Title: **Solar influence on winter severity in central Europe**

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Abstract:

The last two winters in central Europe were unusually cold in comparison to the years before. Meteorological data, mainly from the last 50 years, and modelling studies have suggested that both solar activity and El Niño strength may influence such central European winter coldness. To investigate the mechanisms behind this in a statistically robust way and to test which of the two factors was more important during the last 230 years back into the Little Ice Age, we use historical reports of freezing of the river Rhine. The historical data show that 10 of the 14 freeze years occurred close to sunspot minima and only one during a year of moderate El Niño. This solar influence is underpinned by corresponding atmospheric circulation anomalies in reanalysis data covering the period 1871 to 2008. Accordingly, weak solar activity is empirically related to extremely cold winter conditions in Europe also on such long time scales. This relationship still holds today, however the average winter temperatures have been rising during the last decades.

Main text:

The last two winters in central Europe were relatively cold [*Cattiaux et al., 2010; Guirguis et al., 2011*], major rivers like the Rhine were near to freezing, and smaller rivers froze down to the riverbed. Synoptic analyses of these two winters have shown that the cold temperatures in Europe were caused by anomalous atmospheric circulation patterns [*Cattiaux et al., 2010; Guirguis et al., 2011*], in particular the persistent negative phase of the Arctic Oscillation (AO) and the North Atlantic Oscillation (NAO). This negative NAO phase implies a reduced pressure gradient between

Iceland and the Azores, and is associated with the occurrence of blockings in the eastern North Atlantic, which induces a northerly flow over Europe. The influence of low pressure systems, which can transport warmer, maritime air from the west towards the continent, is reduced, leading to cold winter conditions in Europe [*Guirguis et al., 2011, Sillmann and Croci-Maspoli, 2009*]. These last two winters occurred during a long and pronounced sunspot minimum. The sunspot cycle has long been known to affect stratospheric chemistry and temperature [*Labitzke and van Loon, 1992; Haigh, 1996*]. Evidence for a connection of variations in solar activity with European tropospheric weather was more recently documented in modern meteorological data from the last approximately 50 years [*Bochnicek and Hejda, 2005; Barriopedro et al., 2008; Lookwood et al., 2010, Gray et al., 2010, Woolings et al., 2010*]. The most likely physical mechanism behind it has been demonstrated in several modelling studies [*Shindell et al., 2001, Inerson et al., 2011; Matthes et al., 2006*], which indicate that the solar influence on the stratosphere may propagate downwards and lead also to tropospheric circulation anomalies. Low sunspot activity is, according to these studies, related to a more negative phase of AO and NAO, associated with cold winter conditions in central Europe.

However, meteorological time series of only a few decades are often not long enough for studying the solar forcing with a periodicity of 11 years in a statistically robust way. Moreover, the increase in global surface temperature during the last 50 years may further complicate an investigation of the natural forcing of European winter climate. There are only a few studies that investigated the solar influence on European climate from direct observations [*Lookwood et al., 2010*]. Proxy reconstructions from historical data have been used to understand the severe winter coldness during the maximum of the Little Ice Age from 1675-1704, which can be best explained by a combination of weak solar insolation and interaction with North Atlantic sea surface temperatures [*Wanner et al. 1995; Luterbacher et al. 2001*]. To bridge the gap between these two lines of evidence we use a historical time series spanning the last 230 years, the freezing of a large river in Germany, which represents a robust and easily detectable climate signal (see Fig. 1). This signal is best documented for the river Rhine, which has been used for ship cargo transport since its regulation at the end of the 18th century.

Table 1 list 14 freezing events from 1780 until 1963, when the Rhine was frozen to an extent that people could walk on the ice (Fig. 1), or there is clear evidence for freezing at multiple places along the Rhine between Mainz and Düsseldorf. Local freezing, which is only documented by one single source or is not associated with walkable ice, is not taken into account. Fig. 2 shows these freezing events as a time series plotted together with the time series of sunspot activity. A visual comparison of the two records already indicates a connection between freezing events and sunspot minima. Quantitatively, a freezing event is associated with a minimum in solar activity if it occurred during the 4 winters adjacent to a local minimum in this sunspot curve (e.g., Rhine freezing during the winters 1876/77, 1877/78, 1878/79 or 1879/80 would be associated with the sunspot minimum in 1878). According to this definition, 10 of the 14 freezing events are associated with a solar minimum and are plotted as green lines in Fig. 2a (the remaining 4 events are plotted in red). To test the statistically significance of this relationship we apply a bootstrap method. 14 randomly chosen winters within the period 1770 to 1970 are compared with the sunspot curve, and the number of matches is counted. This experiment is repeated 10,000 times, resulting in a statistical distribution of matching numbers, which can then be compared to the number of matches obtained for the freezing events. If less then 5% (1%) of the random allocations lead to a number of matches equal to or larger than the freezing events, the relationship between solar forcing and river freezing is assumed to be statistically (highly) significant at the 95% (99%) confidence level. According to this test, our empirical observation of 10 freezing events occurring in the 4 winters adjacent to a sunspot minimum is statistically highly significant at the 99% level. Thus, it is highly unlikely that the relationship between historical freezing events and the solar forcing described here is one of chance.

The relative time of the freezing with respect to the nearest sunspot minimum is plotted as a histogram in Fig. 3 and shows that the historical freezing events occurred at about the same numbers in the two years before and after the sunspot minimum. Before we discuss a possible explanation for this observation, we will evaluate another relevant factor. *Toniazzo and Scaife* [*2006*] have shown that moderate El Niño events are related to a more negative NAO and thereby colder winter temperatures in central Europe. In order to test if this relation is also visible in our Rhine freezing time series, the winters with a moderate or strong El Niño in the period 1870-1970 identified by these authors are compared to the Rhine freezing events (Fig. 4). Only during one winter, 1913/14, there is a match between the events.

To identify the atmospheric circulation anomalies in the North Atlantic and European region associated with cold winters during solar minima, Fig. 5a shows the difference in the geopotential height fields at 500 hPa (Z500) between the winters directly following a year with a sunspot minimum and the remainder of the period 1871 to 2008, obtained from the 20th Century Reanalysis dataset [*Compo et al., 1996*]. A strong, statistically significant positive anomaly occurs over the eastern North Atlantic in the region of Iceland, while negative anomalies are found over the Iberian peninsula and over north-eastern Europe (the latter being not significant). These Z500 anomalies are associated with an enhanced northerly flow and cold air advection from the Arctic and Scandinavia towards central Europe, leading to significantly negative temperature anomalies over England, France and western Germany (Fig. 5b). The centre of the cooling is in the region of southern England, the Benelux countries and western Germany down to middle Rhine area. Eastern and southern Germany are not effected as much as the above region. Accordingly, it is only the Rhine and possible some Dutch rivers that provide the possibility to reconstruct this specific temperature anomaly pattern, which corresponds to an anomalously negative NAO and a preference for blockings over the eastern North Atlantic. The statistically significant anomalies of Z500 are mainly restricted to the North Atlantic region, and no larger-scale pattern resampling a negative AO is found, in contrast to, e.g., the model results of *Ineson et al*. [2011] (not shown). The high geopotential anomaly southeast of Greenland (Fig. 5 a) is stronger in the upper than in the lower troposphere indicating a downward propagation of the solar signal from the stratosphere. The Z500 and corresponding temperature anomalies from the 20th Century Reanalysis are similar to the patterns found in previous studies based on other reanalysis data sets covering only the more recent decades [*Barriopedro et al., 2008; Woolings et al., 2010*]. Regional differences, e.g., related to the extent of the cold anomaly over Eastern Europe, might also be due to differences in details of the methodology.

In agreement with the 20th Century Reanalysis central European temperature observations from the CRUTEM3 dataset [*Brohan et al., 2006*] from winters directly following a sunspot minimum are also significantly lower than the average temperature during the remaining winter seasons (Fig. 6a). The relation between cold winter conditions and sunspot activity is thus not specific to rivers alone (which could also be affected by a number of additional factors, for example warm water from the numerous powerplants constructed along the river). The strong variations of the time series in Fig. 6 a, which are largely independent of the sunspot cycle, show the important role of internal, stochastic variability of the atmosphere for European winter temperatures. The relation shown above holds true only for central European temperatures. When the CRUTEM3 winter temperature data are averaged over the whole Northern Hemisphere, no relation to the solar minima is found. This is indicated in Fig. 6b and has the reason that the circulation anomalies associated with sunspot minima only redistribute warm and cold air masses, leading to a cold anomaly over Europe, but also to warm anomalies, e.g., over Greenland and parts of Asia (see again Fig. 5b) [*Lockwood et al., 2010*]. Accordingly, anomalously cold winters in central Europe occurred in the last 2 years, the last 50 years, the last 230 years and the Little Ice Age frequently during times of low sunspot numbers and thus weak solar irradiance. This holds true even for the 21th century, when winters are undoubtedly warmer than during the 20th century, but still, the coldest winters are connected with weak solar activity.

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References:

Barriopedro, D., R. Garcia-Herrera, R. Huth (2008), Solar modulation of Northern Hemisphere winter blocking. *J. Geophys. Res.* 113, D14118.

Bochnicek, J. and P. Hejda (2001), The winter NAO pattern changes in association with solar and geomagnetic activity. *J. Atmos. Solar Terr. Phys.* 67, 17-32 (2005).

Brohan, P., J.J. Kennedy, I. Harris, S.F.B. Tett, and P.D. Jones (2006), Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. *J. Geophys. Res* 111, D12106, doi:10.1029/2005JD006548.

Cattiaux, J., R. Vautard, C. Cassou, P. Yiou, V. Masson-Delmotte, F. Codron (2010), Winter 2010 in Europe: A cold extreme in a warming climate. *Geophys. Res. Lett.* 37, L20704, doi:10.1029/2010GL044613.

Compo, G.P., J.S. Whitaker, P.D. Sardeshmukh, N. Matsui, R.J. Allan, X. Yin, B.E. Gleason, R.S. Vose, G. Rutledge, P. Bessemoulin, S. Brönnimann, M. Brunet, R.I. Crouthamel, A.N. Grant, P.Y. Groisman, P.D. Jones, M.C. Kruk, A.C. Kruger, G.J. Marshall, M. Maugeri, H.Y. Mok, Ø. Nordli, T.F. Ross, R.M. Trigo, X.L. Wang, S.D. Woodruff, S.J. Worley (1996), The Twentieth Century Reanalysis Project. *Q. J. R. Meteorol. Soc.* 137, 1-28, doi:10.1002/qj.776.

Gray, L.J., J. Beer, M. Geller, J.D. Haigh, M. Lockwood, K. Matthes, U. Cubasch, D. Fleitmann, G. Harrison, L. Hood, J. Luterbacher, G.A. Meehl, D. Shindell, B. van Geel, W. White (2010), Solar influences on climate. *Rev. Geophys.* 48, RG4001, doi:10.1029/2009RG000282.

Guirguis, K., A. Gershunov, R. Schwartz and S. Bennett (2011), Recent warm and cold daily winter temperature extremes in the Northern Hemisphere. *Geophys. Res. Lett.* 38, L17701, doi:10.1029/2011GL048762.

Haigh, J.D. (1996): The impact of solar variability on climate. Science 272, 981-984.

Hoyt D.V. and K.H. Schatten, (1997), The role of the sun in climate change, New York Oxford, *Oxf. Univ. Press*, Oxford, New York.

Ineson, S., A.A. Scaife, J.R. Knight, J.C. Manners, N.J. Dunstone, L.J. Gray and J.D. Haigh (2011), Solar forcing of winter climate variability in the Northern Hemisphere. *Nature Geoscience*, DOI: 10.1038/NGEO1282.

Klein Tank, A.M.G., J.B. Wijngaard, G.P. Können, R. Böhm, G. Demarée, A. Gocheva, M. Mileta, S. Pashiardis, L. Hejkrlik, C. Kern-Hansen, R. Heino, P. Bessemoulin, G. Müller-Westermeier, M. Tzanakou, S. Szalai, T. Pálsdóttir, D. Fitzgerald, S. Rubin, M. Capaldo, M. Maugeri, A. Leitass, A. Bukantis, R. Aberfeld, A.F.V. van Engelen, E. Forland, M. Mietus, F. Coelho, C. Mares, V. Razuvaev, E. Nieplova, T. Cegnar, J. Antonio López, B. Dahlström, A. Moberg, W. Kirchhofer, A. Ceylan, O. Pachaliuk, L.V. Alexander, P. Petrovic (2002), Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment. *Int. J. Climatol.* 22, 1441-1453 (2002).

Labitzke, K. and H. van Loon, (1992), Associations between the 11-year solar cycle and the atmosphere. Part V: Summer, *J. Clim.* 5, No. 3, 240-251.

Lockwood (2012). Solar Influence on Global and Regional Climates. Surveys in Geophysics, Volume 33, Numbers 3-4, 503-534. doi: 10.1007/s10712-012-9181-3, available on line (open access) http://www.springerlink.com/openurl.asp?genre=article&id=doi:10.1007/s10712-012-9181-3

Lockwood, M., R.G. Harrison, T. Woolings, S.K. Solanki (2010). Are cold winters in Europe associated with low solar activity? *Environ. Res. Lett.* 5, 024001.

Luterbacher J., R. Rickli, E. Xoplaki, C. Tinguely, C. Beck, C. Pfister and H. Wanner (2001) The late maunder minimum (1675–1715) - a key period for studying decadal scale climatic change in Europe. Clim Change 49:441–462. doi:10.1023/A:1010667524422.

Matthes, K., Y. Kuroda, K. Kodera and U. (2006), Langematz, Transfer of the solar signal from the stratosphere to the troposphere: Northern winter, *J. Geophys. Res.* 111, D06108, doi:10.1029/2005JD006283.

Sillmann, J. and M. Croci-Maspoli (2009), Present and future atmospheric blocking and its impact on European mean and extreme climate. *Geophys. Res. Lett.* 36, L10702, doi:10.1029/2009GL038259.

Shindell, D.T., G. A. Schmidt, M.E. Mann, D. Rind and A. Waple (2001), Solar Forcing of regional climate change during the Maunder Minimum. *Sci. Am.* 294, 2149-2152.

Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.) (2007), IPCC - Climate Change 2007, *Cambridge Univ. Press*, Cambridge, UK & New York, USA, 996 pp.

Toniazzo T. and A.A. Scaife, The influence of ENSO on winter North Atlantic climate (2006), *Geophys. Res. Lett.* 33, L24704, doi:10.1029/2006GL0278881.

Wanner, H., Pfister, C., Brázdil, R., Frich, P., Frydendahl, K., Jonsson, T., Kington, J., Lamb, H.H., Rosenørn, S., Wishman, E. (1995) Wintertime European circulation patterns during the late Maunder Minimum cooling period (1675–1704). Theor Appl Clim 51:167–175. doi:10.1007/BF00867443

Woollings, T., M. Lockwood, G. Masato, C. Bell, L. Gray (2010b) Enhanced signature of solar variability in Eurasian winter climate. Geophys Res Lett 37:L20805. doi:10.1029/2010GL044601

Table 1: Documentation of historical evidence of freezing during the last 230 years for the river Rhine, Germany:

20th century	December 1962 / January 1963 February 1956 February 1954 December 1946 - February 1947 December 1941 - February 1942 January - March 1929 January 1914
19th century	January 1891 February 1880 December 1844 - March 1845 January 1838 January / February 1830 January / February 1823
18th century	December 1783 - February 1784

Figure 1: People gathering on the frozen river Rhine in Mainz in the winter of 1962/63 (historical postcard).

Figure 2: a) Time series of yearly group sunspot numbers from direct astronomical observation [*Hoyt and Schatten, 1997*] (black line) and winters with freezing of the river Rhine (vertical lines; see Table 1). Rhine freezing events are plotted in green if they occurred during one of the 4 winters adjacent to a local minimum in the sunspot curve (see text for details). The years in the top row refer to January of the winter in which the respective freezing event occurred.
b) Winter (DJF) mean temperature observations from three German stations (blue and green lines) from the European Climate Assessment & Dataset [*Klein Tank et al., 2002*]. All temperature anomalies have been calculated relative to the DJF mean of the respective time series. All stations passed the homogeneity tests performed by the ECA&D team (see http://eca.knmi.nl/) for the period 1951-2010. The grey line shows the winter mean temperature anomaly from the observation-based CRUTEM3 dataset [*Brohan et al., 2006*] averaged over the two 5° grid boxes centred at 7.5° long./47.5° lat. and 7.5° long./52.5° lat. Vertical red lines show the Rhine freezing events (see Fig. 2a).

Figure 3: Histogram of the frequency of freezing events relative to the nearest solar minimum.

Figure 4: Time series of sunspot numbers [*Hoyt and Schatten, 1997*] (black curve), Rhine freezing events (red lines) as well as winters with strong (light blue) and moderate (dark blue) El Niño conditions (according to *Toniazzo and Scaife* [*2006*]) for the period 1870-1970.

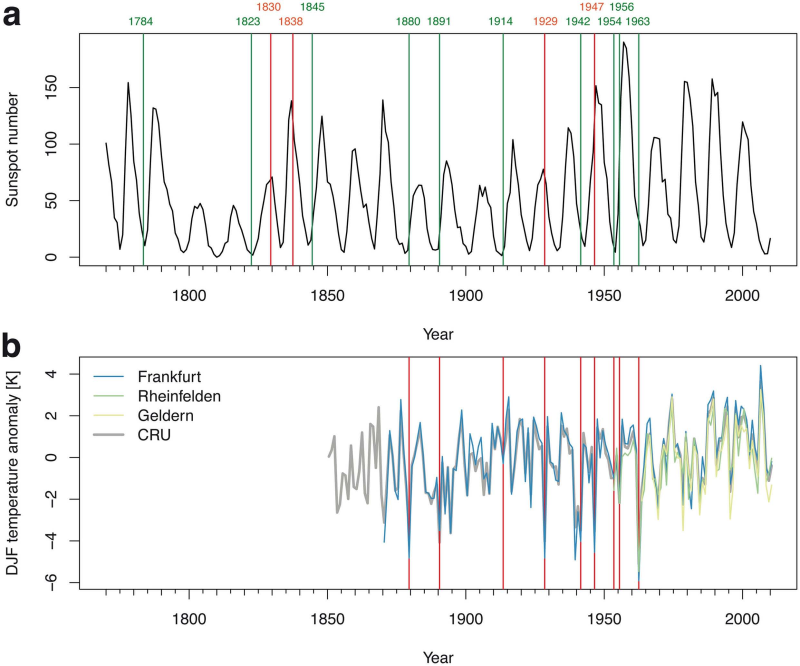
Figure 5: a) Difference in winter mean geopotential height on 500 hPa (Z500) between winters directly following a sunspot number minimum (e.g., 1878/79 corresponding to the minimum in 1878;

13 winters in total) and all other winters in the 20th Century Reanalysis period 1871-2008. The thick green arrow indicates the northerly transport of cold air towards central Europe associated with this anomaly pattern.

b) Difference in winter mean near surface temperature between winters directly following a sunspot number minimum (13 winters) and all other winters in the period 1871-2008, based on 20th Century Reanalysis data. The green dashed lines indicate regions where these differences are statistically significant at the 95% level (based on a two-tailed t-test).

Figure 6: a) Winter mean temperature anomaly time series from the CRUTEM3 dataset (*20*) averaged over the two 5° grid boxes centred at 7.5° long./47.5° lat. and 7.5° long./52.5° lat. (as in Fig. 2b). Red crosses indicate winters directly following a sunspot number minimum, the red dashed line shows the mean over those winters and the green dashed-dotted line indicates the mean of all other winters. These means differ by -0.48 K, which is significant at the 95% level.

b) As in **a**, but for the Northern Hemisphere mean temperature obtained from the HadCRUT3 dataset [*Brohan et al.,* 2006]. Here the difference in the means is 0.05 K, which is statistically not significant.



a
1784
1823
1830
1838
1845
1880
1891
1914
1929
1942
1947
1954
1956
1963
Sunspot number
0
50
100
150
1800
1850
1900
1950
2000
Year
b
Frankfurt
Rheinfelden
Geldern
CRU
DJF temperature anomaly [K]
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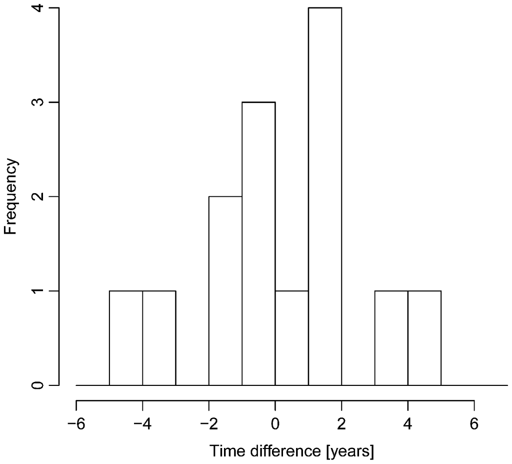
−4
−2
0
2
4
1800
1850
1900
1950
2000
Year



Frequency
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2
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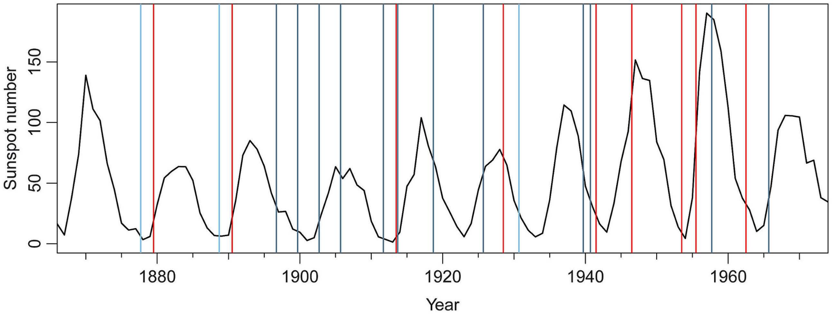
−6
−4
−2
0
2
4
6
Time difference [years]



Sunspot number
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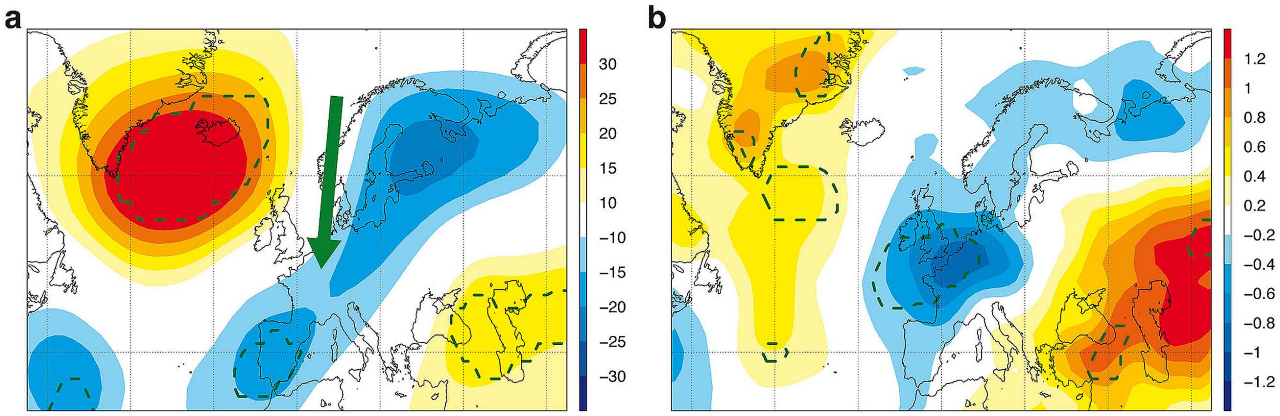
100
150
1880
1900
1920
1940
1960
Year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b
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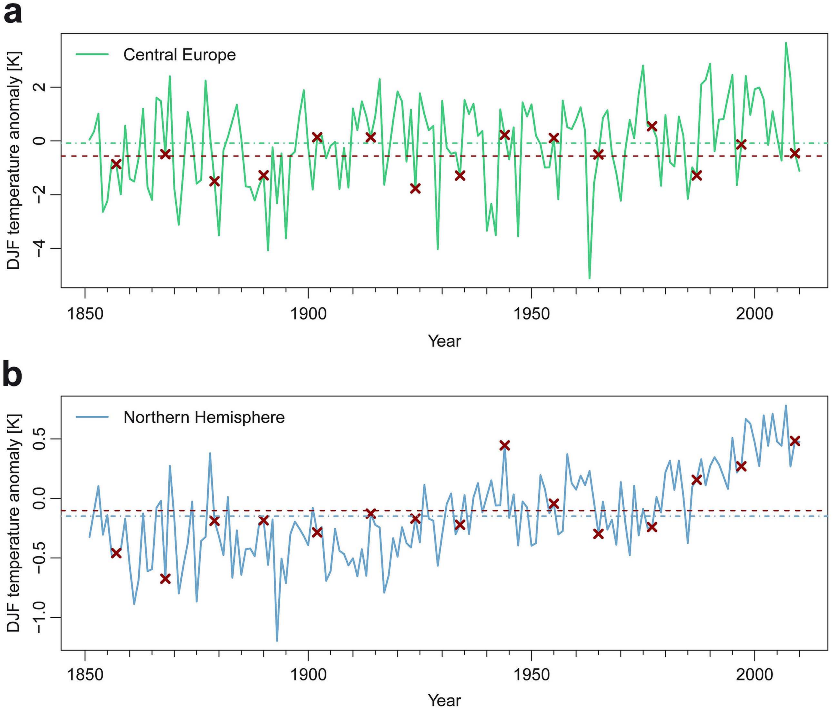
a
Central Europe
DJF temperature anomaly [K]
2
0
−2
−4
1850
1900
1950
2000
Year
b
Northern Hemisphere
DJF temperature anomaly [K]
0.5
0.0
−0.5
−1.0
1850
1900
1950
2000
Year