frequency than cold weather on the territory of Transylvania; many times, the heat waves were mentioned in several consecutive years. Thus, three periods with high frequency of thermal events associated with hot weather can be identified throughout the 16th century. The first occurred at the beginning of the century, from 1,511 until 1,520, followed by a lack of information regarding the thermal regime for seven years (Kiss, 2019). Records about heat events returned in 1527, when the longest period associated with hot weather of the 16th century was singled out, with five HY and 12 HS in 20 years. In the interval 1,527–1,532, HY were reported, after which the historical sources do not mention anything about the weather for two years, and then there is an interval of 11 years (1534–1544) with excessively hot and dry summers, accompanied by LI, which sometimes covered the whole sky and destroyed grain crops causing terrible FA almost every year (excepting only 1535 and 1538) (Cernovodeanu and Binder, 1993; Teodoreanu, 2017). Some sources mention devastating effects associated with HS from this period, as was the case in the summer of 1540, when high thermal values led to the drying up of springs and streams in Transylvania, western Romania and all of Hungary, this year being excessively warm and dry throughout Central and Western Europe (Pap, 1822; Millhoffer, 1899; Réthly, 1962; Réthly, 1998; Rácz, 1999; Rácz, 2001; Dudaş, 2006; Marusek, 2010; Brázdil et al., 2013; Wetter et al., 2014). The third warm period started in the middle of the century (1556). It was manifested intermittently until 1571, when seven consecutive years (until 1577) with particularly hot and dry summers were recorded (Figure 5).

These periods of thermal variations and (mostly) unusually hot weather undoubtedly had a significant impact on the environment and society. Prolonged heat waves, often associated with droughts and unusually cold winters, could affect agricultural production, leading to food shortages, FA, forced migration, and social instability.

4.2 Dry and rainy years

In addition to the analysis of the thermal regime, an essential element in the reconstruction of the 16th century climate in the Transylvania region is the rainfall variability. This factor plays a decisive role in the economic and social stability of the principality, significantly impacting the demographic dynamics and the level of economic development. Fluctuations in precipitation directly

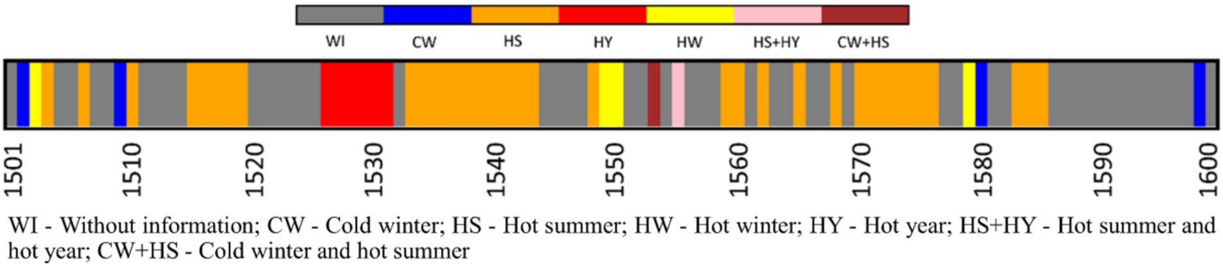

FIGURE 5
Temporal reconstruction of temperature-related climate events from the 16th century on the territory of Transylvania.

influenced agricultural productivity, which conditioned food security, internal migrations, and the resilience of communities to extreme climatic phenomena (Pfister and Brázdil, 1999). In the literature, extended periods of wet conditions have received relatively less attention than droughts, although both can severely disrupt agriculture and society (Posthumus et al., 2009).

During the analyzed period, 29 DY, 14 RY, 11 RS and 25 years with FD were registered on the territory of Transylvania. Data analysis shows that in 20% of cases where FD were reported, they were associated with HS. This moderate relationship suggests that high temperatures may precede intense precipitation, contributing to the creation of favorable conditions for flooding by loading the atmosphere with moisture and intensifying meteorological processes. The proportion of 20% was calculated by identifying years in which FD and HS were reported simultaneously and relating them to the total number of years with FD. Similarly, for RS and RY, 16% of FD cases are associated with heavy rainfall periods. This proportion indicates that, in certain situations, large amounts of precipitation are determining factors in the occurrence of FD.

The calculation of percentages is based on the co-occurrence of events, and the moderate correlation emphasizes the link between extreme climatic conditions and their impact on the studied region. The interpretation of these data provides an insight into the causal relationship between extreme climatic conditions, such as heat or heavy rains, and the occurrence of floods in Transylvania during the analyzed period (Figure 6).

In the first decade of the century, historical sources mention the presence of the following dry years: 1503, when the drought affected parts of Transylvania and Hungary (Réthly, 1962; Topor, 1964; Dudaş, 2006; Kiss, 2017); 1504, when the drought affected the western part of Hungary (Réthly, 1962; Kiss, 2017) and 1507 (Kiss and Nikolić, 2015; Kiss, 2017), when they affected other parts of Hungary. In the following decade, the drought affected most of Central and Western Europe, and in 1511, the good wines obtained in Transylvania were mentioned due to the summer drought (Teodoreanu, 2017). Also, in the interval 1516–1520, DY were recorded throughout the west and center of Romania, including the territory of Transylvania (Kiss, 2019).

In the following years, droughts became increasingly frequent. In the summer of 1534, a severe drought in the Făgăraș district led to widespread FA (Cernovodeanu and Binder, 1993). Historical sources describe 1549 as a particularly dry year in Transylvania, with fires reported due to prolonged drought from April through most of the year (Réthly, 1962; Topor, 1964; Rácz, 2001; Teodoreanu, 2017). High temperatures were recorded in Sibiu in April 1556 (Réthly, 1962; Rácz, 1999; Rácz, 2001; Dudaş, 2006), and by 1560, droughts affected both western Hungary and Transylvania (Réthly, 1962; Dudaş, 2006). Similarly, in 1563, a dry summer and autumn hit Transylvania, western Romania, and Hungary (Millhoffer, 1899; Réthly, 1962; Dudaş, 2006). In July–August 1566, a heatwave exacerbated the drought in western Transylvania and eastern Hungary, contributing to the Turks' conquest of Gyula fortress (Réthly, 1962; Réthly, 1970; Cernovodeanu and Binder, 1993).

The 1570s were also marked by dry conditions. In May 1572, the Sultan ordered supplies for Timisoara due to possible crop failure from drought (Haţegan, 2005). From 1573 to 1577, heat and drought led to famine, wars, and a large plague epidemic in Transylvania (Mărculeţ and Ştef, 2005; Teodoreanu, 2017). After heavy rains in May 1580, another drought occurred, lasting through summer and autumn (Réthly, 1962; Rácz, 1999; Rácz, 2001). The drought continued into 1584, and by 1585–1586, summers were so dry that rivers dried up, and mills became unusable (Mărculeţ and Ştef, 2005). In 1590, drought struck Braşov and much of Transylvania and Hungary (Dudaş, 1999; Pap, 1822; Réthly, 1962; Dudaş, 2006), a fact also confirmed by OWDA models.

In addition to frequent droughts, the 16th century is also characterized by a high frequency of RY and excess rainfall events, especially in its second half. Since the beginning of the century, there have been recorded situations with excess precipitation, often accompanied by FD. Thus, in 1501 there was a RS with large FD in the Danube region (Teodoreanu, 2017) and in Central Europe (Linzbauer, 1852; Topor, 1964; Réthly, 1970; Kiss, 2012; Kiss and Laszlovszky, 2013), which extended to Transylvania (Millhoffer, 1899; Réthly, 1962; Dudaş, 2006). The summer of 1508 is recorded in several sources (Réthly, 1962; Topor, 1964; Cernovodeanu and Binder, 1993; Rácz, 1999; Rácz, 2001; Dudaş, 2006; Kiss, 2012; Kiss and Laszlovszky, 2013) as being excessively wet, with almost daily precipitation in Transylvania between May 29 and August 24 resulting in FD that also affected western Romania, Hungary and even Moldova (Réthly, 1962). FD also expanded in the following year (1509), with an RS recorded in western Transylvania (Millhoffer, 1899; Réthly, 1962; Annales of Braşov cited by Topor, 1964; Cernovodeanu and Binder, 1993; Dudaş, 2006). In July 1521, rains generated into FD of the Drava at Osijek or of the Drina and Sava in the confluence area (Millhoffer, 1899; Réthly, 1962), in the period July–October 1526, rains and FD are mentioned in Belgrade, in the west of Vojvodina, in the south of Hungary and Szeged (Réthly, 1962; Réthly, 1970; Réthly, 1998; Topor, 1964; Rácz, 1999; Rácz, 2001; Dudaş, 2006; Kiss, 2012), and in Braşov in August large FD washed the walls of the fortress, demolished the main gate,

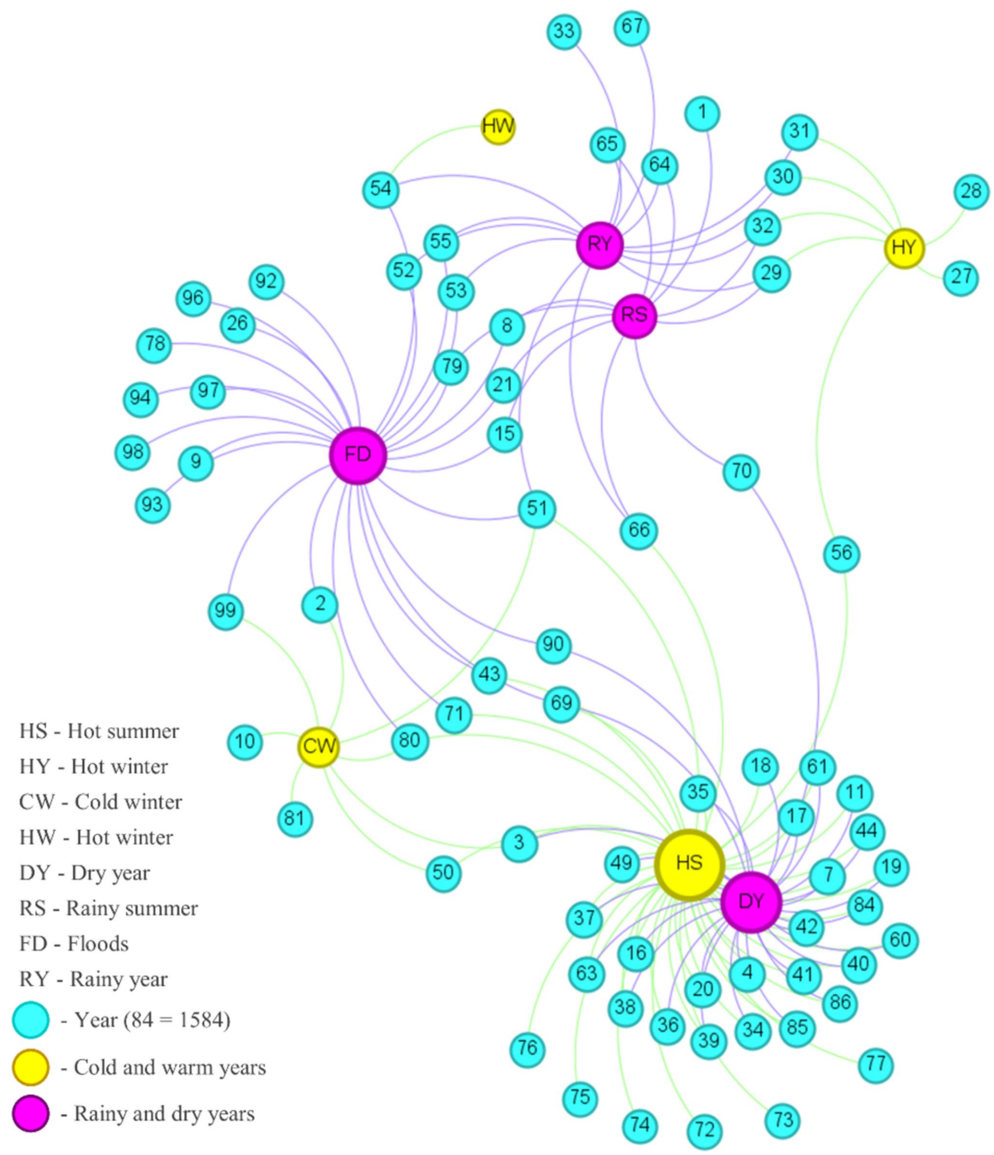

FIGURE 6
The temporal network of the thermal and pluviometric regime in the 16th century. Correlations between years and climatic events associated with temperature and precipitation.

and the fish also got caught in the big church (Annals of Brașov cited by Teodoreanu, 2017).

The period 1529–1533 was again characterized by abundant precipitation in the Brașov area (the most significant in July–August 1529), FD and plague, but also in western Romania, the south-west of the Pannonian Plain and Transylvania (in November 1530, heavy precipitation in Buda) (Réthly, 1962; Rácz, 1999; Rácz, 2001; Cernovodeanu and Binder, 1993; Dudaș, 2006; Kiss, 2012), between June and August 1532 rains in the area of the city of Belgrade and in the south-west and west of Hungary (Réthly, 1962; Rácz, 2001). The year 1533 was also rainy with H and FD (Mărculeț and Ștef, 2005); the largest being recorded in Țara Bârsei and the Depression of Sibiu (Annals of Brașov cited by Teodoreanu, 2017).

After a very rainy October in 1543, which hindered the Turks' progress between Buda and Constantinople, the mid-16th century saw frequent excess precipitation (Réthly, 1962; Rácz, 1999; Rácz, 2001). In 1551, heavy rains in Banat, combined with cold air, forced the Turks to lift the siege of Timisoara, though they returned and captured it the following year (Dudaș, 1999; Guboglu and Mehmet, 1966; Hațegan et al., 2006; Mehmet, 1980). In 1552, Cluj experienced heavy rains, and by autumn 1553, unusual weather events like October strawberries were reported. The following winter was warm, leading to malnutrition and a deadly plague in 1553–1554, particularly in southern Transylvania (Cernovodeanu and Binder, 1993; Mărculeț and Ștef, 2005). The 1554–1555 period was marked by excess precipitation, causing floods in Maramureș (Dudaș, 1999).

Following a decade of either dry years or limited recorded events, another cycle of heavy rainfall began in 1564. This period brought poor wine quality in Transylvania and heavy autumn rains in the Pannonian Plain, Slovakia, and western Hungary (Pap, 1822; Réthly, 1962; Cernovodeanu and Binder, 1993). In 1565, flooding affected the Târnava Mare River near Mediaș (Dudaș, 1999). In 1566, heavy rainfall and swamping made the Turkish siege of Gyula difficult, while the Danube and Drava Rivers, as well as three major rivers in western Romania, also experienced floods (Réthly, 1962; Rácz, 1999; Rácz, 2001). By 1,569, heavy rains impacted Sighișoara and Mediaș, continuing the pattern of frequent precipitation (Dudaș, 1999).

The following decade began with FD in 1571 (Dudaș, 1999) and ended also with FD, in 1578, when they "*kept a chain in Transylvania, both in spring and winter, the seeds planted on the plains and in gardens have not sprouted*" (Mărculeț and Ștef, 2005), a fact confirmed by other historical sources that record excess precipitation accompanied by FD in June in Transylvania (Réthly, 1962; Cernovodeanu and Binder, 1993; Dudaș, 2006) and, generally a wet year in western Hungary, at Sopron (Réthly, 1962). The year 1,579 was characterized by an extreme RS (Teodoreanu, 2017), and 1,580 by a rainy spring that generated a new FD in May in Transylvania (Réthly, 1962; Rácz, 1999; Rácz, 2001; Dudaș, 2006).

The last decade of the 16th century saw 7 years of excess precipitation and frequent FD. In 1590, heavy rains affected Brașov and southern Transylvania (Dudaș, 1999), while in December 1592, FD was recorded again in western Romania and Transylvania (Réthly, 1962; Dudaș, 2006). In 1593, significant rainfall across Hungary, Transylvania, and Slovakia caused widespread FD, with waters rising to half a man's height in Transylvania on August 20, and more FD followed due to heavy rains and H in late August (Millhoffer, 1899; Réthly, 1962; Topor, 1964; Dudaș, 1999). The summer of 1594 was also characterized by FD in Transylvania and western Romania, and 1596 had FD both north and south of the Pannonian Plain (Réthly, 1962; Rácz, 1999; Rácz, 2001).

In 1597, abundant precipitation again led to FD across Transylvania, western Romania, and into Hungary and Slovakia (Réthly, 1962; Dudaș, 2006), and in 1598, large FD were recorded, with a suburb of Alba Iulia submerged (Millhoffer, 1899; Réthly, 1910). In 1599, during the siege of Oradea, rains lasted over a month, causing floods and delays in the Ottoman advance. Turkish chroniclers noted swollen rivers and non-stop rains for over 40 days from late August to early October, creating further challenges for the Ottoman army (Guboglu and Mehmet, 1966; Réthly, 1998; Ibrahim Pecevi quoted by Teodoreanu, 2017).

The temporal analysis of the events related to the rainfall regime indicates two distinct sequences within the 16th century on the territory of Transylvania. Thus, the first half of the century recorded significantly more information, covering 33 years, compared to only 29 in the second half, the remaining 38 years not recording any information in the historical sources. At the same time, the first half is characterized by a higher incidence of reports about events associated with drought (20 years) compared to those considering FD, RY or RS (13 years). The second half was wetter, in 19 years FD, RY, RS or a combination of the three were reported, in 7 years DY was recorded, and the information about the remaining 3 years is contradictory (FD + DY and RS + DY)

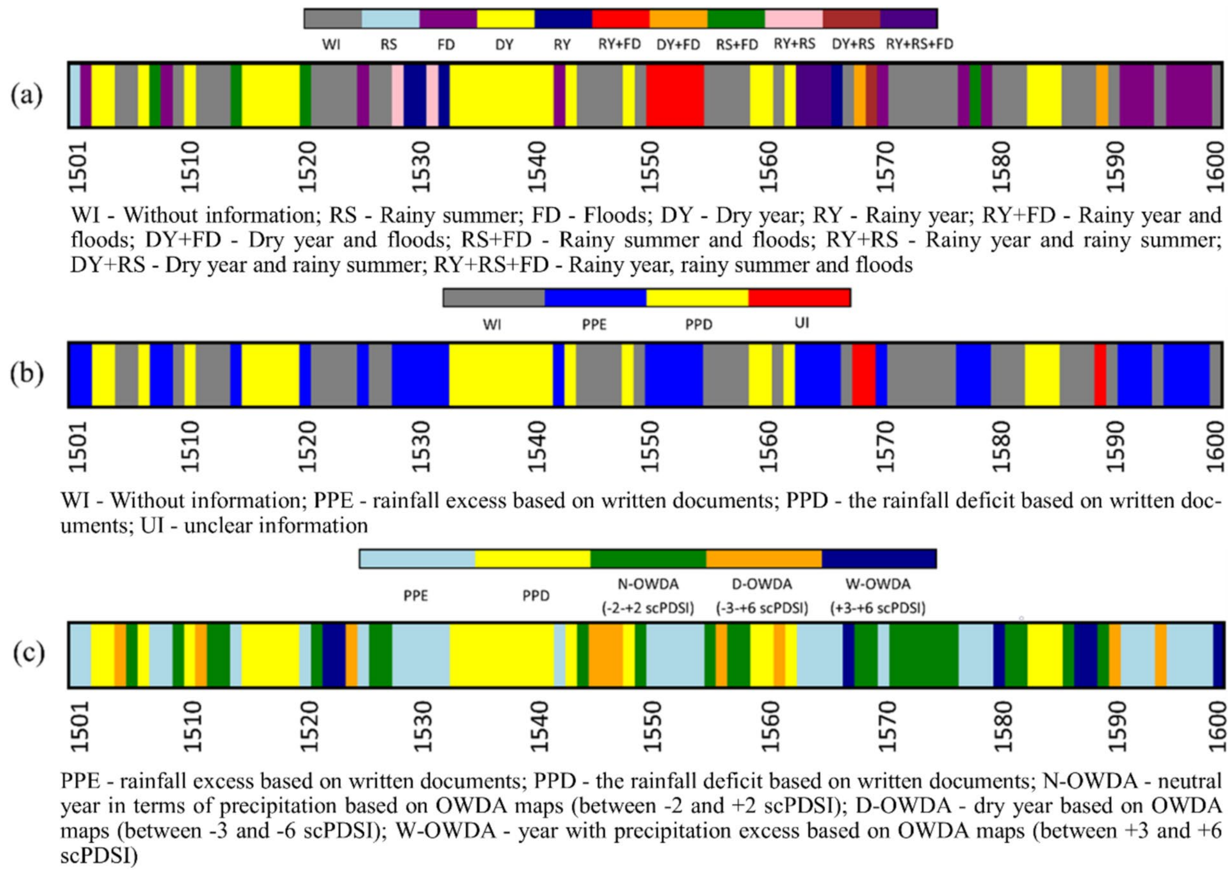

FIGURE 7
The temporal reconstruction of the variations of climatic events related to the rainfall from the 16th century on the territory of Transylvania (**A**—reconstruction based on the testimonies from the historical documents; **B**—simplified reconstruction of the periods with excess and pluviometric deficit; **C**—the completed data series based on OWDA maps).

being noted with UI (unclear information), which makes impossible a general characterization of the weather of the respective year in terms of rainfall excess or deficit. However, the integral analysis of the century highlights a higher prevalence of events associated with rainfall excess (33 years) compared to those characterized by rainfall deficit (27 years) (Figures 7A,B).

Considering the fact that the information in the written documents covers only 62% of the 16th century, for a more accurate characterization of the climate in this historical period, the years in which no testimonies were recorded were corroborated with the existing proxy data in the OWDA maps (Cook et al., 2015). Thus, five different categories were individualized, data expressing the rainfall excess based on written documents (PPE), data expressing the rainfall deficit based on written documents (PPD), data indicating a neutral year in terms of precipitation based on OWDA maps (between −2 and +2 scPDSI) (N-OWDA), data expressing a DY based on OWDA maps (between −3 and −6 scPDSI) (D-OWDA) and representing a year with precipitation excess (between +3 and +6 scPDSI) (W-OWDA) (Figure 7C). The obtained values illustrate with even greater fidelity the fact that the first half of the 16th century was dry, with 25 years with events associated with pluviometric deficit, 15 years with excess and nine neutral years. In the second half, the scale tilts for the years with excess precipitation (25 years), so that the dry ones are found in the amount of 10, and the neutral ones in the number of 15 (Figure 7C).

Corroboration of information from historical sources with proxy data extracted from OWDA maps confirms the trend identified within the analyzed written documents, clearly illustrating a change from drought conditions in the first half of the century to wetter conditions in the second half.

4.3 Calamities associated with the climate

In the 16th century, historical documents record a variety of natural calamities, which can be directly or indirectly associated with climate. Some of these events had a considerable magnitude and affected large regions of Transylvania, leaving deep traces in the collective memory of the era, while others were recorded sporadically, mentioned only in passing in the historical sources. Regardless of their nature and scale, these calamities have contributed significantly to the deterioration of living conditions, intensifying the population's suffering and amplifying mortality rates. It is important to emphasize that historical documents from that period fail to cover all dangerous manifestations of nature exhaustively. Often, they reflect only the events of significant impact, which attracted the attention of the chroniclers either because of considerable material damage or human losses or because of their unusual or terrifying character. Although numerous other phenomena naturally occurred, they were not recorded for various reasons, such as widespread illiteracy among the population, disinterest in common events, or habituation to these phenomena, given their repetitiveness.

Among the most frequent and devastating disasters recorded in this century, PE stands out (30 years), followed by FA (23 years) and LI (9 years). These are mostly interconnected, so in 17 years, PE and FA were reported together. This is, to some extent natural, because FA has the potential to make people much more prone to diseases (including PE), and the action of PE, by decreasing the number of the population and implicitly the labor force, ultimately determines FA. LI is most often recorded together with FA, all having a strong relationship with HS and DY (Figure 8). The extreme manifestations associated with the climate that have been recorded less and have a lower degree of danger are H (10 years), WH (2 years), FI (4 years), EQ (4 years), SS (2 years), and TS (1 year) (Figure 8).

Although historical sources document numerous epidemics that affected the population in the past, such as smallpox, leprosy, and cholera, the most feared of these, due to its high mortality rate and devastating impact on society, was the plague. This highly pathogenic disease was responsible for decimating large segments of the European population, causing waves of panic and suffering unprecedented in the continent's sanitary history. In many years, the mortality caused by PE has reached alarming levels, even increasing several times compared to the usual level. In Europe, the bubonic plague (with the lowest mortality, approx. 50–70%), but also the pneumonic plague (almost 100% death rate) circulated; overall, the mortality of the plague rising to 60–80% (Boia, 2020). Manifested with different intensities on the European continent between the 14th century and the beginning of the 19th century, it seems that the PE would have acted more moderately in the 16th century, in the sense that strong waves were not individualized, but rather sporadic cases.

This terrible disease spread in the Middle Ages and over the Romanian principalities, in the 16th century the records were considerably more numerous than in the previous centuries. Historical sources mention in this sense the presence of the black plague, also known in history as the "*black death*"; a variety of the bubonic plague, so named because of the black spots that appeared on the faces of the sick (Zietz and Dunkelberg, 2004).

In Transylvania, there were mentions of the black plague in the years 1508, 1510, 1520, 1523, 1529, 1530, 1533, 1551–1556, 1567, 1569, 1571–1575, 1585–1588, and 1600, but the outbreaks had lower intensity than in other countries, evidenced by the lower number of reported deaths (Cservenyi, 1934; Armbruster, 1980; Goldenberg, 1973; Dudaş, 1999). The most affected were human agglomerations, cities, and fairs, but even in the villages, the misery maintained the epidemic; only some villages in the mountains were safer, and the disease penetrated less often, being brought by refugees. The most dramatic consequences were the epidemics of the years 1551–1556, when the disease was brought from Wallachia, where it claimed thousands of human lives and several thousand other inhabitants were forced to take refuge south of the Danube. In Braşov it caused the death of 5000 inhabitants, and in Sibiu, in 1554 alone it killed 320 people. Between 1585 and 1586 in Oradea, 100–120 inhabitants died daily due to the plague, and many fled to the mountains, but escaping the plague, thousands died of hunger (Cservenyi, 1934; Szabo, 1963; Binder, 1993; Dudaş, 1999; Figure 9A).

Besides the PE, the FA was also a calamity that seriously affected people's lives in the Middle Ages. Rudimentary technique, subsistence agriculture, stagnant economy, social stratification, invasions of foreign invaders, LI, invasions of mice, but above all, the capricious climate established periods of FA throughout the European continent. In Transylvania, historical sources signal the appearance of shorter or longer periods of price increases or shortages of agricultural products, of years with high FA, without presenting the causes, but only the events experienced and the dramatic aspects of the calamities: the destruction of crops, the increase in prices, lack of food, death of animals and people. This is what happened in the years 1534, 1535, and 1536 when the prolonged FA caused most of the inhabitants of Transylvania to eat grass,

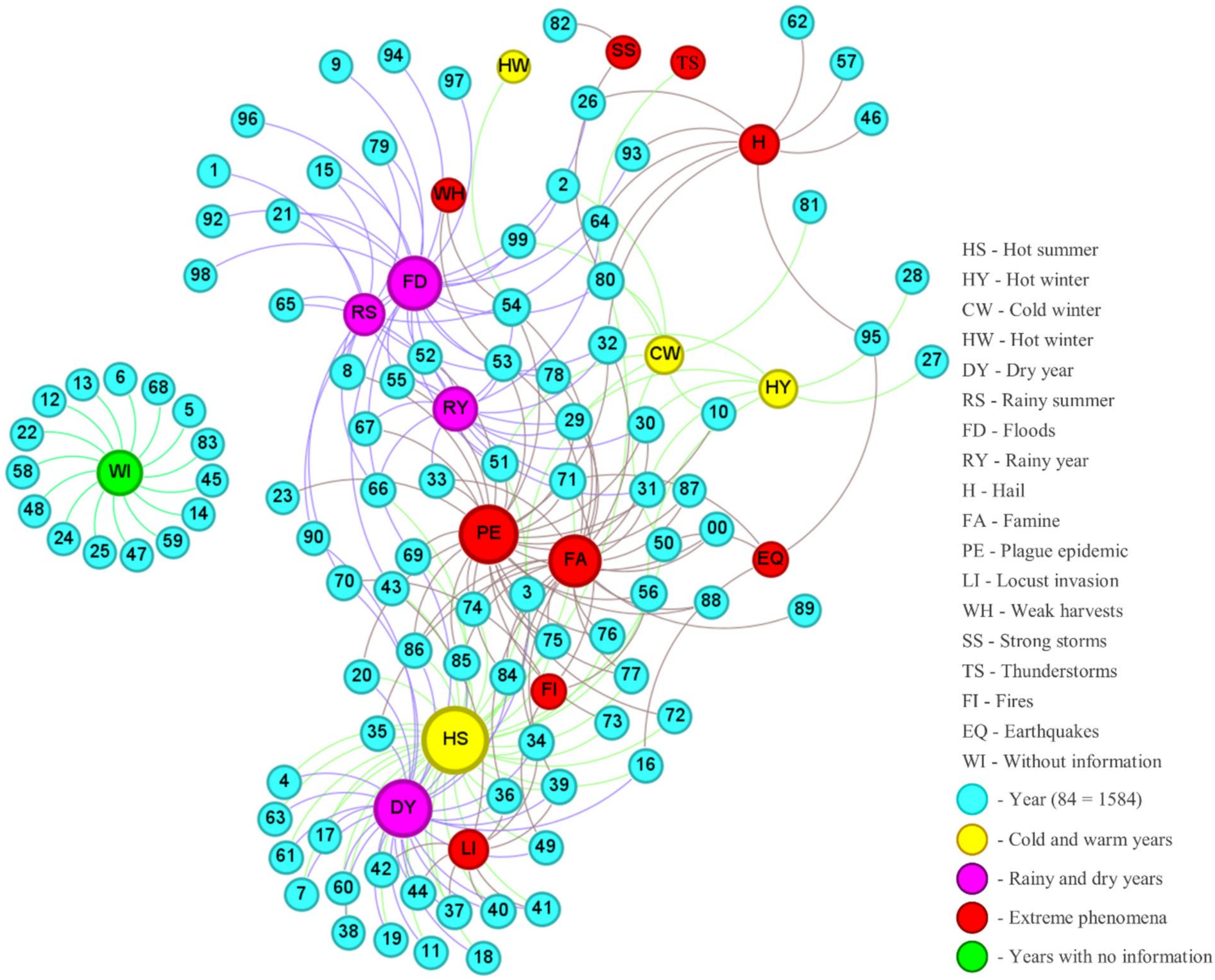

FIGURE 8
The temporal network of the thermal and pluviometric regime, respectively the natural calamities associated with the climate in the 16th century. Correlations between years and climatic events associated with temperature, precipitation and special events associated with the climate.

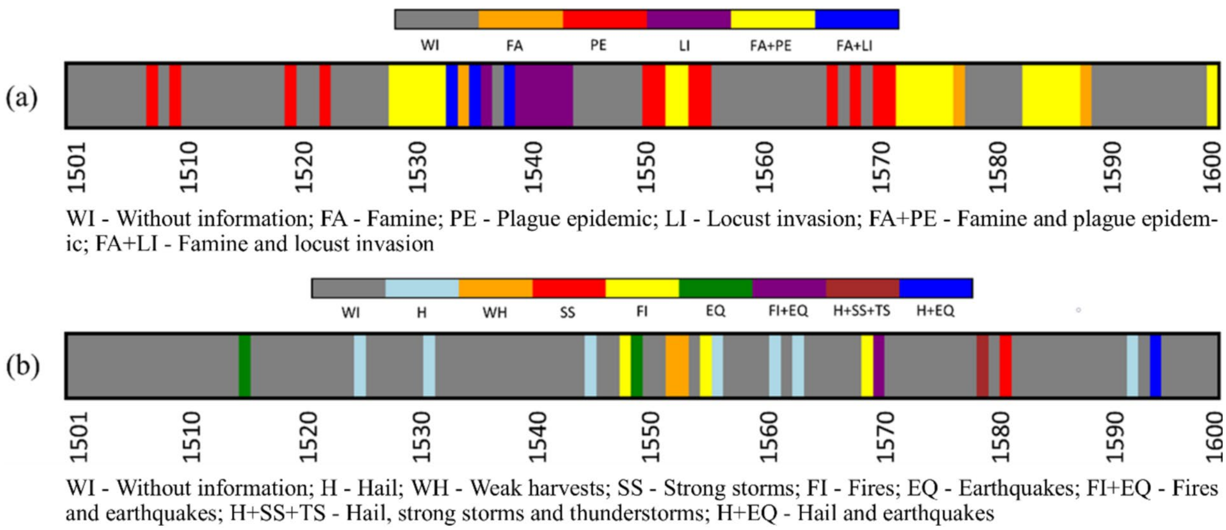

FIGURE 9
The temporal reconstruction of the variations of natural calamities associated with the climate in the 16th century on the territory of Transylvania (**A**—dangerous events mentioned frequently in historical sources, with a high destructive potential; **B**—dangerous events mentioned sporadically).

many losing their minds from hunger. Also, in the years 1553, 1578, 1586, 1589, and 1600, there was "*expensive and great famine*" in Transylvania (Foreign Travelers about the Romanian Countries, 1970). Although the causes were not consistent, the direct relationship between FA and PE, LI, HS, and DY provides an indication of the possible sources of these events (Figure 9). This was precisely indicated in the year 1,539 when the documents of the time mention that there was a large FA in Moldova and Wallachia due to the LI that decimated the harvests (Grigore Ureche cited by Teodoreanu, 2017; Figure 9A).

LI was mentioned in numerous cases and as a separate event, which played an amplifying role of social insecurity and uncertainty in the Middle Ages. The culprit for these calamities was *Pachytulus migratorius*, which came from the immense reeds of the Danube Delta and from the marshes of the lower courses of the great rivers. Dry environments provide suitable soil and climatic conditions for the growth, development, and reproduction of locusts; warm years and summers provide the ideal conditions. Such an invasion could be catastrophic, because the insects were part of huge flocks, which had the ability to devour the vegetation on large areas, causing FA and WH in particular. The largest LI of the 16th century occurred in 1542 and 1,544 when they decimated the crops of Wallachia, Transylvania and Hungary. To drive them away, the inhabitants used the bells and thunderbolts, which, together with the bad weather, contributed to their destruction, so that large piles were gathered from the dead locusts, some even fattening the pigs with them (Armbruster, 1980; Dudaş, 1999).

H was mentioned in 10 different years in Transylvania. In 1526 H had the size of a hen's egg on June 24 in central Transylvania, in 1533 in Brasov a particularly large H was recorded, in 1546 there was an unusually large H in Medias, and in 1557 H as "*goose egg*" on 18 June, recorded in Transylvania (Cernovodeanu and Binder, 1993; Dudaş, 1999; Annales of Braşov cited by Teodoreanu, 2017). In 1564, on July 25, unusual H fell in almost all of Transylvania, and in 1590 and 1593 there was unusual H and FD in Medias, respectively in Brasov (Dudaş, 1999). SS was mentioned only twice in the analyzed period, in 1580 and 1582. In 1582 on the 29th of September, there was such a big storm, as it was said that it had never been seen before in the city of Cluj, which uprooted the trees and raised the roofs of the houses, people believed that it is sent by divinity to punish the crimes committed by them (Teodoreanu, 2017). In 1580, in addition to the SS, the TS were also mentioned, on September 30, when a terrifying storm broke out that shook a tower in the city of Cluj and started a fire that killed 14 people and made 60 poor (Teodoreanu, 2017; Figure 9B).

Less mentioned, but just as destructive are FI, caused most of the time by heat waves. Having a well-developed wood civilization, the inhabitants of Transylvania were frequently exposed to them, especially in villages, where the houses and outbuildings were made of wood, covered with straw, reeds, shingles, but also in cities, where the buildings were very close and the fire was spreading fast. In the 16th century, Transylvania witnessed some FI of significant proportions, which took place in the context of extreme climatic conditions, such as prolonged and intense drought. Among the most devastating FI of the period is that of 1,549, when flames consumed a number of forests in the region. In 1556, on March 31, a major fire broke out in Sibiu, destroying 556 houses. Another major fire occurred in Sibiu on September 7, 1570, when 1,303 houses were destroyed. In 1571, an entire town was consumed by flames, and in 1585, a devastating fire engulfed the city of Timişoara, which was destroyed (Cernovodeanu and Binder, 1993; Figure 9B).

In the end, more associated with geological causes than with climatic ones, EQ were also present in Transylvania, acting to degrade society and the economic situation of the principality. Thus, in the 16th century, only two such events were reported (probably those with a special character), in 1516 and 1550.

The historical data suggest a strong correlation between FA and PE, with cases of FA without PE being extremely rare. The PE occurred in three distinct periods: a five-year span at the beginning of the century (1529–1533), a six-year period in the mid-century (1551–1556), and a longer 13-year interval toward the end of the century (1567–1588). These concentrated periods likely indicate successive waves of disease, as evidence outside these intervals is minimal (Figure 9A). LI were mostly concentrated in the middle of the century (1534–1544) and disappeared from records afterward, suggesting that they were episodic rather than characteristic of the period. In contrast, H and FI were reported more frequently, occurring in 12 years of the 16th century, likely due to their destructive impact on agriculture and human life, which often led to FA. Meanwhile, EQ and SS were recorded only sporadically, being documented in six isolated years, possibly due to their rare and exceptional nature, which evoked fear among contemporaries (Figure 9B).

5 Discussion

Climatological analysis of the 16th century reveals the fact that there were several years in which no evidence of the weather could be identified. The lack of climate data can be attributed to a variety of factors. First, it is important to note that at that time, people generally recorded only exceptional weather events that were outside the usual norm. Thus, in the years in which no evidence was found, it is possible that the weather was relatively stable and favorable, with no extreme events worth recording (Guidoboni, 1998). This is also expressed by Briffa et al. (1999) and Knapp et al. (2002), which indicate, based on proxy data, that in the 16th century, there were extended periods characterized by climatic stability and the absence of extreme events. It is also essential to recognize that access to education, and the ability to read and write was limited to a few people, usually clergy members or nobility. In small communities, the lack of such educated eyewitnesses could explain the absence of documentation for certain periods. Therefore, as Pfister (1999) mentioned, this absence of information should not necessarily be interpreted as a lack of climatic events, but rather as a reflection of the documentation norms and social priorities of the time.

The analysis of the periods in which the testimonies were recorded indicates that the great majority of the analyzed century is characterized by relatively warm weather, with HS and HY, particularly CW and CY, being mentioned very rarely. This aspect is even more interesting as it is contradictory because in the 16th century, the European continent was in the midst of manifestation of the LIA, made concrete by the cooling of the weather and the expansion of the mountain glaciers (Scott and Hoppa, 2019; Nicolussi et al., 2022). However, many works (Luckman, 2000; Bertler et al., 2011) indicate that the LIA manifested differently over time, characterized by great temporal and spatial variability. Thus, the LIA would have manifested itself most strongly in the 15th century in the central and eastern Pacific, in the 17th century in Europe (especially the central and eastern), and in the southeast of North America, respectively in the 19th century on the coasts of Alaska and the rest of the remaining regions (Neukom et al., 2019). Therefore, on the territory of Transylvania, it is possible that the period of maximum manifestation of LIA was individualized in the 17th century, during the Maunder Minimum, and in the 16th century it was manifested with a lower intensity. This is also indicated by Stangl and Foelsche (2022), who compare the climate of Transylvania in the 17th and early 18th centuries with that of Germany, Austria and Switzerland in the same period, characterized by very cold weather.

In addition to low temperatures, the LIA is also characterized as a wetter period in various regions, as indicated in the studies of Vincent et al. (2005), Zeng et al. (2012) or Stevens et al. (2018). Generalized wet periods were also identified in the information obtained from the bibliographic sources for the territory of Transylvania in the 16th century, concentrating especially in the second half of the century (but in general, the years of this century were reported more as being wet rather than dry). When droughts have been reported, they have often been accompanied by high temperatures, making it difficult to discern the primary cause of the drought—whether it is excessive heat or a lack of precipitation, both of which can significantly contribute to the drought (Camenisch and Salvisberg, 2020). A dose of subjectivism certainly crept into this information, because the rural societies of the 16th century in Transylvania, closely tied to the soil and poorly equipped technically, generally living at the lower limit of subsistence, were extremely sensitive even to relatively small changes in the climate, which could disrupt the fragile agricultural mechanism. Thus, most of the time, a small variation in one or more climate indicators could trigger a chain reaction such as climate disturbances—agricultural disasters—FA—epidemics, which leads to even more FA and even more suffering.

A detailed comparison between the climate data from historical sources from Western Europe and those from Transylvania indicates notable differences, highlighted in the work of Teodoreanu (2017). In Europe, the 16th century was predominantly characterized by cold climatic conditions, with events associated with cold being approximately twice as numerous as those associated with extreme heat. In contrast, in Transylvania, excessively HY and HS prevailed. Cold-related events in Western Europe are relatively evenly distributed throughout the century, with a slightly increased frequency in the second half, but with a more pronounced intensity after 1,560. Proxy data indicate a generalized cooling trend for Europe in the 16th century, but with occasional heating pads. For example, tree-ring reconstructions in the Alps suggest that cold winters were more common in the second half of the century, but summers remained relatively warm in some periods (Casty et al., 2005).

Regarding the ratio between RY and DY, three times more events associated with excess precipitation than with droughts (the normal situation in some places due to atmospheric circulation and the influence of sea currents) were reported in Western Europe (Wetter et al., 2014), while in Transylvania the latter prevail. Also, in Western Europe, droughts were more frequent in the second half of the century, while in Transylvania, this period was marked by FD and years of abundant precipitation. These are also supported by the OWDA maps, which indicate that in Western Europe, droughts were more frequent in the second half of the century, especially in regions such as Spain, southern France, and northern Italy. The events contrast with those in Transylvania, where droughts are generally more frequent during this period (Camenisch et al., 2016).

6 Conclusion

The 16th century was called by Romanian historians Cernovodeanu and Binder (1993) the *turbulent age* because the Romanian Principalities came under Ottoman suzerainty, and the states around them were transformed into Turkish pashaliks. To these social upheavals were added those determined by the climate, with excessively HS, droughts and FD, PE, LI, and FA.

The obtained results indicate that in the 16th century, in Transylvania, 40 HS, seven HY, eight CW and one HW were documented, with hot and dry summer periods that had a significant impact on agriculture and social stability, as observed in the period 1,556–1,577, when seven consecutive years of particularly hot and dry summers were recorded. Regarding the rainfall regime, 29 DY, 25 years with FD, and 14 RY were recorded, with the intense drought of 1,534 causing extreme FA, and in 1579, with a rainy summer that generated major FD, reflecting the variability of precipitation and their devastating impact on the population. The capricious climate also determined other natural calamities in Transylvania in the 16th century. Thus, FA was frequent, often caused by severe droughts and LI, as was the case in 1534 and 1,586, while devastating FI, fuelled by climatic conditions, they destroyed entire cities, such as Sibiu in 1556 and Timișoara in 1585. All this was doubled by the PE, with severe outbreaks in the years 1551–1556 and 1585–1586, causing the decimation of the population, as was the case in Oradea, where between 100 and 120 people died daily. Even if their origin is not the climate, we must not overlook the destruction caused by wars and the desolations of foreign invaders that led to a significant decrease in the population in Transylvania. The above-mentioned events led to a low standard of living for the inhabitants of these lands, although the province had a recognized high natural potential.

Although methodological limitations, especially the lack of testimonies (information of any kind) for a considerable number of 15 years, prevent us from formulating definitive conclusions regarding the climatic evolution of the 16th century in Transylvania, the analysis of the available data still reveals two essential climatic characteristics. The first of these is the great climatic variability, evidenced by considerable fluctuations between periods of severe drought and episodes of heavy rainfall, which have had significant consequences for agriculture and social stability. The second notable feature is the presence of dangerous climatic phenomena (such as heat waves, droughts, and FD) whose intensity is comparable to that of phenomena recorded during the instrumental period of modern climate determinations.

Despite these shortcomings, the available historical documents constitute an invaluable resource, providing valuable data that allowed the detailed reconstruction of these climatic events and their impact on Transylvanian society in the 16th century. By corroborating historical sources with modern proxy data, not only a deeper understanding of past climate variability, but also obtaining relevant information for managing current and future climate variability.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

OG: Conceptualization, Data curation, Formal analysis, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. TC: Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing – original draft. ŞB: Data curation, Investigation, Methodology, Writing – original draft. CM: Investigation, Methodology, Resources, Visualization, Writing – review & editing. MD: Investigation, Methodology, Software, Writing – review & editing. MS: Conceptualization, Formal analysis, Validation, Writing – original draft. MM: Investigation, Methodology, Software, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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