Severe winters during the Maunder Minimum and large scale drivers in Eastern Europe

Carmen - Andreea BĂDĂLUȚĂ[1,2,3]*, Monica IONITA[4] and Gheorghe BĂDĂLUȚĂ[1]
[1] Department of Geography, Ștefan cel Mare University, Suceava, Romania
[2] Stable Isotope Laboratory, Ștefan cel Mare University, Suceava, Romania
[3] Institute for Geological and Geochemical Research, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, Budapest, Hungary
[4] Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany

* Correspondence to: Carmen - Andreea Bădăluță. E-mail: carmen.badaluta@usm.ro.

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ABSTRACT: In this study we have developed an index which accounts for the occurrence of extreme cold winters based on documentary index and their social impact from Eastern Europe, over the Maunder Minimum period. In total, 41 harsh winters were extracted for the period from AD 1645-1715, and it's the longest one, on record, over this area. Our investigation shows that the harsh winters occurrence rate is variable in the three areas of Eastern Europe and it`s spans in two periods: the Early Maunder Minimum (EMM) and the Late Maunder Minimum (LMM). The results obtained show that the number years of harsh winters has increased considerably during the EMM (AD 1645– 1665) and have an occurrence rate ~ 0.83/year. During the LMM we observe a small decrease in the occurrence rate (~ 0.52/year). However, during the transition period between EMM and LMM in Ukraine and southwestern part of Russia the harsh winter occurrence rate (from ~ 0.15/year to ~ 0.45/year) show the maximum (~ 0.45/year), in opposition to the Carpathian regions where the minimum is recorded. The opposite trend in the harsh winter occurrence rate could be the product of different action of large-scale atmospheric circulation or the Carpathian Mountains barriers.

KEY WORDS: severe winters, documentary data, Maunder Minimum, Eastern Europe, large - scale atmospheric circulation.

1. Introduction

The Maunder Minimum period (MM) covers a relatively short time span (AD 1645-1715) and it is known as the coldest period from the Little Ice Age over Europe and corresponds with a period characterized by the lowest sunspot activity over the last millennium. Also, MM was associate with an enhanced volcanic eruption (Briffa et al., 1998) and an increased in atmospheric ^{14}C (Stuiver and Braziunas, 1993). During the Maunder Minimum the temperature reconstructions (T) from the Northern Hemisphere (NH) show a cold peak (anomaly to T = -0.18°C, relative to the 1902-1980 calibration period) (Mann et al. 1999). Thus, the cooling in the 17th century was different at the hemispheric level. This period was the coldest century in Europe (anomaly to T = -0.6°C), while in North America the highest cooling in the last millennium was recorded in the 19th century (Mann, 2002). In the same time the harsh winters affected human societies and harvest productivity. For understanding the climate changes over the past, the winter severity were analyzed on different proxy indicators, such as: dripwater or speleothems from the caves (Mangini et al., 2005, Fohlmeister et al., 2012, Ersek et al., 2018), ice core (Perșoiu et al., 2011, Perșoiu et al., 2017), ice river regime, like Thamisa (Lamb, 1977), etc. Besides these, the winter severity is also studied based on historical documents (Pfister et al., 1984, 1992, 1994) but they are few in number, their share being low in Eastern Europe (Yavuz et al., 2001, Ionita et al., 2018). In order to reconstruct the variability of winter air temperature, here we will present the record of harsh winter occurrence rate based on historical documents from the eastern part of Europe. The study analyzes a relatively short period of time (only 70 years) but has been noted by important climate changes that are highlighted by the magnitude of its impact on the environment and society.

2. Study area

The present study is concentrated in the eastern part of Europe and includes Romania, Republic of Moldova, Ukraine and southwestern Russia (Figure 1).

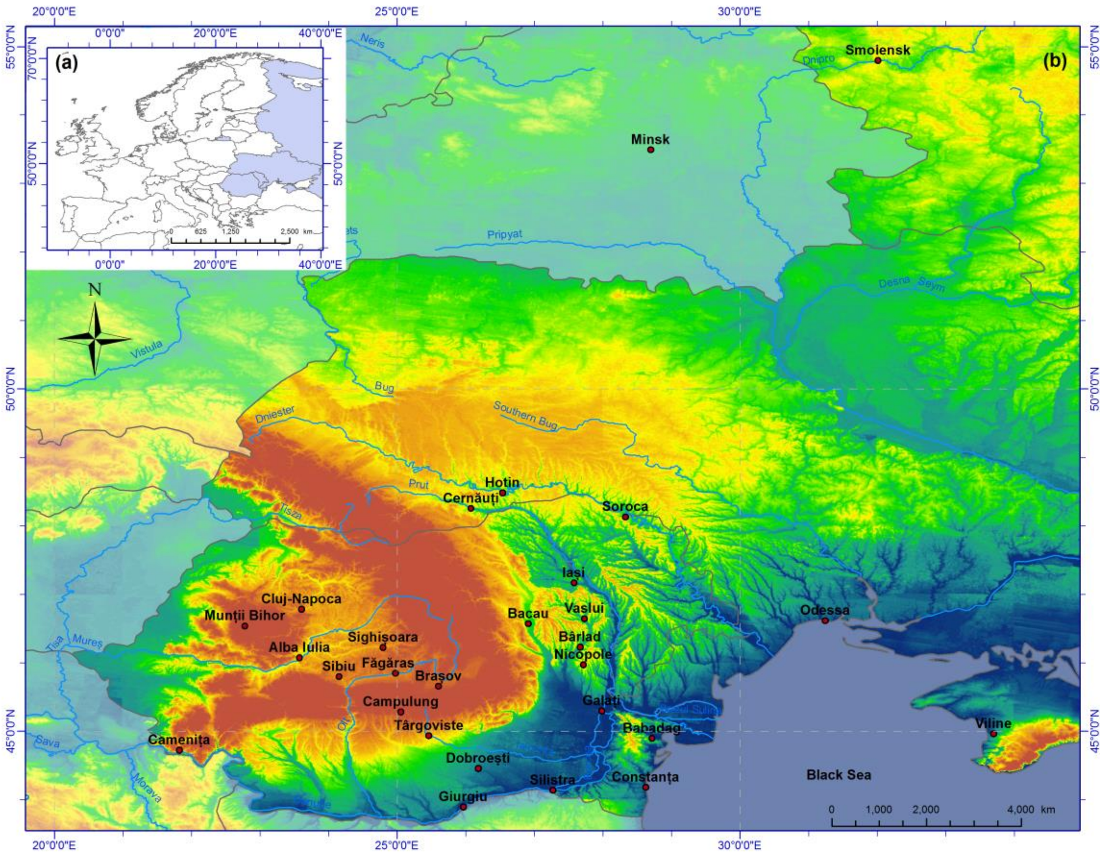

Figure 1 (a) Location of the study site in Europe and (b) localities / regions where harsh winters occurred between Minimum Maunder Period (AD 1645 – 1715).

The Eastern Europe (EEU) is characterized by a temperate transition climate in the west and south (Romania), a temperate continental climate in the Republic of Moldova, Ukraine and Russia, and Mediterranean climate on the southern Crimean coast. The air temperature and precipitation amount are influenced by the prevailing large-scale atmospheric circulation, land cover and orography. The western regions are strongly influenced by the Atlantic Ocean sea surface temperature, which results in higher rainfall and moderate temperatures in all seasons, whereas the eastern regions are influences by continental which generate low rainfall and low/high temperature in winter/summer. The winters in the EEU are milder and more humid in the west, whereas in the eastern are colder and drier. These differences are due influence of the large-scale atmospheric circulation in particular the North Atlantic Oscillation, the Arctic Oscillation and the Siberian High (known also as Siberian Anticyclone).

3. Methods

Data on the severity of winters in Maunder Minimum period were drawn from literary and narrative sources, which were subsequently embodied in climate descriptive books and scientific articles. For a better interpretation of the severe winters we span the Eastern Europe territory in three areas: 1) the Intra – Carpathian region (IC), which include Transylvania; 2) the Extra – Carpathian region (EC) where were included Moldova, Wallachia, Dobrogea and Republic of Moldova and 3) Ukraine (UA) and southwestern Russia (RUS). Data sources are shown in Table 1. In total 41 severe winters were recorded over the period AD 1645-1715 (Figure 2). In order to define the intensity of the harsh winters obtained from historical documents we classified the winter indices on the three scale according to the classification used by other historical climate studies (eg. Phister, 1998; Glaser, 2008). The winter index was classified as: 1 - cold winter, 2 - very cold winter, 3 - extreme cold winter (rough). Figure 4 shows the intensity / magnitude of the winters classified by regions, such as: IC, EC and UA and RU. Besides magnitude, we also determined the rate of occurrence of extreme events (Mudelsse et al., 2004), which is defined as:

$$\lambda(t)=h^{-1}\sum_{n=1}^{m} K\left(\frac{t-T_n}{h}\right)$$

where, T_n represent the timing of the n^{th} harsh winter event with unit of year; m defined the number of harsh winter events occurrence; K() represent the Gaussian kernel function and h is the breadth of the kernel function (h = 5 years).

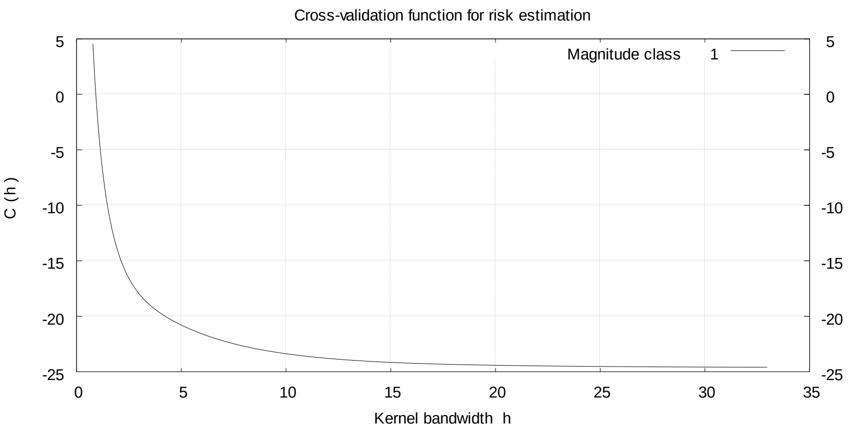

Figure 2 Determination of bandwidth, h [year], for Kernel occurrence rate estimation of harsh winters (magnitude class 1) in EEU. The cross validation function has h = 5 years.

The confidence intervals (90%) around λ(t) were established using a bootstrapped methodology: N simulated harsh winter events were plotted from T_n with replacement and simulated λ calculated. This operation was repeated 2000 times and a percentile-t confidence band was calculated. The trends in the occurrence rate were certified using the Cox and Lewis statistical test (Cox and Levis, 1966) and it is shown in Figure 3.

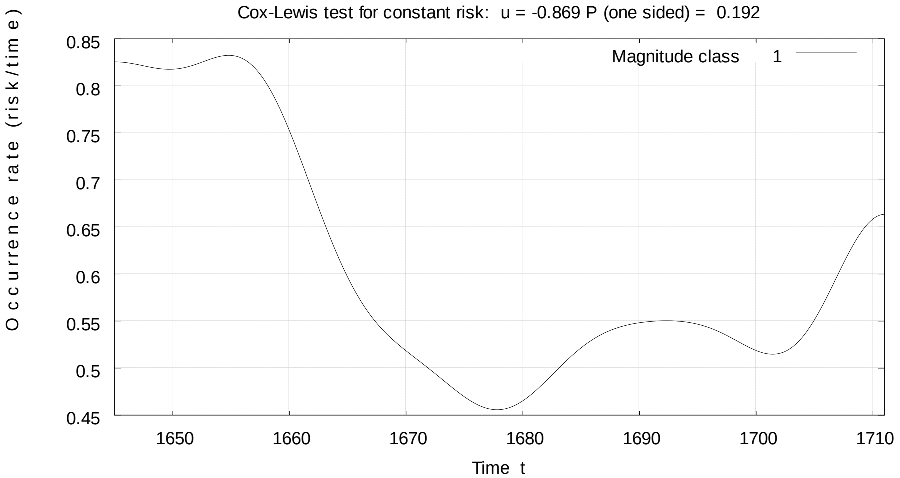

Figure 3 The occurrence rate of harsh winters in Eastern Europe based on Cox-Lewis test for magnitude class 1. Kernel estimation using a bandwidth of 5 years.

In order to understand the variability and the drivers of cold winters, proxy data was collected also at regional level. These proxies include: the irradiance estimates derived from the 'O Be measurements (Bard et al, 1997), winter NAO index (Trouet et al., 2009), DJF rainfalls anomalies (Pauling et al., 2006), DJF air temperature anomalies (Luterbacher et al., 2004), δ^{15}N proxy indicator for DJF precipitation reconstruction (Cleary et al., 2017), δ^{13}C – proxy for winter hydroclimate (Feurdean et al., 2015), δ^{18}O – proxy for winter temperature, d-excess (Perșoiu et al., 2017) and Danube ice cover (Ionita et al., 2018). DJF anomalies represent the average of the December, January and February months.

Table 1. Data sources of severe winters in Eastern Europe

Data sources	Year	Title of issue	Journal	Volume	Pages
Dudaș, F.	1999	Catastrofe naturale în Transilvania	Published by Vest		176
Mihăilescu, C.	2004	Clima și hazardurile Moldovei – evoluția, starea, predicția	Publised by Licorn		191
Topor, N.	1964	Ani ploioși și secetoși	Institutul Meteorologic		304
Teodoreanu, E.	2012	Apercu sur le climat des siecles passes sur le territoire de la Roumanie	RRG.	56 (1)	71-86
Teodoreanu, E.	2013	Hydro-climatic events during the Little Climatic Optimum in Romania	RRG.	57 (1)	8-Mar
Teodoreanu, E.	2014	Little Ice Age in Romania in the vision of a syrian traveler	PESD	8 (1)	139-145
Teodoreanu, E.	2017	In căutarea timpului trecut. Schiță de climatologie istorică	Paideia		364

4. Results and discussion

4.1. Harsh winters variability and intensity in the eastern part of Europe

Figure 4 show the variability and intensity of the harsh winters in the Eastern Europe during the Maunder Minimum, based on documentary data. In total, 41 years with harsh winters were identified in all regions of the EEU (Figure 4a), but they were distributed differently in the three analyzed regions (Figure 4b, 4d and 4f). Overall, 19 harsh winters were recorded in IC region, 19 in EC and 18 in UA and southeastern RUS. In order to understand the possible trends in the occurrence of harsh winters we split our time series in two periods: Early Maunder Minimum (EMM, AD 1645 - 1665) and Late Maunder Minimum (LMM, AD 1685 - 1715). The results show a high increase of occurrence rate of harsh winters during the EMM in IC and EC, and less high in the eastern part. Between EMM and LMM we observe an increase in the occurrence rate of harsh winters in UA and SE RUS and a decrease in IC and EC regions. This increase in the North and East of Eastern Europe may be due to the intensification of the Siberian Anticyclone and the NAO positive index. During the LMM we observe an increase in the occurrence rate of harsh winters in IC and EC and a slow decrease, in RUS and UA, these being attributed to the weakening of the polar vortex and the NAO index. Another indicator to quantify the severity of winters is its magnitude.

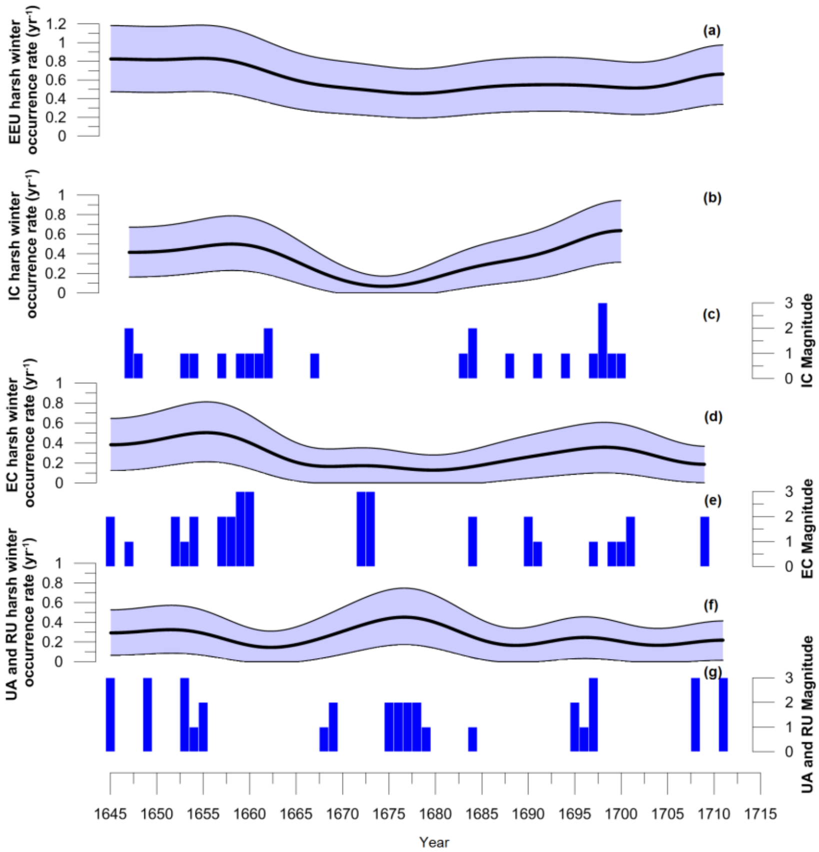

Figure 4 Occurrence rate of harsh winters during the Maunder Minimum (AD 1645 – 1715) with bootstrap 90% confidence band (shaded) from class 1 for EEU in (a), IC in (b), EC in (d) and UA and RU in (f). Harsh winter magnitude is represented by blue bars in IC (c), EC (e) and UA and RU (g).

For the EEU region the magnitude it is shown in Figure 4 (4c, 4e and 4g). The results show that the IC region recorded 15 cold winters (class 1) were, 3 very cold winters (class 2) and only one extreme cold winter (class 3). Over the EC region we found 6 cold winters, 9 very cold winters and 4 extreme cold winters. In Ukraine and Russia 5 cold winters, 7 very cold winters and 6 extreme cold winters were recorded. Based on these findings we can conclude that the winters in Russia and Ukraine were much colder compared to the Intra - Extra - Carpathian regions. Similar results were registered when looking at the occurrence rates of ice cover regime for the Danube River (Ionita et al., 2018) and Elbe (Mudelsee et al., 2004), or the freezing of Bosphorus (in AD 1658, 1667, 1669) (Yavuz et al., 2007).

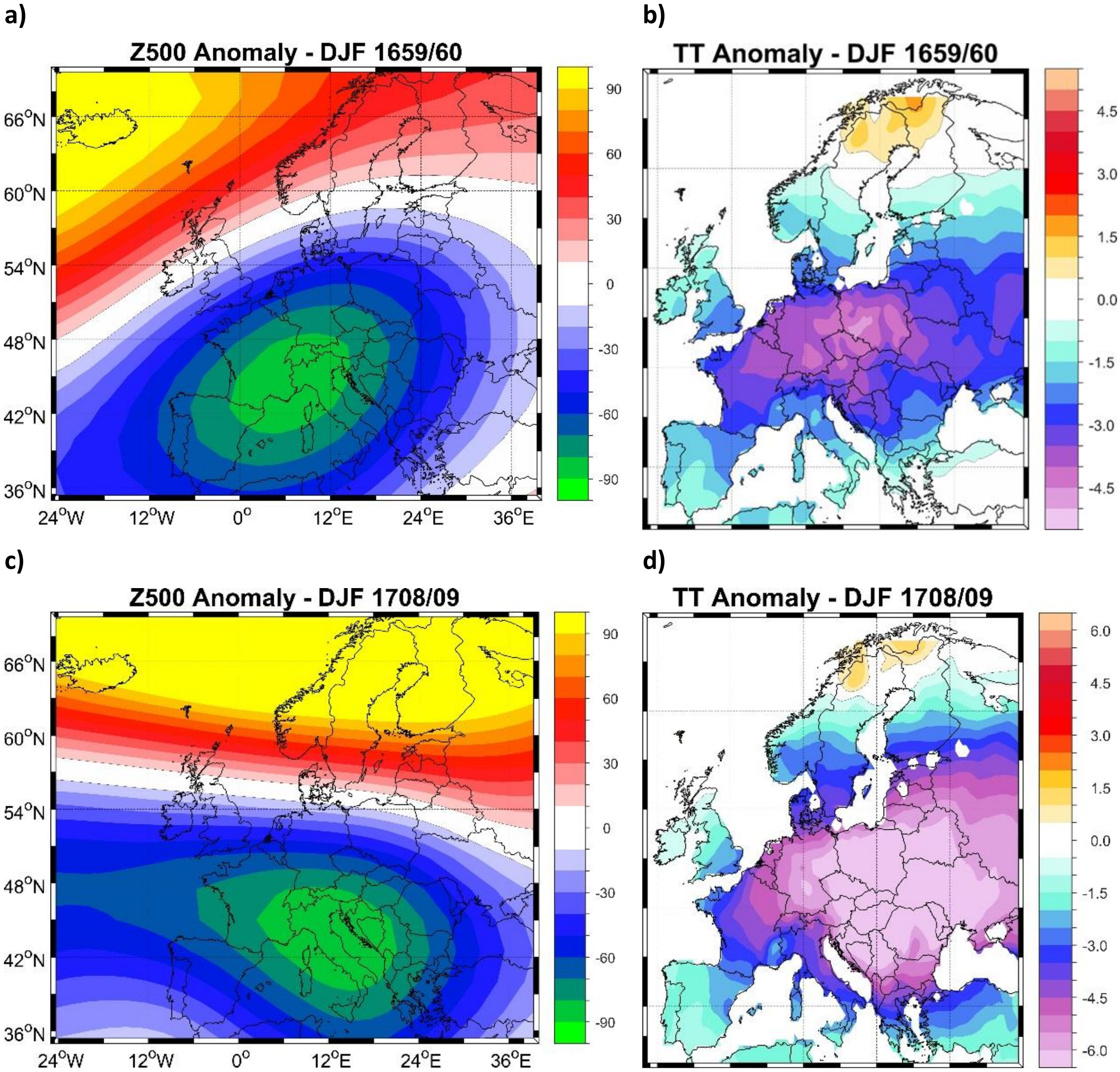

Figure 5 Z500 anomalies (left panel) and TT anomalies (right panels) for two extreme cold winters: (a) and (b) winter 1659/60, (c) and (d) winter 1708/1709. Scale units: TT (°C) and Z500 (hPa).

4.2. Large scale drivers

The occurrence rate of cold winters is mainly related to the prevailing large-scale atmospheric circulation, which determines temperature variability both at regional and hemispheric level. Ionita et al. (2018) showed that the occurrence of cold winters from the eastern part of Europe are associated with an anticyclonic circulation situated over the British Isles and a cyclonic circulation centered over the Eastern Europe and Black Sea, which favors the ice formation on the Danube River, due to the advection of cold and dry air from the north-eastern part of Europe. Also, Teodoreanu (2016) associated the occurrence of cold winters from Romania with large-scale atmospheric circulation. Moreover, Rîmbu et al. (2015) show that the appearance of extreme cold winters from eastern and central Europe are associated with the intensification of the blocking circulation over the Scandinavian Peninsula and the British Isles. In order to identify the main drivers that cause cold winters were computed the composite maps of height geopotential at 500 mb maps for two extremely cold winters in Eastern Europe (Figure 5).

4.2.1 Winter 1659 – 1660

Winter 1659 – 1660 was different in the Eastern Europe regions. Dudaș (1999) show that the winter was cold and they have frozen all the vineyards of Transylvania. Instead, Teodoreanu plays this winter in the EC as a very cold one when the Danube was freezing and the ice had a thickness of 1.50 - 1.75 m. The composite map of height geopotential at 500 mb (Figure 5a) show that harsh winter is associated with a cyclonic circulation centered over Mediterranean areas, Central and Eastern Europe and an anticyclonic circulation centered over the Island and British Isles and Scandinavian Peninsula. These centers favors the advection of dry and cold air from the Eastern Europe, so the temperatures anomalies to be between -3 °C in IC and -3.5 in EC, Ukraine and southeastern Russia (Figure 5b).

4.2.2 Winter 1708/1709

Winter 1708/1709 is known as the most severe winter of the last 500 years in Europe. Historical records show that between January 7 and February 3-4 was a severe and hard-to-live frost. During this time the snow was about half a foot, but it was unevenly deposited, due to the wind blowing from N and NV (Teodoreanu, 2017). Where the snow was lacking, the crops froze. This harsh winter is the result of an anticyclonic circulation centered over Scandinavian Peninsula and the British Isles and a cyclonic circulation centered over the central part of Europe, which favors the advection of cold and dry air from Siberia over the south-eastern part of Russia, Ukraine, Republic of Moldavia and Romania (Figure 5c). In this situation in many parts of Europe the temperature anomaly below -5 °C (Figure 5d). Similar results were observed in the temperature reconstruction of Europe since 1500, based on tree ring, ice cores and historical documents (Luterbacher, 2004). As a result, the effects of winter have been felt throughout the whole Europe, with frosts of the Baltic, Black, Adriatic Seas and the Mediterranean Sea margins, but also the freezing of large rivers such as the Danube, Ebro, Rhone, Meuse, or lakes like Zuyderzee, Constance, and Zurich. Moreover, the rigor of winter has left large scars on the biosphere level (eg, freezing of trees, vines, autumn crops, animals and birds) and the hydrosphere (large ice on the main rivers and lakes), which in the last phase caused famine, broncho-pulmonary disease and mortality in Eastern Europe.

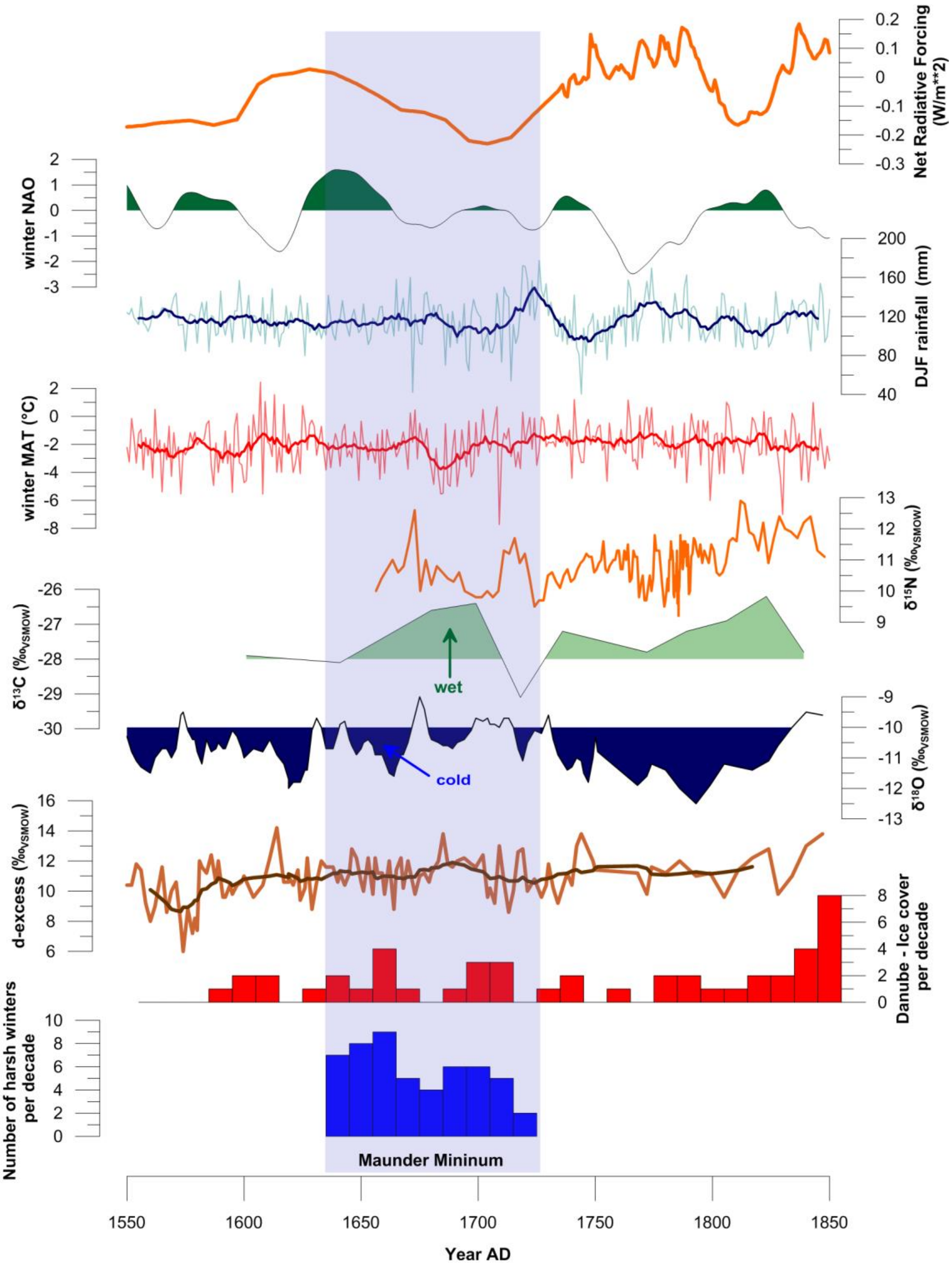

Figure 6 Characteristics of the Minimum Maunder winters based on: the irradiance estimates derived from the 'O Be measurements (Bard et al, 1997), winter NAO index (Trouet et al., 2009), DJF rainfalls anomalies (Pauling et al., 2006), DJF air temperature anomalies (Luterbacher et al., 2004), $\delta^{15}N$ proxy indicator for DJF precipitation reconstruction (Cleary et al., 2017), $\delta^{13}C$ – proxy for winter hydroclimate (Feurdean et al., 2015), $\delta^{18}O$ – proxy for winter temperature, d-excess (Perșoiu et al., 2017) and Danube ice cover (Ionita et al., 2018).

5. Conclusion

Our study reproduces the overall cold season image during MM in EEU, based on documentary evidence. To have a clear picture regarding to the winters during the Minimum Maunder, the paper includes variability, magnitude, frequency and large scale drivers. The study demonstrates that the harsh winters from the Eastern Europe are generated by the prevailing large – scale atmospheric circulation, especially with the anticyclonic circulation centered over Scandinavian Peninsula and the cyclonic circulation centered over central and eastern part of the Europe (Figure 5). During extreme cold winters the cold air is pushed from Siberia over the Eastern part of Europe. Furthermore, the pronounced activity of cyclonic circulation generates heavy snowfall (Phister, 1998).

The study identifies a maximum of cold winters during the EMM and LMM in the IC and EC regions. Instead, in Ukraine and southeastern of Russia the maximum occurrence of harsh winter was recorded between EMM and LMM (~ AD 1665 – 1685). Figure 6 show the frequency of harsh winter over EEU (last panel) in comparison with other proxy indicators from Carpathian regions. In this figure we can observe that during the MM an increase of hydrological condition based on $\delta^{13}C$, over the NE part of Carpathian Mountains (Feurdean et al., 2015), and similar with precipitation anomaly for this regions (Pauling et al., 2006). Moreover, the winter NAO reconstruction (Trouet et al., 2009), δ15N from guano, δ18O from ice core (Persoiu et al., 2017) and Danube ice cover (Ionita et al., 2018) show more cooler and wet winters during EMM, compared to LMM period. In addition to these proxy indicators, d-excess indicates that most rainfall sources in the IC came mainly from the Atlantic Ocean, and only during the transition period its values indicate warmer sources (perhaps Mediterranean sources) that are reflected in the decreasing of occurrence rate of harsh winters and in the Danube ice cover, respectively.

Additionally, our study makes important contributions to the climate during the Maunder Minimum on the EEU, being the only one to address the harsh winters analysis based on historical documents. In conclusion the harsh winter reconstruction can be used as a proxy indicator for the air temperature variability in winter, over the eastern part of Europe.

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