1,200 Years of NAO-modelled European Climate History

Marco Morando (✉ marco.morando@rina.org)

RINA <https://orcid.org/0000-0003-3577-8982>

Research Article

Keywords: climate change, climatology, little ice age, sunspot number, solar activity

Posted Date: February 21st, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1375722/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

1,200 Years of NAO-modelled European Climate History

Marco Morando¹

¹ marco.morando@rina.org

Abstract

In his previous article “Arctic Sea Ice’s Amplification as a Complement to Anthropogenic Global Warming”, the author considered the amplification of solar radiation variations, via Arctic Sea’s ice cover albedo, as forcing to climate change. The same model is used here to extend the data input from the period 1200 – 2100 AD of the previous study to the period 800 – 2160 AD. In addition, the present study reconstructs the North Atlantic Oscillation index across the 1,200-year period. Based on its correlation with temperature and precipitation, the model reconstructs the climate anomalies due to NAO in several different European and neighbouring regions and sums them to the previous article’s results. The regional overall results of the model are compared with quantitative and qualitative benchmarks from literature, to evaluate the level of accuracy in simulating the historical data. Therefore, the aim of this article is not only to present the modelled results, but also to relate them to the major climatic and agricultural events of European history.

Introduction

If a new grand solar minimum is coming^{1, 2, 3}, it is important to understand how the solar activity decrease, measured by the sunspot number (SSN), will impact on climate change. As outlined in the author’s previous study “Arctic Sea Ice’s Amplification as a Complement to Anthropogenic Global Warming”⁴, positive feedback mechanisms, as the Arctic Amplification (AA), may amplify the sun-led influence on global temperature anomaly. Indeed, the sun’s activity forcing on the oceans’ temperatures may influence the Arctic Sea ice extension (SIE). Increase or decrease of ice melting may consequently change the Arctic regions’ albedo, and albedo variations may impact on the reflection of sun radiation, with large consequences on the Earth’s overall energy balance. In addition, the Atlantic Multi-decadal Oscillation (AMO) variations may cause changes of the Arctic Atlantic sector ice cover (AASIC). This suggests that the AMO may be a second cause of the earth’s albedo variation, due to its influence on AASIC, especially in the Greenland and Barents seas. In the model, both AA and AMO are accounted for, respectively as primary and secondary forcing.

The present study adds, to the above-mentioned forcing, the North Atlantic Oscillation (NAO) impact, differentiated on a regional scale. NAO is an atmospheric phenomenon (not a marine phenomenon like the AMO) over the North Atlantic Ocean. It is defined as the difference of sea level pressure (SLP) between the Azores High and the Icelandic Low.

The NAO is a strong driver of European climate since its influence goes well beyond temperature: it also governs the precipitation patterns across the continent and controls the direction and strength of winds and the location of storm tracks across the North Atlantic⁵.

A large SLP difference between the Azores High and the Icelandic Low (called NAO+) produces warmer and wetter conditions over northern Europe and most of north-eastern North America⁶. In contrast, a smaller SLP difference (NAO-) brings colder conditions to eastern North America and northern Europe, by more-frequent intrusions of Arctic airmasses⁶.

The present article reports the modelled reconstruction of the NAO index across 1,200 years and the climatic anomalies (temperature and precipitation) obtained applying NAO correlations in several European regions. For temperature, the NAO-caused anomaly is summed to the anomalies due to AA and AMO variations to obtain the total regional anomaly. The regional results of the model are compared to quantitative and qualitative benchmarks from literature to provide a reference of the level of accuracy it has in reconstructing the historical data. Quantitative benchmarks are included in the figures, while qualitative benchmarks are reported in the text (often as quotes) and conceptually linked to the quantitative results of the model.

Furthermore, the comparison with qualitative and quantitative historical benchmarks helps highlighting the strengths and weaknesses of the model, but also enables to match its results with the records of major climatic and agricultural events in the European history.

The model does not consider the manmade greenhouse gases forcing (i.e., anthropogenic global warming, AGW). This assumption is aimed at simplifying the model by considering only the natural climate change forcing. In addition, natural forcing shall be the cause of any climate change before the industrial era, which started in 1850 AD. Concerning the last century and the future one, the model should be complemented with the AGW effects. A further model combining natural and manmade forcing will be object of a further study by the author.

Results

World and European Average Temperature Anomaly

The reconstructed average global temperature from 800 AD to 2160 AD is compared with the reconstructed European Temperature anomaly in Figure 1.

Figure 1. Modelled average global temperature anomaly (grey line) vs. modelled average European temperature anomaly (cyan line) from year 800 AD to 2160 AD. On x-axis the date in years and on y-axis the temperature anomalies in °C. All the grand solar minima are indicated: Oort (1050 AD), Wolf (1300 AD), Spörer (1450 – 1550 AD), Maunder (1650 – 1720 AD), Dalton (1810 AD), Gleissberg (1920) and Modern (estimated 2040 AD)

In Figure 1, the European temperatures are more influenced by solar minima periods with respect to the global average temperatures. Indeed, the global temperature anomaly is mainly the mathematical integration of the solar activity variations⁴. It shows a long and rather continuous decrease from the Medieval Climate Optimum (MCO: 850 – 1250 AD) to the deepest of the Little Ice Age (LIA): the Maunder minimum (1650 – 1720 AD), and then a rather steep increase up to modern maximum. Instead, the European average temperature anomaly shows a strong decrease during each solar minimum.

Several benchmarks have been used to compare the model results. Figure 2 (a) compares the world average temperature with quantitative benchmarks, and data on reconstructed temperatures from 900 to 2000 are from Spencer⁷ (data shifted of +0.2°C). Figure 2 (b) compares the European average temperature with benchmark data from Luterbacher et al.⁸ (no shift is applied).

Figure 2. **(a)** Modelled global temperature anomaly (cyan line) vs. benchmarks (grey line) from year 800 to 2020. **(b)** Modelled European temperature anomaly (cyan line) vs. benchmark (grey line) from year 800 to 2020. Period **(1)** is the MCO, **(2)** is the Wolf minimum and **(3)** is the Spörer minimum.

Figure 2 (b) shows the MCO (just interrupted by the Oort minimum in 1050 AD), when average temperature in Europe was similar as today, the climate was stable, and the consequent social well-being sustained the flourishing of Romanic and Gothic construction across Europe. The figure shows the Wolf minimum (about 1300 AD) which led to the Great Famine across central and northern Europe and led to the death by starvation and famine-related diseases of about 1.5 million people in a decade across the continent, before the Black Death from 1346 to 1353 escalated the crisis of the 14th century. It also shows the following warmer period peaking in 1400, which saw the beginning of the Renaissance period, which lasted about two centuries across the following Spörer minimum.

Total SIE Anomaly

The total SIE anomaly has been already presented in the previous study⁴. Here, updated and time-extended results are presented. Figure 3 compares the result for the SIE overall reconstruction with historical benchmarks from 1880 to 2010. As benchmarks, March SIE data are from ACSYS, AARI sea ice data⁹ and September SIE data are from Alekseev et al.¹⁰.

Figure 3. Author's modelled SIE (cyan line) vs. benchmark data from year 1200 to 2010 (grey line). The benchmark is the average of March and September SIE. On x-axis the date in years and on y-axis the average SIE in million km²

Regions identified for the Model

A set of regions across the European continent and its neighbourhood is selected for the analysis. For each region, the results in terms of temperature and precipitation anomalies are provided and compared with quantitative and qualitative benchmarks from literature. The selected regions are defined as illustrated in Figure 4.

Figure 4. Map of Regions selected for the Analysis

Model Results and Benchmarks for Greenland Temperature and Precipitations

Greenland's existence was detected at the beginning of the 10th century, when Gunnbjörn Ulfsson saw its coasts forced by a storm while sailing from Norway to Iceland¹¹. During the 980s, Erik the Red and his explorers sailed from Iceland and successfully reached the coast of Greenland¹². It is visible in Figure 5 (c) that the first settlements correspond to a period of about +0.5°C average annual temperature anomaly.

The Vikings settled in two different locations: the Eastern Settlement (Tunulliarfik Fjord, Eiriksfiord, Igaliku / Einarsfiord, and Sermilik Fjord, in the current municipality of Kujalleq), and the Western Settlement (Nuup Kangerlua fjord in the modern municipality of Sermersooq). Archaeologists identified the ruins of about 615 farms: 520 in the Eastern Settlement and 95 in the Western Settlement. The population, at their height, was estimated at 10,000 and 2,000 peoples¹³. It is visible in Figure 5 that the settlements endured in a period of about 0 to +1°C average annual temperature anomaly.

Figures 5 (c) and 5 (d) compare the model results with quantitative benchmarks: for temperature, Kobashi et al.¹⁴ is used; for Baffin Bay ice shelf extent, estimated from glacial varves' (layers of ice) thickness, Young et al¹⁵ is used.

Figure 5. Model results and benchmarks for Greenland. **(a)** Model reconstruction of winter (cyan line) and summer (grey line) temperature anomaly. **(b)** Model reconstruction of winter (cyan line) and summer (grey line) precipitation anomaly. As a reference, today average precipitations are 1.5 mm d⁻¹ in winter and 2.5 mm d⁻¹ in summer. **(c)** Modelled yearly temperature anomaly (cyan line) compared with benchmark (grey line, shifted of 1.7°C). **(d)** Modelled 100 years moving average temperature anomaly (cyan line) compared with Greenland ice shelf extension (varve thickness, dimensionless, grey line). Period **(1)** indicates the start of Norse settlements and the Oort minimum, **(2)** is the warmer period associated with the Wolf minimum and **(3)** indicates the end of the settlements, after the Wolf minimum.

In America, the Norse discovered different regions: Helluland (land of the flat stones, today Baffin Island), Markland (the land of forests, Today Labrador coast) and Vinland (the land of wine, today in Newfoundland)¹⁶. The Norse settlement at L'Anse aux Meadows (Newfoundland, Canada) has been dated to 986–1022 AD by carbon method¹⁷, and corresponds to a temperature anomaly of about +0.5°C, as indicated in Figure 5.

Greenland settlements declined in the middle of the 14th century, as indicated in Figure 5 (a) and (c). It has been questioned why, if the NAO-, corresponding to the Wolf minimum, brought higher temperatures in Greenland at the beginning of the century, the Norse settlements ended shortly after it: actually, the model shows that the Wolf minimum led to a global cooling which was not recovered after its end, but the NAO- allowed the Vikings to well survive during the Wolf minimum itself. Nevertheless, immediately after the minimum ended in 1350, the NAO+ added a local cooling to the previously caused global cooling. The sum of the two components created a very cold period: the Western Settlement was abandoned in 1350, clearly corresponding to a temperature anomaly of -0.5°C in Figure 5 (a) and (c). In 1379, Inuit attacked the Eastern Settlement¹⁸. The last documented event in the East settlement was the Marriage in Hvalsey church (1408 AD)¹⁹.

It is noteworthy to observe, from figure 5 (d), that the glaciers' retreat periods correspond to the solar minima. Even if the global temperatures reduction underpins the overall cooling trend starting from the MCO, the various grand solar minima, and especially the Maunder Minimum, correspond clearly to a temporary retreat of the Greenlandic glaciers in the Baffin Bay.

Model Results and Benchmarks for Svalbard Region's Temperature and Precipitations

Figure 6 compares the model results with reference benchmarks: for temperature, the benchmark 1 is D'Andrea et al.²⁰ and benchmark 2 is Lehner et al.²¹. The Icelandic ice drift observations are from Kim²².

Figure 6. Model Result and benchmarks for the Svalbard Region. (a) Model reconstruction of winter (cyan line) and summer (grey line) temperature anomaly. (b) model reconstruction of winter (cyan line) and summer (grey line) precipitation anomaly. As a reference, today average precipitations are 1.33 mm d⁻¹ in winter and 0.67 mm d⁻¹ in summer. (c) Temperature anomaly comparison with benchmarks: model in cyan line, dotted grey line is benchmark 1 and continuous grey line is benchmark 2. (d) Iceland observations of drift ice (dimensionless, grey line) compared with modelled Svalbard region winter temperature (°C, continuous cyan line) and modelled total Arctic SIE (dimensionless dotted cyan line). Period (1) is the Wolf Minimum, (2) is the Spörer minimum and (3) is the Maunder minimum.

As illustrated in Figure 6 (d), the observations of drift ice from the Iceland coasts are well explained by both the temperature anomaly in the Svalbard region and the total SIE in the Arctic. Indeed, even if Iceland is located outside the Svalbard sector, it receives drift ice mostly from this Arctic Sea region. Especially the conditions in the Greenland Sea are important, but also the overall sea ice pack formation in the entire Svalbard area up to Novaya Zemlya (Barents Sea area). All the major solar minima, which in Svalbard region are correlated to lower

temperatures (opposed to Greenland), are well visible in drift ice observations reported in Figure 6 (d): Wolf Minimum in 1300, Spörer minimum from 1450 to 1500 and especially Maunder minimum from 1600 to 1700.

Model Results and Benchmarks for Fennoscandia Temperature and Precipitations

Figure 7 compares the model results with reference benchmarks: for temperature the benchmark is Luoto²³.

Figure 7. Model Result and benchmarks for Fennoscandia. (a) Model reconstruction of winter (cyan line) and summer (grey line) temperature anomaly. (b) Model reconstruction of winter (cyan line) and summer (grey line) precipitation anomaly. As a reference, today average precipitations are 1.33 mm d⁻¹ in winter and 2 mm d⁻¹ in summer. (c) Modelled summer temperature anomaly compared with the benchmark. Period (1) is the Wolf Minimum, (2) is the Maunder minimum.

Both winter and summer temperatures decrease during periods of low solar activity, and consequent NAO-. Instead, from Figure 7 (b), it is possible to see that the winter precipitations are directly correlated to NAO, but summer precipitations are inversely correlated. This a common feature of the central and northern European regions, where NAO- periods are characterised by dry winters and wet summers.

The Wolf minimum is remarkably visible in 1300 in Figure 7 (a), (b) and (c), and was cause of agricultural marginal land desertion, as it is well documented from the beginning of the 14th century to the two following centuries. In 1406, English guests invited to a royal wedding in Denmark reported no wheat cultivation in the country and vast areas of completely uncultivated land²⁴. In Norway, two farms and villages out of 19 showed desertion frequencies slightly lower than 50%²⁵. Quoting from Derry²⁶: “A bird flying over the country, especially in the west and north, could have noticed the woodland and wild slowly reconquering what had once been won from them by the axe”.

Figure 7 (c) shows that, according to both the model and the benchmark, summer temperatures reached their lowest value during the Maunder Minimum.

Model Results and Benchmarks for British Temperature and Precipitations

Figure 8 compares the model results with reference benchmarks: for temperature the benchmark is Met Office²⁷, and for precipitations it is Büntgen et al.²⁸.

Figure 8. Model Result and benchmarks for the British Region. **(a)** Model reconstruction of winter (cyan line) and summer (grey line) temperature anomaly. **(b)** Model reconstruction of winter (cyan line) and summer (grey line) precipitation anomaly. As a reference, today average precipitations are 2.33 mm d⁻¹ in winter and 2 mm d⁻¹ in summer. **(c)** Modelled yearly temperature anomaly (cyan line) compared with the benchmark (grey line). **(d)** Modelled winter precipitation anomaly (mm d⁻¹, cyan line) compared with the benchmark (grey line, dimensionless). Period **(1)** is the MCO, **(2)** is the Wolf Minimum, **(3)** is the Maunder minimum, **(4)** is the Dalton minimum and **(5)** is the modern warming period.

Warm temperatures in England in the MCO show an anomaly of +0.8°C in 950 AD and in 1200 AD in Figure 8 (a) and 8 (c). They are comparable to to-day values, which show an anomaly of +1.2°C in 1980 - 2000 AD in Figure 8 (a) and 8 (c). During MCO, the history of grape cultivation in England started. Quoting the History of English Wine by Stanlake Park Wine Estate²⁹: “A few vineyards were also cultivated during the Saxon period, but it was the Norman nobles who arrived with William the Conqueror in 1066 who really led to the introduction of successful viticulture and English wine making. Domesday Book thus records more than 40 vineyards, with the area to the west of London being particularly prominent. Wine making expanded considerably in England during the Middle Ages, particularly on monastic and ecclesiastical estates”.

The warm conditions are stopped by the Wolf minimum and the subsequent Great Famine at the beginning of 1300s, clearly visible in Figure 8 (a) and 8 (c) with a temperature anomaly of -1°C. In 1315-1318, a famine unprecedented since the beginning of the Middle Age hit the British Isles, Northern France, Germany, and

Scandinavia³⁰. In England, large amounts of arable land were turned into non-arable land in few years and at least 10% of the entire population died by starvation and famine-related diseases³¹. Figure 8 (b) clearly shows a strong increase in summer precipitations during the Wolf minimum, which washed away fertile soil. Quoting from History of English Wine²⁹: “The acquisition of Aquitaine by the crown in the middle of the 12th century, through the marriage of Henry to Eleanor of Aquitaine, provided a more reliable source of wine for England’s growing urban population and nobility, and this, together with a worsening climate in the later medieval period led to a decline in England’s wine making”.

The same happened in the cereals production. Quoting from Fagan³²: “Thought the 13th century, the Winchester manors in southern England had enjoyed more or less constant yields of about three bushels for every one sown. The 1316 crop was only 55.9 percent of normal, the lowest between 1271 and 1410”.

During the Maunder minimum and the Dalton minimum, respectively in 1650 – 1700 and in 1800 - 1820, the River Thames often froze, and frost fairs were occasionally held on the surface of the River Thames in London. There were pubs, fruit sellers, barbers, and shoemakers’ shops on the sea ice³³. The first recorded frost fair was in 1608 and the last in 1840³⁴.

From Figure 8 (a) and (c), it is possible to observe an increase in the average annual temperatures of about 1.5°C from 1700 AD to 2000 AD. After the end of the LIA (about 1850), a warmer period began, and the grape cultivation restarted. In the second half of the 20th century, commercial grape growing and wine making really began to take off²⁹.

Model Results and Benchmarks for Central European Temperature and Precipitations

Figure 9 (a) and (c) show a temperature reduction of 1 – 1.5°C during the Wolf minimum (1300 - 1320 AD), when the Great Famine hit Central Europe. Quoting Fagan³⁵: “The cold weather and torrential rains of late summer 1315 prevented thousands of hectares of cereals from ripening fully. Fall planting of wheat and rye failed completely. Hay could not be cured properly. Hunger began within months. ‘there began a dearth of wheat... from day to day the price increased’, lamented a chronicler in Flanders. By Christmas 1315, many communities through north western Europe were already desperate”. In 1316, 1317, 1319 and 1323 the grape cultivation in Neustadt in Germany is reported to have been hardly hit and the wine production low or of bad quality³⁶:

After the start of the Spörer minimum (1500s), the low temperatures and summer high precipitations levels persist in Figure 9 (a) and 9 (b); during this period, farmers in Waasland (northern Belgium) pioneered the four-field crops rotation. The sequence of four crops (wheat, turnips, barley, and trifold, the last used to feed livestock) became later (before end of the 17th century) a key innovation in Britain, where it is known as the Norfolk four-course system. Differently from the medieval three-field system, this innovative development does not include a fallow section in rotation, thus maximising the soil yield³⁷.

But in Central Europe one nation failed to adopt the innovations and suffered the coldest period of the Maunder minimum (from 1650 to 1700), with a drop of temperature of further 0.5°C, as visible in Figure 9 (a) and (c). Quoting Fagan³⁸: “The bitterly cold winters of the late seventeenth century found France ill prepared for food shortages. Agricultural production declined seriously after 1680, then tumbled disastrously during the cold and wet years between 1687 and 1701. Most French peasants were still firmly wedded to wheat, which is notably intolerant of heavy rainfall”. Less than one century later, the wheat subsistence agriculture in France contributed reaching the conditions which led to the French Revolution.

Figure 9 compares the model results with reference benchmarks: for temperature the benchmark is Ljungqvist³⁹ and for precipitations it is Büntgen et al.²⁸.

As clearly visible from Figure 9 (b), the climate during the grand solar minima (leading to preponderantly NAO-oscillation) is dry in winters and very wet in summers.

Figure 9. Model Result and benchmarks for the Central Europe. **(a)** Model reconstruction of winter (cyan line) and summer (grey line) temperature anomaly. **(b)** Model reconstruction of winter (cyan line) and summer (grey line) precipitation anomaly. As a reference, today average precipitations are 2 mm d^{-1} in winter and 2.5 mm d^{-1} in summer. **(c)** Modelled summer temperature anomaly (cyan line) compared with the benchmark (grey line). **(d)** Modelled winter precipitation anomaly (cyan line, mm d^{-1}) comparison with the benchmark (grey line, dimensionless). Period **(1)** is the Wolf Minimum, **(2)** is the Spörer minimum and **(3)** is the Maunder minimum.

Model Results and Benchmarks for East European Temperature and Precipitations

Figure 10 shows that the MCO was stable and warm in Eastern Europe (except for the Oort minimum around 1050 AD), up to most of the 13th century. According to Klimenko et al.⁴⁰: “The decades of the 1230s and 1240s were mild and no extreme weather events were recorded”.

The model shows a change at the beginning of 1300s, with an anomaly of about -1°C of winter temperatures during the Wolf minimum. The precipitation anomaly increases strongly in this period. According to Klimenko et al.⁴⁰: “In the last quarter of the thirteenth and the early fourteenth centuries, the chronicles mention more often the ‘great storms and unusual floods, dry summers would follow the rainy warm seasons. The decades of the 1340s and 1350s were relatively stable in terms of climate: except for four ‘great storms’ no other extremes are mentioned at that time”.

In the second half of the 14th century, a dry period is obtained by the model. According to Klimenko et al.⁴⁰: “The last 40 years of this century were very dry: 11 dry years were recorded which resulted in the fully dried rivers, forest, and peat bogs fires. At the same time, the number of cold winters, early frosts and late springs increased”.

According to historical records, the maunder Minimum was characterised by strong variability of the climate. Quoting from Klimenko et al.⁴⁰: “The climate in the second half of the seventeenth century was very variable. Between years 1640 and 1659 eleven summers were extremely dry. On the other hand, the anomalously rainy summers with frosts in the early and late summers were also recorded”.

Figure 10 compares the model results with reference benchmarks: for both temperature and precipitations, the benchmark is Klimenko et al.⁴⁰. Both summer and winter precipitations are negatively correlated with NAO, as shown in Figure 10 (b).

Figure 10. Model Result and benchmarks for the East European Region. (a) Model reconstruction of winter (cyan line) and summer (grey line) temperature anomaly. **(b)** Model reconstruction of winter (cyan line) and summer (grey line) precipitation anomaly. As a reference, today average precipitations are 1.5 mm d⁻¹ in winter and 2.83 mm d⁻¹ in summer. **(c)** Modelled winter temperature anomaly (cyan line) compared with the benchmark (grey line). **(d)** Modelled yearly precipitation anomaly (cyan line) compared with the benchmark (grey line, dimensionless). Period **(1)** is the Oort minimum, **(2)** is the end of the MCO, **(3)** is the Wolf Minimum, **(4)** is the recovery after the Wolf minimum, and **(5)** is the Maunder minimum.

Model Results and Benchmarks for Alpine Temperature and Precipitations

In the Alpine region, the glaciers' advances and retreat periods are of specific interest. The alpine glaciers have been inexorably retreating in the last two centuries. For example, the Rhône Glacier retreat is well documented, as reported in Figure 11.

Figure 11. **(a)** Rhonegletscher um 1870, unknown author, public domain, via Wikimedia Commons. **(b)** Der Rhonegletscher mit Gletsch und Furkapass um 1900, unknown author, public domain, via Wikimedia Commons **(c)** Rhonegletscher 2008, Adrian Michael, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons

Glaciers expand under the condition of high winter precipitations (snow precipitations) and / or of lower summer temperatures (preventing the excessive melting). Differently from the Greenland or Fennoscandia, in the Alps these two conditions are in phase during grand solar minima (NAO-), as shown in Figure 12. If they are not in phase, it is indeed more difficult to quantify which of the two conditions is prevailing.

The Aletsch Glacier is the largest glacier in the Alps (about 23 km long) and is in the eastern Bernese Alps, in the Swiss canton of Valais. The Gorner Glacier (about 12 km long) is a valley glacier found on the west side of the Monte Rosa massif close to Zermatt in the canton of Valais. Figure 12 (e) shows the three major peaks of glacial extensions occurring in correspondence of the Wolf, Maunder and Dalton minima, when both higher winter precipitations and lower summer temperatures happened. The Spörer minimum does not appear to have had a strong influence on the glacial expansion. It is important to note that the glaciers retreat in the last phase of the MCO is similar (if we exclude the Aletsch glacier advance during the Oort minimum), even if not so extreme, as the modern warming period.

Figure 12 compares the model results with reference benchmarks: for temperature the benchmark is Maggi et al.⁴¹ and for precipitations it is Longman et al.⁴². Both summer and winter precipitations are negatively correlated with NAO, as shown in Figure 12 (b).

Figure 12. Model Result and benchmarks for the Alpine Region. **(a)** Model reconstruction of winter (cyan line) and summer (grey line) temperature anomaly. **(b)** Model reconstruction of winter (cyan line) and summer (grey line) precipitation anomaly. As a reference, today average precipitations are 1.5 mm d^{-1} in winter and 3.33 mm d^{-1} in summer. **(c)** Modelled summer temperature anomaly (cyan line) compared with the benchmark (grey line). **(d)** Modelled yearly precipitation anomaly (cyan line) compared with the benchmark (grey line, dimensionless). **(e)** Aletsch glacier (cyan line) and Gorner glacier (grey line) extent, the higher is the absolute value of the extension, the larger is the glacier extension. Period **(1)** is the MCO, **(2)** is the Wolf Minimum, **(3)** is the Spörer minimum, **(4)** is the Maunder minimum, **(5)** is the Dalton minimum and **(6)** is the modern warming period.

Model Results and Benchmarks for the Italian Peninsula Temperature and Precipitations

Figure 13 compares the model results with reference benchmarks: for temperature the benchmark is Trouet⁴³.

Figure 13. Model Result and benchmarks for the Italian Peninsula. (a) Model reconstruction of winter & summer (cyan line) temperature anomaly. (b) Model reconstruction of winter (cyan line) and summer (grey line) precipitation anomaly. As a reference, today average precipitations are 3 mm d⁻¹ in winter and 1 mm d⁻¹ in summer. (c) Modelled summer temperature anomaly (cyan line) compared with the benchmark (grey line). Period (1) ranges from the MCO to the end of the Maunder minimum, (2) is the modern warming period.

Temperature benchmarks show a stronger variability ($\pm 2^{\circ}\text{C}$) than the model results ($\pm 1^{\circ}\text{C}$) in the benchmarked period in Figure 13 (c). In addition, it is interesting to note that modelled summer and winter temperatures anomalies are equal in Figure 13 (a).

It is interesting to note that the level of winter precipitations shown in Figure 13 (b) is remarkably lower during the modern warming period, than in any other period from the MCO to the end of the Maunder. Winter precipitations are far more important in the region than summer ones, whose absolute value as well as anomaly is lower, according to Figure 13 (b).

Quoting Fagan on the level of rainfalls in the period around 1100 AD⁴⁴: “Higher rainfall spread out over much of southern Europe and the western Mediterranean. As a result, some Sicilian rivers were navigable in ways that would be impossible today. Medieval bridges, like the one in Palermo, still span them but are far longer than now necessary, simply because the rivers were wider nine hundred years ago”.

Model Results and Benchmarks for Iberian Temperature and Precipitations

Figure 14 compares the model results with reference benchmarks: for temperature the benchmark is Dorado Linan et al.⁴⁵ and for precipitations it is Oliva et al.⁴⁶.

Figure 14. Model Result and benchmarks for Iberia. (a) Model reconstruction of winter (cyan line) and summer (grey line) temperature anomaly. **(b)** Model reconstruction of winter (cyan line) and summer (grey line) precipitation anomaly. As a reference, today average precipitations are 1.33 mm d⁻¹ in winter and 0.5 mm d⁻¹ in summer. **(c)** Modelled summer temperature anomaly (cyan line) compared with the benchmark (grey line). **(d)** Modelled yearly precipitation anomaly (cyan line) compared with the benchmark (grey line, flood relative frequency on Iberic Atlantic rivers, dimensionless). Period **(1)** ranges from the Wolf minimum to the end of the Spörer minimum and **(2)** is the Maunder Minimum.

In figure 14 (a) and (c), the Wolf minimum is identified by a temperature anomaly of about -0.5°C and the recover after the wolf minimum is very limited in the region and the temperature anomaly keeps stable during the Spörer minimum. According to Azevedo Pereira et al⁴⁷, in Portugal: “Periods of famine, pestilence and wars raged in the country at the same time that climatic conditions deteriorated, leveraged by the Wolf Minimum (1280-1350) and Spörer Minimum (1460-1540) periods. The seasons of the year were colder and with high rainfall, with particular incidence on the Atlantic coast and mountainous areas. In the peninsular register, two periods of concentration of episodes of torrential rain occurred between 1310-1330 and between 1360-1390”.

Figure 14 (a) and (c) show, during the Maunder minimum and its aftermath, temperature drop of additional -0.5°C. Figure 14 (d) shows the modelled average yearly precipitation anomaly in comparison with the cumulative probability density function (obtained from the analysis of radiocarbon dates collected from units representing paleo floods and extreme fluvial events in rivers on Atlantic Ocean sides of the Iberian Peninsula⁴⁶).

The strong increase of both winter and yearly average precipitations is clearly visible during the Maunder minimum. According to Azevedo Pereira et al.⁴⁷, in Portugal: “In the 15th century, the climate continued to cool, with an expansion of glaciers in the highest points of the Iberian Peninsula, as well as several snow. In the Maunder Minimum stage (1645-1715), the LIA intensified in Portugal. Periods of very low temperatures and extreme events have multiplied. In Lisbon, for example, the month of January had rain, snow and strong winds causing landslides and killing people (Gazeta do Mês de Janeiro, 1642, p. 5)”.

Model Results and Benchmarks for Balkans’ Temperature and Precipitations

Figure 15 compares the model results with reference benchmarks: for temperature the benchmark is Vadas and Ràcz⁴⁸, and for precipitations it is Longman et al.⁴².

Figure 15. Model Result and benchmarks for the Balkans. **(a)** Model reconstruction of winter (cyan line) and summer (grey line) temperature anomaly. **(b)** Model reconstruction of winter (cyan line) and summer (grey line) precipitation anomaly. As a reference, today average precipitations are 1.5 mm d⁻¹ in winter and 2.33 mm d⁻¹ in summer. **(c)** Modelled yearly temperature anomaly (cyan line) compared with the benchmarks (grey dotted line for summer and grey continuous line for winter). **(d)** Modelled yearly precipitation anomaly (cyan line) comparison with the benchmark (grey line, JJA Precipitations anomaly in the Southern Carpathians, dimensionless). Period **(1)** is the MCO, **(2)** is the Wolf minimum and **(3)** is the 17th century.

The MCO is shown in Figure 15 as a stable and warm period in the Balkans.

Figure 15 shows that both summer and winter temperature anomalies tend to peak of at least $+0.5^{\circ}\text{C}$ during grand solar minima: the first peak is in 1300 (next to the Wolf minimum), and the second one in 1450 – 1500 (next to the Spörer minimum). This behaviour is confirmed from literature, reporting that the MCO lasted in the first half of the 14th century and cooling only started in its second half. Concerning precipitations, according to both the model and the benchmark, the Figure 15 (b) and (d) shows the first half of the 14th century as dry in the Balkans' summers (as well as in the yearly average), differently from model results for the central and northern Europe, where intensely wet summers seasons are modelled: the Great Famine spared the Balkans.

Indeed, quoting Rabb⁴⁹: "The warming in the region of the Carpathian Basin was temporarily succeeded by a colder period in the 8th century, and then from the 9th century the climate became warmer again around Europe. This 'climatic optimum' was about 1°C higher average temperature than today, but what is more important, it came with heavier rainfall than before. Since this advantageous weather coincided with the 'agricultural revolution', the invention of new cultivation methods and resulting from this a sudden increase in produce, this period can be considered as the golden age of the medieval period. [...] From the 12th century the number of famines decreased, since the achievements of the agricultural revolution had matured by this time. In this period, people finally changed millet and sorghum to wheat and crop fertilization became widespread. The excess produced by the high average yields made the development of towns with large populations possible together with a general increase in the population. This process lasted until the middle of the 14th century, when the already unstable balance was upset. [...] Contrary to the climate of the Carpathian Basin, which became drier, Western Europe was afflicted by rather cold and rainy weather in the first half of the 14th century".

Concerning the 17th century, the model shows that the coldest period is in the first half of the century and not during the Maunder Minimum of 1650 – 1700. Again, from Rabb: "The permanent cooling of the Carpathian Basin had started in the 1550's and was at its worst in the years of 1595-1602, when the Danube froze many times (1594/95, 1601/02, 1607/08)".

Model Results and Benchmarks for Anatolian Temperature and Precipitations

Figure 16 shows an increasingly wet and warm climate from 800 to 1050, in accordance with the period of vast prosperity associated to the Byzantine era. According to Izdebski et al.⁵⁰, archaeological and paleoenvironmental proxies (reconstructed based on increasing number of coins finds and of cereal pollens) show that the economic expansion in the Byzantine Empire began after 850 – 900 and lasted up to 1050 – 1100.

In Anatolia, the solar grand minima correspond to warmer and wetter peaks: the signal is well visible in both the model results and in the benchmarks in Figure 16 (b) and (c), corresponding to the Oort minimum, the Wolf minimum, the Spörer minimum and the Maunder minimum.

The model shows a very dry and cold period around 1590s-1600s, which is associated to a deep crisis in the Ottoman Empire. The temperature anomaly is of -0.5°C according to the model and of -1.5°C according to the benchmark. Quoting Izdebski⁵⁰: "Expansion thus buffered Ottoman systems of resource, labour, and military mobilisation from small impacts but exposed them to a growing risk of systemic breakdown in the face of multiple, larger shocks. This situation helps explain the scale of crisis in the empire during the 1590s-1600s. During 1591-96, central Anatolia experienced one of its longest and deepest droughts of the past millennium, as described by contemporary sources and confirmed by tree-ring and lake sediment studies. Drought during the spring growing season appears to have been especially damaging to the grain crop in central and western Anatolia during the middle years of the decade. Food prices more than doubled and some primary accounts suggest food was often unavailable. [...] The combination of drought and cold likely contributed to the outbreak of a major epizootic disease, which affected sheep and cattle across Anatolia, the Crimea, and the Balkans, eventually passing through Hungary into Central Europe. The death of livestock deprived Ottoman peasants of a major source of wealth and subsistence, and deprived Ottoman armies of a key source of protein".

Figure 16 compares the model results with reference benchmarks: for temperature the benchmark is Xoplaki et al.⁵¹ and for precipitations it is Izdebski et al.⁵⁰.

Figure 16. Model Result and benchmarks for Anatolia. **(a)** Model reconstruction of winter (cyan line) and summer (grey line) temperature anomaly. **(b)** Model reconstruction of winter (cyan line) and summer (grey line) precipitation anomaly. As a reference, today average precipitations are 1.4 mm d^{-1} in winter and 0.67 mm d^{-1} in summer. **(c)** Modelled summer temperature anomaly (cyan line) compared with the benchmark (grey line). **(d)** Modelled yearly precipitation anomaly (cyan line) compared with the benchmark (grey line, dimensionless) in Byzantine era and in Ottoman era. Period **(1)** is the MCO peaking in the Oort minimum, **(2)** is the Wolf minimum, **(3)** is the Spörer minimum, **(4)** is the cold and dry period around 1600 AD and **(5)** is the Maunder minimum.

Model Results and Benchmarks for North-eastern African Temperature and Precipitations

In North-eastern Africa, the solar grand minima correspond to locally warmer periods: the signal is well visible both in the model and in the benchmark, especially for the Oort minimum, the Wolf minimum and the Maunder minimum in Figure 17. Therefore, the deepest period of LIA (1700 - 1800) is not marked by a cold anomaly comparable with that of central and northern Europe.

All solar minima are associated to dry periods in the region. Referring to the period (4) of Figure 17 (d), both the model and the benchmark show very dry conditions during the Dalton minimum and wetter conditions after 1850.

Quoting Felis et al.⁵²: “The climate of the Sahara and Arabian Deserts during the Little Ice Age is not well known, due to a lack of annually resolved natural and documentary archives. We present an annual reconstruction of temperature and aridity derived from Sr/Ca and oxygen isotopes in a coral of the desert-surrounded northern Red Sea. Our data indicate that the eastern Sahara and Arabian Deserts did not experience pronounced cooling

during the late Little Ice Age (~1750–1850) but suggest an even more arid mean climate than in the following ~150 years. The mild temperatures are broadly in line with predominantly negative phases of the North Atlantic Oscillation during the Little Ice Age. The more arid climate is best explained by meridional advection of dry continental air from Eurasia. We find evidence for an abrupt termination of the more arid climate after 1850, coincident with a reorganization of the atmospheric circulation over Europe”.

Figure 17 compares the model results with reference benchmarks: for temperature the benchmark is Lüning et al.⁵³ and for precipitations it is Felis et al.⁵². Summer temperature anomaly is not very sensitive to NAO variations, mainly due to summer precipitation extremely low absolute value.

Figure 17. Model Result and benchmarks for North-eastern Africa. (a) Model reconstruction of winter (cyan line) and summer (grey line) temperature anomaly. **(b)** Model reconstruction of winter (cyan line) and summer (grey line) precipitation anomaly. As a reference, today average precipitations are 0.2 mm d⁻¹ in winter and 0.003 mm d⁻¹ in summer. **(c)** Modelled yearly temperature anomaly (cyan line) compared with the benchmark (grey line, dimensionless). **(d)** Modelled yearly precipitation anomaly (cyan line) compared with the benchmark (grey line, dimensionless). Period **(1)** is the Oort minimum, **(2)** is the Wolf minimum, **(3)** is the Maunder minimum, **(4)** is from the Dalton minimum to the modern warming period.

Discussion

The aim of this article is to extend the results of the previous study⁴ to a longer timeframe, but especially to consider the additional influence of the NAO on European and neighbouring regional climate. The NAO is a strong driver of European climate: it influences goes well beyond the very temperature anomaly, as it predominantly governs the precipitation variations in the continent. The match of the model results with qualitative and quantitative benchmarks is rather satisfactory, showing a good connection with temperature and precipitation benchmarks from other authors, as well as with the main climate-led historical events in the continent.

Furthermore, it shall be pointed out that several quantitative temperature and precipitation reconstructions available in literature are inconsistent: the model could help ordering and identifying the most effective ones since it establishes a single criterion (based on NAO) to model several geographical areas. For this reason, the model can be considered as very robust under a conceptual point of view.

In addition, there is a remarkable aspect which cannot be evinced from the average temperature and precipitation anomalies: the NAO has strong influence not only on long-period averages, but also on short-term variability of the climatic / weather conditions. Atmospheric blocking events in the north Atlantic are large high-pressure systems interrupting west-to-east atmospheric flow, occurring during NAO- index. They cause days of quasi-stationary weather patterns, leading to extreme weather events and climate anomalies over Europe⁵⁴. Therefore, solar minima are correlated to sharp increase of cold snaps, heat waves, droughts, and strong storms, as reported from past records. Quoting Kim²²: “the climate exhibited much more aberration in the late 1200s and early 1300s compared to other eras. British climate shows that the frequency of cold, harsh winters, cool, wet summers, and droughts all increased in frequency, indicating how the climate patterns swung from extreme to extreme. In general, the climate in the late Middle Ages had become more of an Atlantic climate with heavier precipitation and cooler summer temperatures”.

As said in the introduction, AGW effects were not included in the present model, considering only forcing due to solar activity (and consequently NAO variations) and AMO changes. The 2016 – 2020 temperature peak is therefore not well detailed by the model, but AGW would well explain it. The model forecast, for the period from 2020 to 2160, will probably be strongly affected by AGW. A combined model based on both AGW, and natural forcing should be developed to account the entirety of the forcing on climate change. This combined model will be object of a further study by the author.

Methods

The applied model expands the approach presented in the previous article “Arctic Sea Ice’s Amplification as a Complement to Anthropogenic Global Warming”⁴, which explains the Mechanisms 1 and 2 described below. The same model is run a second time, extending the input data range to the period 800 – 2160 AD.

In addition, the present study adds two further steps (constituting the Mechanism 3) to estimate the NAO index across 1,200 years and to apply its effects on the temperature and precipitation anomaly of different European and neighbouring regions.

The model rationale is reported in Figure 18: the SSN counts are considered as representative of the solar activity and as the primary forcing on the mechanism 1 and 3. AMO is the forcing of mechanism 2 and is likely independent from the solar activity.

The mechanism 1 considers the oceans as the Earth’s heat storage body. Nevertheless, variations of Oceans’ Heat Content (OHC), due to accumulated changes in Total solar irradiation (TSI), are insufficient to justify the historical temperature anomaly. Positive feedback mechanisms, as the AA, amplify the OHC changes, via variations of the SIE. Increase or decrease of ice smelting changes consequently the Arctic regions’ albedo, and albedo variation impacts on the reflection of sun radiation, with large consequences for the Earth’s overall temperature anomaly (Global T1).

The mechanism 2 considers that a positive AMO index (AMO+) implies a local increase of temperature in the Atlantic sector of the Arctic Ocean, corresponding to a cooling in its equatorial sector. The opposite happens with a negative AMO index (AMO-). Years with AMO- (AMO+) correspond to above-normal (below-normal) December AASIC. Therefore, the AMO variability is considered as a second cause of the earth’s albedo variation, due to its influence on AASIC (concurring with solar activity to the overall Arctic Sea ice’s albedo). The AMO variations, differently from sun-led OHC changes, do not represent a net variation of Earth’s heat balance, but a displacement of heat from the Southern sector (AMO-) to the Northern sector (AMO+) of the Atlantic Ocean.

Nevertheless, the AASIC anomaly reverts in a net increase or decrease of Earth's heat balance, with consequent variation of the temperature anomaly (Global T2).

In mechanism 3, solar grand minima are correlated to NAO- (with impacts on regional temperature T3 and precipitation anomaly, different for each considered region). The total temperature anomaly of each region is determined as the sum of T1, T2 and T3 anomalies.

Figure 18. Model Rationale. The sign – means reduction and + means increase.

The 1-dimensional model presented in the previous study⁴ is a Taylor expansion of the (unknown) functions $\Delta T(y)$ and $\Delta SIE(y)$ depending on a variety of local and geographical parameters, where second and higher order terms are neglected (retaining only the first order terms of the expansion, the problem was linearised). The approach applied here is similar, but it introduces a differentiation of the results for different geographical areas, representing a 2 (temperature and precipitations) x 12 (regions) = 24-dimensional linear model.

Step1 (Mechanism 1): From SSN to TSI

Input Data

SSN input data from 1200 to 1337 are obtained from Solanki et al.⁵⁵, where the data are adapted from Carbon14 data (lower range of confidence level). Data from 1337 to 1575 are obtained from Solanki, where the data are adapted from Beryllium 10 data. Data from 1575 to 1650 are obtained from Solanki, where the data are adapted from Carbon14 data (lower range of confidence level). Data from 1651 to 1699 are obtained from Eddy⁵⁶, where the data are reconstructed mainly from reported observations of the time.

The observed SSN counts from 1700 to 2019 are obtained from the Royal Observatory of Belgium⁵⁷. SSN forecast data from 2021 to 2040 are from NOAA¹.

Data from 2041 to 2160 are assumed by the author, considering that the Modern Minimum will extend the 26th solar cycle foreseen by NOAA SSN for three additional solar cycles, similarly to the past Maunder minimum, and after it would finally settle on values like solar cycle 24th.

Total Solar Irradiation (TSI) data are from NASA⁵⁸ for years from 1655 to 2018.

The overall set of data inputs for SSN is reported in Figure 19.

Figure 19. Dataset on SSN. On x-axis the date in years and on y-axis the SSN count as reconstructed from the quoted sources

Model Description

SSN counts are representative of the solar activity (defined by both quantitative TSI and its spectral characterisation), but the correlation is not linear. The model finds the correlation between SSN count and TSI for the overlapping period (1655 to 2018). Since TSI is strongly influenced by prolonged periods of solar grand minima, two different equations have been used in function of the 11-year SSN moving average. Period of grand solar minima have been characterised by 11-year SSN moving average below 35 per month for prolonged periods, as well as periods of solar maxima by values above 35 per month for prolonged periods.

$$\text{if (11 years moving average SSN} < 35\text{): } TSI(y) = 4 \times 10^{-6} \times SSN(y)^3 + 6 \times 10^{-4} \times SSN(y)^2 + 0.0342 \times SSN(y) + 1360.3 \quad (1)$$

$$\text{if (11 years moving average SSN} > 35\text{): } TSI(y) = 0.0052 \times SSN(y) + 1360.75 \quad (2)$$

Where:

- TSI (y)= TSI (W/m2) in the year y
- SSN (y)= SSN monthly counts in the year y
- y= Considered year

The overall R^2 on the period 1655 – 2018 is 0.85, coefficient of correlation (R) is 0.92.

Model Output

The TSI data series from 800 AD to 2160 AD are obtained. Unabridged data from SORCE have been used for 1655 – 2018 interval in the next step, while the equations (1) and (2) have been used for the other years.

Step 2 (Mechanism 1): From TSI to solar radiative forcing (RF_sun)

Input Data

Input data are the modelled TSI data. TSI is referred to orthogonal metered sun radiation.

Model Description

The model is unchanged with respect to its version explained in the author's previous study⁴.

Model Output

The solar RF data series from 800 AD to 2160 AD are obtained.

Step 3 (Mechanism 1): From RF_sun to delta OHC_sun

Input Data

Input data are the modelled RF_sun data.

Model Description

The model is unchanged with respect to its version explained in the author's previous study⁴.

Model Output

The result is the value of delta OHC_sun.

Step 4 (Mechanism 1): From delta OHC_sun to delta T_sun

Input Data

Input data are the modelled OHC_sun.

Model Description

The model is unchanged with respect to its version explained in the author's previous study⁴.

Model Output

The solar-induced component of global average temperature anomaly on the entire period from 800 AD to 2160 AD is obtained.

Step 5 (Mechanism 1): From T_sun to Arctic Amplification (delta SIE and delta global T1)

Input Data

Input data is the modelled data series T_sun.

Model Description

The model is unchanged with respect to its version explained in the author's previous study⁴.

Model Output

The delta SIE_partial variation obtained multiplying the above constant by the T_sun values on the entire period from 800 AD to 2160 AD is obtained. The average temperature anomaly global T1 is obtained multiplying the above constants by the T_sun values.

Step 6 (Mechanism 2): From AMO to delta AASCIC and delta global T2

Input Data

Data on the yearly AMO index are from the National Ocean and Atmosphere Administration⁵⁹ for the years 1856 - 2019.

Data from 1585 to 1855 are from Knudsen et al.⁶⁰.

Data from 1200 to 1584 are assumed as the average value of the time interval 1585 – 2019, lacking any literature reference to further extend the data.

Data from 2020 to 2100 are assumed by the Author, assuming the oscillation period of 30 – 40 years of the last two centuries will continue. The overall data set used is reported in Figure 20.

Figure 20. Dataset on AMO. On x-axis the date in years and on y-axis the AMO index value

Model Description

The model is unchanged with respect to its version explained in the author's previous study⁴.

Model Output

The delta AASIC variation on the entire period from 800 AD to 2160 AD is obtained. The total average temperature anomaly induced by AMO (global T2) on the entire data series from 800 AD to 2160 AD is obtained.

Step 7 (Mechanisms 1 and 2): Obtaining the average global T1 + T2 and SIE anomaly

Input Data

Input data are modelled global T1, T2, delta SIE_partial and delta AASIC.

Model Description

The model is unchanged with respect to its version explained in the author's previous study⁴. K1 temperature offset is arbitrarily set at 0.40°C. K2 SIE offset is arbitrarily set of $10.9 \times 10^6 \text{ km}^2$.

Model Output

The total average temperature anomaly global T1 + T2 and total delta SIE on the entire period from 800 AD to 2160 AD are obtained.

Step 8 (Mechanism 3): Reconstructing the NAO Index

Input Data

Input data are SSN counts as reported in Figure 19.

Model Description

NAO index correlation with SSN count is taken from Hernandez and al.⁶¹.

$$\text{if } (SSN < 25): NAO(y) = 0.04 \times SSN(y) - 0.79 \quad (3)$$

$$\text{if } (SSN > 25): NAO(y) = 0.01 \times SSN(y) - 0.04 \quad (4)$$

Where:

- $SSN(y) =$ SSN monthly count in the year y

- NAO (y)= NAO index in the year y
- y= Considered year

Model Output

The NAO index reconstructed on the entire period from 800 AD to 2160 AD is reported in Figure 21.

Figure 21. Dataset on NAO. On x-axis the date in years and on y-axis the NAO index value as reconstructed

Step 9 (Mechanism 3): Reconstructing the temperature T1 + T2 + T3 and precipitations anomaly in several regions

Input Data

Input data are global average T1 + T2 and NAO index.

Model Description

The NAO index is correlated with summer and winter temperatures T3 and precipitations in the different regions based on the coefficients reported in Table 1. Winter temperature and precipitations correlations are from Trigo et al.⁶². Summer temperature and precipitations correlations are from Hanna and Cropper⁶³.

Table 1. NAO index correlation with summer and winter temperatures T3 and precipitations anomalies for the different regions

	Ft - winter TMP corr (°C / 2NAO)	Ft - summer TMP corr (°C / 2NAO)	Fp - winter PRE corr (mm d-1 / 2NAO)	Fp - summer PRE corr (mm d-1 / 2NAO)
Europe	1.5	1.07	-0.2	-0.2
Greenland	-3	-1.39	-0.3	0.75
Svalbard	1.7	3.4	0.2	0.06
Fennoscandia	2.8	0.75	0.3	-0.225
Britain	1.5	0.96	0.6	-0.93
Central Europe	2.5	1.25	0.3	-0.675
East Europe	2	0.5	-0.25	-0.94
Alps	1	0.83	-0.75	-0.56
Italian Peninsula	-0.3	-0.3	-0.3	0.043
Iberia	-0.5	0.5	-1.25	-0.078
Balkans	-0.6	-1.2	-0.75	0.83
Anatolia	-2	-0.5	-0.5	0.08
North East Africa	-1	-0.4	0.3	0.003

Regional T3 and precipitation correlation with NAO index is obtained as:

$$Regional\ T3\ (y) = Ft \times NAO\ (y) \quad (5)$$

$$T\ (y) = global\ T1\ (y) + global\ T2\ (y) + regional\ T3\ (y) \quad (6)$$

$$PRE\ (y) = Fp \times NAO\ (y) \quad (7)$$

Where:

- Regional T3 (y)= regional temperature anomaly due only to NAO variations in the year y
- T (y)= regional temperature total anomaly in the year y
- PRE (y)= regional precipitation anomaly in the year y
- Ft = regional correlation factor between TMP and NAO index
- Fp = regional correlation factor between PRE and NAO index
- NAO (y)= NAO index in the year y
- global T1 (y)+global T2 (y)= result of Step 7
- y= Considered year

Model Output

The regional total temperature anomaly T and the precipitation anomaly are reconstructed on the entire period from 800 AD to 2160 AD for each considered region. They are reported in the Results section.

Acknowledgements

I thank Giada Barla, Leonardo Caminiti, Federica Cugnach and Marco Martinelli for their assistance for reviewing this article.

Additional Information

The Author has no conflict of interest concerning the article and has received no funds from any source for drafting this article.

Availability of materials and data

Materials, data and associated protocols are available to readers without undue qualifications in material transfer agreements. No restrictions on the availability of materials or information are given. All images have been drawn by the author, except for Figure 11. All Figures drawn by the author are available for reproduction or adaptation without asking the author's permission.

Author contributions

Marco Morando provided the only contribution to this article.

References

-
- ¹ National Oceanic and Atmospheric Administration. Space Weather Prediction Centre. Predicted Sunspot Number and Radio Flux. Retrievable at <https://www.swpc.noaa.gov/products/predicted-sunspot-number-and-radio-flux> (2021)
- ² Shepherd, S. J., Zharkov, S. I. & Zharkova, V. V. Prediction of solar activity from solar background magnetic field variations in cycles 21–23. *The Astrophysical Journal*, **795:46** (8pp), 2014 November 1 <https://doi.org/10.1088/0004-637X/795/1/46> (2014)
- ³ Abdussamatov, H. I. Bicentennial decrease of the total solar irradiance leads to unbalanced thermal budget of the earth and the little ice age. Pulkovo Observatory of the RAS (2011)
- ⁴ Morando, M. Arctic Sea Ice's Amplification as a Complement to Anthropogenic Global Warming. Research Square preprint. <https://doi.org/10.21203/rs.3.rs-528550/v1> (2021).
- ⁵ Hurrell, J. W. The North Atlantic Oscillation: Climatic Significance and Environmental Impact. American Geophysical Union. ISBN 9780875909943. (2003)
- ⁶ *Encyclopædia Britannica*. North Atlantic Oscillation. Encyclopædia Britannica, inc. Retrievable at <https://www.britannica.com/science/North-Atlantic-Oscillation> (2021)
- ⁷ Spencer, R. 2000 years of Global Temperatures: The 2007-2008 Global cooling event. www.drroyspencer.com/ (2007)
- ⁸ Luterbacher, J. et al. European summer temperatures since Roman times. *Environ. Res. Lett.* (2016)
- ⁹ ACSYS, AARI sea ice data. Arctic Climate System Study (ACSYS). The ACSYS Historical Ice Chart Archive (1553-2002) published on CD-ROM (2003).
- ¹⁰ Alekseev, G., Glok, N., and Smirnov, A. On assessment of the relationship between changes of sea ice extent and climate in the Arctic. *International Journal of Climatology*, **36**, **3407–3412**. doi:10.1002/joc.4550 (2016)
- ¹¹ *Landnámabók*. First copy not survived; the oldest surviving examples are copies made in the second half of the 13th century
- ¹² *Greenland-Guide, The Norse History of Greenland 982 – 1500*. Retrievable at <https://greenland-guide.gl/the-norse-history-of-greenland-982-1500/> (2021)
- ¹³ Fitzhugh, W. W., Ward, E. I. Vikings: The North Atlantic Saga. Smithsonian Institution Press. ISBN 978-1560989707. U.S. National Museum of Natural History (2000).
- ¹⁴ Kobashi, T., Shindell, D. T., Koder, K., Box, J. E., Nakaegawa, T., and Kawamura, K. On the origin of multidecadal to centennial Greenland temperature anomalies over the past 800 yr. *Climate of the Past*, European Geosciences Union (2013)
- ¹⁵ Young, N. E., Schweinsberg, A. D., Briner, J. P., Schaefer, J. M. Glacier maxima in Baffin Bay during the Medieval Warm Period coeval with Norse settlement. *Science Advances* (2015)
- ¹⁶ *Icelandic sagas: Eirik the Red's Saga, Saga of the Greenlanders, Hauksbók and Flatey Book*
- ¹⁷ Ledger, P. M., Girdland-Flink, L., Forbes, V. New horizons at L'Anse aux Meadows. *Proceedings of the National Academy of Sciences*. 116 (31): 15341–15343. doi:10.1073/PNAS.1907986116. eISSN 1091-6490. ISSN 0027-8424. PMC 6681721. PMID 31308231 (2019)
- ¹⁸ Diamond, J. Collapse: How Societies Choose to Fail or Succeed. Viking. ISBN 978-0-14-303655-5. pp. 217,222 (2005)
- ¹⁹ Arneborg, J., Nyegaard, G., Vésteinsson, O. and Hammond, A. Norse Greenland. *Journal of the North Atlantic*, Special Volume 2, 2009–2010. Eagle Hill Institute (2008)

-
- ²⁰ D’Andrea, W. J., Vaillencourt, D. A., Balascio, N. L., Werner, A., Roof, S. R., Retelle, M., and Bradley, R. S. Mild Little Ice Age and unprecedented recent warmth in an 1800 year lake sediment record from Svalbard. *Geology* 40 (11): 1007–1010 (2012)
- ²¹ Lehner, F., Born, A., Raible, C. C., Stocker, T. F. Amplified Inception of European Little Ice Age by Sea Ice–Ocean–Atmosphere Feedbacks. *Climate and Environmental Physics and Oeschger Centre for Climate Change Research, University of Bern* (2013)
- ²² Kim, S. Early Years of the Little Ice Age in Northern Europe, 1300-1500. Korean Minjok Leadership Academy International Program. Research Paper, AP World History Class (2007)
- ²³ Luoto, T. How cold was the Little Ice Age? A proxy-based reconstruction from Finland applying modern analogues of fossil midge assemblages. *Department of Geosciences and Geography Environmental Change Research Unit (ECRU)* (2013)
- ²⁴ Lamb, H. H. *Climate: Present, Past and Future*. Vol. 2. pp 454, 456. London: Metheun (1977)
- ²⁵ Sandnes, J. Settlement Developments in the Late Middle Ages (approx. 1300-1540). p 93. *Desertion and Land Colonization in the Nordic Countries C. 1300-1600*. Ed. Svend Gissel. Uppsala: Almqvist & Wiksell International, 78-114 (1981)
- ²⁶ Derry, T. K. *A Short History of Norway*. p 72. Greenwood P (1979)
- ²⁷ *Met Office*. CET annual anomaly 1659 – 2017: reconstructed TB 1538 – 1658, 5 year moving average – global atmospheric CO2 ppmv.
- ²⁸ Büntgen, U., Tegel, W. European tree-ring data and the Medieval Climate Anomaly. *PAGES news*, Vol 19, No 1 (2011)
- ²⁹ *Stanlake Park Wine estate*, History of English Wine. Retrievable at: <https://www.stanlakepark.com/pages/history-of-english-wine> (2021)
- ³⁰ Jordan, W. C. *The Great Famine: Northern Europe in the Early Fourteenth Century*. p 182. Princeton University Press (1996).
- ³¹ Seavoy, R. E. *Famine in Peasant Societies*. p 73. Greenwood Press (1986)
- ³² Fagan, B. *The Little Ice Age. How Climate Made History 1300 – 1850*. p 39. Basic Books (2000).
- ³³ *Historic UK*. The Thames Frost Fairs. Retrievable at <https://www.historic-uk.com/HistoryUK/HistoryofEngland/The-Thames-Frost-Fairs/> (2019)
- ³⁴ Lockwood, M., Owens, M., Hawkins, E., Jones, G. S., Usoskin, I. Frost fairs, sunspots and the Little Ice Age. *Astronomy & Geophysics*. 58 (2): 2.17–2.23. doi:10.1093/astrogeo/atx057 (2017)
- ³⁵ Fagan, B. *The Little Ice Age. How Climate Made History 1300 – 1850*. p 30. Basic Books (2000).
- ³⁶ Fagan, B. *The Little Ice Age. How Climate Made History 1300 – 1850*. p 40. Basic Books (2000).
- ³⁷ *Encyclopædia Britannica*. Norfolk four-course system. Encyclopædia Britannica, inc. Retrievable at <https://www.britannica.com/topic/Norfolk-four-course-system> (2021)
- ³⁸ Fagan, B. *The Little Ice Age. How Climate Made History 1300 – 1850*. p 155. Basic Books (2000).
- ³⁹ Ljungqvist, F. C. A regional approach to the medieval warm period and the little ice age. *Stockholm University* (2010)
- ⁴⁰ Klimenko, V., Solomina, O. N. Climatic Variations in the East European Plain During the Last Millennium: State of the Art. *The Polish Climate in the European Context: An Historical Overview*. pp.71-101 (2010)

-
- ⁴¹ Maggi, V., de Amicis, M., Ravazzi, C., Pini, R., Vallè, F., Leonelli, G., Brunetti, M., Maugeri, M. Pollen-based temperature variations over the last 3000 years in the Alpine region. Deliverable NextData D1.4.C
- ⁴² Longman, J., Veres, D., Ersek, V., Haliuc, A., Wennrich, W. Runof events and related rainfall variability in the Southern Carpathians during the last 2000 years. Nature Scientific Report (2019)
- ⁴³ Trouet V. A Tree-Ring Based Late Summer Temperature Reconstruction (Ad 1675–1980) for the Northeastern Mediterranean. Laboratory of Tree-Ring Research, University of Arizona (2014)
- ⁴⁴ Fagan, B. The Little Ice Age. How Climate Made History 1300 – 1850. **p 18**. Basic Books (2000).
- ⁴⁵ Dorado Linan, I., Buntgen, U., Gonzalez-Rouco, F., Zorita, E., Montavez, J. P., Gomez-Navarro, J. J., Brunet, M. Heinrich, I., Helle, G., Gutierrez, E. Estimating 750 years of temperature variations and uncertainties in the Pyrenees by tree-ring reconstructions and climate simulations. Climate of the Past, European Geosciences Union (2012)
- ⁴⁶ Oliva, M., Ruiz-Fernández, J., Barriendos, M., Benito, G., Cuadrat, J. M., Domínguez-Castro, F., García-Ruiz, J. M., Giral, S., Gómez-Ortiz, A., Hernández, A., López-Costas, O., López-Moreno, J. I., López-Sáez, J. A., Martínez-Cortizas, A., Moreno, A., Prohom, M., Saz, M. A., Serrano, E., Vicente-Serrano, S. M. The Little Ice Age in the Iberian Mountains. ScienceDirect (2018)
- ⁴⁷ Azevedo Pereira, O. N., Rosário Bastos, M. The “Little Ice Age” (LIA) in Europe – particularly Portugal (an attempt at a synthesis). Academia Letters (2021)
- ⁴⁸ Vadas, A., Rácz, L. Climatic Changes in the Carpathian Basin during the Middle Ages. The State of Research. Global Environment (2013)
- ⁴⁹ Rabb, P. Natural conditions in the Carpathian Basin of the middle ages. Periodica Polytechnica (2007)
- ⁵⁰ Izdebski, A., Mordechai, L., White, S. The Social Burden of Resilience: A Historical Perspective. (2018)
- ⁵¹ Xoplaki, E., Fleitmann, D., Luterbacher, J., Wagner, S., Zorita, E., Telelis, I., Toreti, A., Izdebski, A. The Medieval Climate Anomaly and Byzantium: A review of the evidence on climatic fluctuations, economic performance and societal change. Quaternary Science Reviews (2016)
- ⁵² Felis, T., Ionita, M., Rimbu, N., Lohmann, G., Kölling, M. Mild and Arid Climate in the Eastern Sahara-Arabian Desert During the Late Little Ice Age. Geophysical Research letters (2019)
- ⁵³ Lüning, S., Schulte, L., Garcés-Pastor, S., Danladi, I. B., & Gałka, M. The Medieval Climate Anomaly in the Mediterranean region. Paleoclimatology and Paleoclimatology, 34, <https://doi.org/10.1029/2019PA003734> (2019)
- ⁵⁴ Wazneh, H., Gachon, F., Laprise, R., de Vernal, A., Tremblay, B. Atmospheric blocking events in the North Atlantic: trends and links to climate anomalies and teleconnections. Climate Dynamics (2021)
- ⁵⁵ Solanki, S. K., Usoskin, I. G., Kromer, B., Schüssler, M., Beer, J. Grand minima and maxima of solar activity: new observational constraints 2004, Astronomy & Astrophysics (2007).
- ⁵⁶ Eddy, J. A. The Maunder Minimum, *Science*, New Series, Vol. 192, No. 4245, **pp. 1189-1202** (1976)
- ⁵⁷ *SILSO data/image*, Royal Observatory of Belgium, Brussels. Sunspot Index and Long-term Solar Observations. Retrieval at <http://www.sidc.be/silso/datafiles#total> (2019)
- ⁵⁸ NASA. Solar Radiation and Climate Experiment (SORCE). Retrieval at http://lasp.colorado.edu/home/sorce/data/tsi-data/#historical_TSI
- ⁵⁹ National Ocean and Atmosphere Administration (NOAA). Retrieval at <https://www.esrl.noaa.gov/psd/data/correlation/amon.us.long.data> (2019)

⁶⁰ Knudsen, M. F., Jacobsen, B. H., Seidenkantz, M.-S. and Olsen, J. Evidence for External forcing of the Atlantic Multidecadal Oscillation since termination of the little ice age. *Nature Communications* (2013)

⁶¹ Hernández, A., Sánchez-López, G., Pla-Rabes, S., Comas-Bru, L., Parnell, A., Cahill, N., Geyer, A., Trigo, R. M. & Giral, S. A 2,000-year Bayesian NAO reconstruction from the Iberian Peninsula. *Nature* (2020)

⁶² Trigo, R. M., Osborn, T. J., Corte-Real, J. M. The North Atlantic Oscillation influence on Europe: climate impacts and associated physical mechanisms. *Climate Research* (2002)

⁶³ Hanna, E., Cropper, T. E. North Atlantic Oscillation. *Oxford Research Encyclopaedia of Climate Science* (2017)