Multicentennial megadrought in northern Europe coincided with a global El Niño–Southern Oscillation drought pattern during the Medieval Climate Anomaly

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ABSTRACT

The El Niño–Southern Oscillation (ENSO) is a pacemaker of global climate, and the accurate prediction of future climate change requires an understanding of the ENSO variability. Recently, much-debated aspects of the ENSO have included its long-term past and future changes and its associations with the North Atlantic and European sectors, potentially in interaction with the North Atlantic Oscillation and the Atlantic Multidecadal Oscillation. Here we present the first European dendroclimatic precipitation reconstruction that extends through the alternating climate phases of the Medieval Climate Anomaly and the Little Ice Age. We show that northern Europe underwent a severe precipitation deficit during the Medieval Climate Anomaly, which was synchronous with droughts in various ENSO-sensitive regions worldwide, while the subsequent centuries during the Little Ice Age were markedly wetter. We attribute this drought primarily to an interaction between the ENSO and the North Atlantic Oscillation, and to a lesser (or negligible) degree to an interaction between the ENSO and the Atlantic Multidecadal Oscillation.

INTRODUCTION

The El Niño–Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the Atlantic Multidecadal Oscillation (AMO) are the three main drivers of global hydroclimate (Kiladis and Diaz, 1989; Hurrell, 1995; Hoerling et al., 2001; Sutton and Hodson, 2005; Seager et al., 2007a; Herweijer and Seager, 2008). Recently, the much-debated aspects of the ENSO have included its long-term past and future changes (Cane, 2005) and its associations (teleconnections) with the North Atlantic and the European sectors (Fraedrich, 1994; Emile-Geay et al., 2007), which may be strongly related to anomalies in the NAO and the AMO (Seager et al., 2007a). The suggested European ENSO associations appear statistically strongest in winter and spring (Lloyd-Hughes and Saunders, 2002; Pozo-Vázquez et al., 2005; Brönnimann et al., 2007) and there appears to be an especially strong seasonal link to precipitation (Kiladis and Diaz, 1989; van Oldenborgh et al., 2000). Since the instrumental period is too short to reliably detect the long-term ENSO versus precipitation anomalies (van Oldenborgh and Burgers, 2005), and multicentennial and millennial precipitation data are far too scarce in Europe, the low-frequency (decadal and longer) changes in these associations (Brönnimann et al., 2007) are barely understood. This issue can be surmounted using geological or paleontological proxy records that preserve ancient climatic variations with high precision.

Tree rings are commonly used as proxies for past climates (Fritts, 1976; Briffa et al., 1992; Cook et al., 2004). They are annually resolvable and can be directly calibrated against the instrumental records, producing paleoclimate records at interannual to centennial time scales with high accuracy and precision. The lack of precipitation-indicative millennia-long chronologies has so far impeded reconstruction of past moisture conditions in large parts of Europe. Our newly developed tree-ring chronology covers the time frame from A.D. 660 through the present day and reconstructs precipitation variability for northern Europe. The reconstruction demonstrates highly variable precipitation conditions over the late Holocene, especially at centennial time scales, and reveals a multicentennial drought phase during medieval time. Comparisons with previous proxy studies and model runs suggest that the European megadrought correlates with a global drought pattern, which is associated with anomalous ENSO and NAO events. Our findings may have implications for assessing not only the past but also the future of climate change.

MATERIALS AND METHODS

Our paleoclimatic work uses hundreds of moisture-sensitive tree-ring records from Finland (61°–62°N and 29°–28°E) that originate from a total of 563 trees (both living and dead). A series of Scots pine (*Pinus sylvestris* L.) tree rings were measured, cross dated, and standardized (Fritts, 1976). The regional curve standardization (RCS) was applied, because it is quite valuable for paleoclimate studies (Briffa et al., 1992) (GSA Data Repository Fig. DR1[1]). Standardized tree-ring series were averaged in the mean chronology. The chronological variance was adjusted to temporal variations in sample size (Osborn et al., 1997). The expressed population signal statistic (Wigley et al., 1984) shows that the chronology has been reliable since A.D. 670.

Climatic calibration was based on the homogenized (Tuomenvirta, 2004) instrumental data of four meteorological stations (Savonlinna, 61°48′N, 28°50′E; Lappeenranta, 61°05′N, 28°09′E; Punkaharju, 61°48′N, 29°20′E; Tohmajärvi, 62°14′N, 30°21′E). The precipitation total for May and June (1909–1993) was used as a target variable. This was computed as an average of four normalized records, and the variance in this time series was further adjusted for sample size variations (Osborn et al., 1997).

Precipitation anomalies in the region correlate markedly over wide areas of northern Europe, from northwest Russia and Fennoscandia to Baltic, Poland, northern Germany, the Benelux

[1]GSA Data Repository item 2009044, tree-ring ageing curves (Fig. DR1), spatial precipitation correlations (Fig. DR2), precipitation and atmospheric index correlations (Fig. DR3), precipitation and sea-surface temperature correlations (Fig. DR4), and comparison between USA and European precipitation records (Fig. DR5), is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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countries, and the British Isles (Fig. DR2). The reconstructed precipitation variability could represent climatic anomalies over correspondingly wide areas. In Europe, the strongest ENSO association is found for sea-surface temperatures (SSTs) in the NINO3 region (5°S–5°N and 90°–150°W) during December–February and for precipitation during March–May. This association is also found in a band from southern England eastward into Asia (van Oldenborgh et al., 2000; Lloyd-Hughes and Saunders, 2002). Our correlations confirm this pattern in Central Europe (Fig. DR3). Precipitation (May–June) correlates positively with the NINO3 and the AMO indices and negatively with the NAO index in this region and adjacent areas (Fig. DR3). The regional precipitation anomalies in the study region correlate negatively to SSTs over the Norwegian Sea, positively to SSTs over much of the other parts of the North Atlantic, and positively to SSTs over the equatorial Pacific and the coastal waters off western South America (Fig. DR4).

TABLE 1. CALIBRATION AND VERIFICATION FOR THE RECONSTRUCTION

Calibration period*	1909–1951	1951–1993	1909–1993
Verification period	1951–1993	1909–1951	
Calibration (R)†	0.67	0.48	0.63
Verification (RE)§	0.23	0.46	

*The full period was divided into two subperiods for cross validation to ensure the reliability of the transfer function.
†Quantified by Pearson correlation (R).
§Quantified by reduction of error statistic, RE (Fritts, 1976).

RESULTS

Pearson correlation between pre-whitened (Box and Jenkins, 1970) RCS indices and similarly treated climatic records is highly significant ($r = 0.51$, $p < 0.0001$). Without pre-whitening, the correlation between the records is higher (Table 1). In order to build the reconstruction, mean and variance of chronology were adjusted to the precipitation record. The reconstruction accounts for 40% of the total precipitation variability. At lower frequencies, the explained variance is even higher, nearly 90%, and the records closely follow each other (Fig. 1). The independent verification shows a constant relationship between the records over the separate verification periods. Reduction of error statistics (Fritts, 1976) is positive for both subperiods, indicating skill in the reconstruction (Table 1).

Our reconstruction covers the classical climatic periods of the Little Ice Age (LIA), the Medieval Climate Anomaly (MCA), and the Dark Ages Cold Period (DACP) (Lamb, 1965, 1977, 1982) (Fig. 1). The special feature of this period in climate history is the distinct and persistent drought, from the early ninth century A.D. to the early thirteenth century A.D. This interval precisely overlaps the period commonly referred to as the MCA, due to its geographically widespread climatic anomalies both in temperature and moisture (Stine, 1994). Moreover, the reconstruction also agrees well with the general picture of wetter conditions prevailing during the cool periods of the LIA (here, A.D. 1220–1650) and DACP (here, A.D. 720–930).

The medieval drought represents a uniquely prolonged rainfall deficit within the period of our reconstruction. Throughout the eleventh and twelfth centuries A.D., only a few decadal periods of wetness interrupted the long-term event. Regionally, the drought in our record is consistent with evidence of lower lake levels in part of northwest Russia (Kremenetski et al., 2004) and a lower-than-mean water table in a bog in southwest Finland (Väliranta et al., 2007), which dates to medieval time. In Central Europe, early documentary evidence suggests that dry summers may have prevailed between A.D. 1000 and 1300 (Lamb, 1965; Alexandre, 1987; Tol and Langen, 2000). The twelfth and thirteenth centuries are known to have had dry summers in England and Wales (Lamb, 1965) as well as in central Spain (Benito et al., 2003), though the winters in these regions may actually have been wet. Thus, the long-term anomalies in winter precipitation may have been different than those of summer precipitation, with wetter winters during the MCA and relatively drier winters during the LIA in these regions. This may also explain the indication of a wet Medieval Period according to the stalagmite record from a cave in Scotland, where the annual bandwidth correlates with the annual precipitation (Proctor et al., 2002). Large-scale changes during the MCA and the LIA were likely similar to changes in winter conditions, at least in the UK (Lamb, 1965).

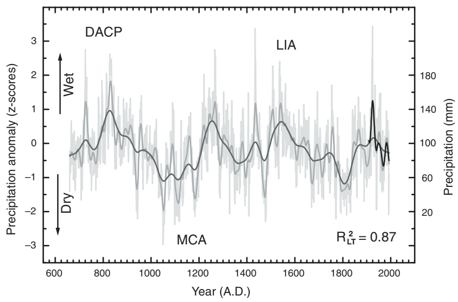

Figure 1. Precipitation anomalies since A.D. 660. Variations are shown with respect to 1909–1993 period as interannual (light gray line), multidecadal (medium gray for reconstructed, black line for observed), and centennial (dark gray line) time scales. Reconstruction covers classical climatic periods of the Little Ice Age (LIA), Medieval Climate Anomaly (MCA), and Dark Ages Cold Period (DACP), and captures much of the long-term variability (R^2_{LT}) observed. Vertical axis refers to standard deviations (z scores) of calibration period (total variability) as well as reconstructed bimonthly (May–June) totals.

The global medieval drought that we found occurred in striking temporal synchrony with the multicentennial droughts previously described for North America (Stine, 1994; Cook et al., 2004, 2007), eastern South America (Stine, 1994; Rein et al., 2004), and equatorial East Africa (Verschuren et al., 2000; Russell and Johnson, 2005, 2007; Stager et al., 2005) between A.D. 900 and 1300 (Fig. 2). Despite the lack of a correlation on shorter time scales (Fig. DR5), the comparison between these regions shows unquestionably that the medieval drought was followed by wetter times. The global evidence argues for a common force behind the hydrological component of the MCA.

Previous studies have associated coeval megadroughts during the MCA in various parts of the globe with either solar forcing (Verschuren et al., 2000; Stager et al., 2005) or the ENSO (Cook et al., 2004, 2007; Rein et al., 2004; Herweijer et al., 2006, 2007; Graham et al., 2007; Seager et al., 2007a). The evidence so far points to the medieval solar activity maximum (A.D. 1100–1250), because it is observed in the $\Delta^{14}C$ and ^{10}Be series recovered from the chemistry of tree rings and ice cores, respectively (Solanki et al., 2004). Recent developments in proxy-model comparisons (Cobb et al., 2003; Cane, 2005; Mann et al., 2005; Emile-Geay et al., 2007; Graham et al., 2007) have shown that possible mechanisms for solar forcing may lie in the dynamics of the equatorial Pacific, particularly in the instability mechanism of the Bjerknes (1969) ocean-atmospheric feedbacks, which underlie the natural oscillatory behavior of the ENSO.

Millennial records of $\delta^{18}O$ from Pacific coral indicate persistent La Niña–like conditions from the tenth to the thirteenth centuries, showing considerable overlap with the MCA. Likewise, the coral record shows El Niño–like conditions over the following centuries, with concomitant overlap with the LIA (Cobb et al., 2003). Recent model experimentation supports the empirical results from these corals. The Zebiak and Cane (1987) model of the tropical Pacific-coupled ocean-atmosphere system was recently employed to examine the response of the region's SSTs to solar radiative and volcanic forcing during the current interglacial period (Mann et al., 2005; Emile-Geay et al., 2007). The models reproduced the tendency for La Niña– and El Niño–like conditions during the MCA and the LIA, respectively. Moreover, the decadal and longer variability in NINO3 output correlated negatively with the solar proxies.

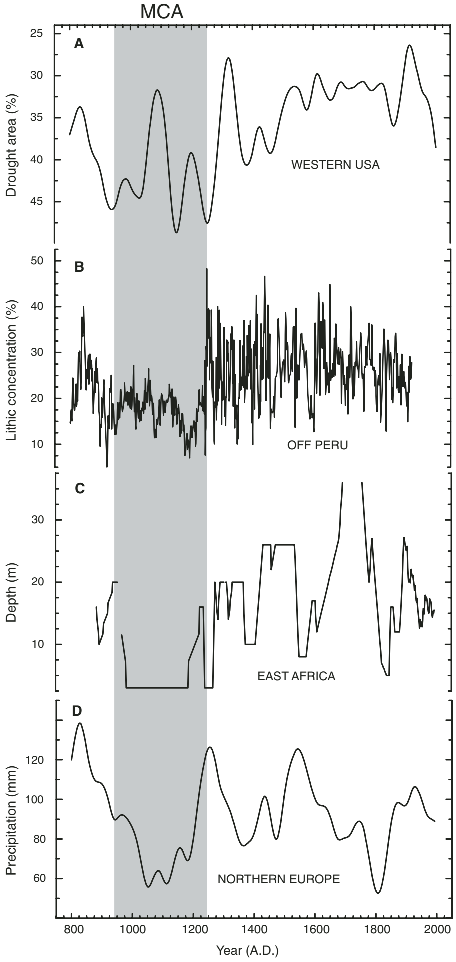

Figure 2. Drought synchrony during Medieval Climate Anomaly (MCA; gray area) exemplified for four continents. A: Spatially representative dendroclimatic evidence from western United States expressed as drought area index reconstruction (vertical axis reversed) that demonstrates spatial extent of phenomenon (Cook et al., 2004). Low-frequency component of record was isolated with 100 yr cubic spline. B: Marine record off coastal Peru shows period of extreme drought without strong El Niño–related flooding between A.D. 800 and 1250. Lithic concentration indicates intense storm-induced runoff by local rivers with El Niño–Southern Oscillation correspondence (Rein et al., 2004). Simultaneous wetland desiccation was evident in Argentina (Stine, 1994). C: Sedimentology inferred changes in lake-level variations in Naivasha Lake (Kenya) indicate persistent medieval lowstand (Verschuren et al., 2000) coeval with other lakes over wider region (Verschuren et al., 2000; Russell and Johnson, 2005; Stager et al., 2005). D: Low-frequency component of European precipitation record (Fig. 1) was isolated (100 yr cubic spline) from the total variability.

These results provide justification for linking the globally widespread droughts (Stine, 1994; Verschuren et al., 2000; Cook et al., 2004, 2007; Rein et al., 2004; Russell and Johnson, 2005; Stager et al., 2005; Herweijer et al., 2006, 2007; Graham et al., 2007; Seager et al., 2007a) to the behavior of the ENSO, since La Niña–like conditions (i.e., cooling of the NINO3 region) are typically associated with dry conditions in these areas (Seager et al., 2007a; Herweijer and Seager, 2008).

Our record (Fig. 1) provides evidence of principal importance that overwhelmingly demonstrates the occurrence of a coeval, persistent, hydrological anomaly in the northern part of Europe, an area quite distant from the key regions of the ENSO. Recent proxy-model studies have suggested mechanisms to show how ENSO variability would generate substantial effects over the North Atlantic, potentially via the NAO and the AMO (Seager et al., 2007a). Positive associations between the anomalies in the NINO3 region and precipitation in the region during the instrumental period (Herweijer and Seager, 2008; Figs. DR3 and DR4), although not strong, could suggest that the medieval influence was at least partly due to a coinciding ENSO anomaly. In addition, SST-forced paleoclimate models, along with instrumental observations, have provided evidence that La Niña–like conditions in the equatorial Pacific may induce a circulation pattern over the North Atlantic that is typical of a positive NAO phase (Fraedrich, 1994; Emile-Geay et al., 2007; Graham et al., 2007). A positive NAO may also have been achieved and enhanced due to radiative forcing, involving changing tropospheric temperature gradients, by a downward control from the stratosphere (Shindell et al., 1999, 2003; Rind et al., 2004). Given the negative association between the NAO index and spring precipitation in the region, these mechanisms could well be expected to have caused the medieval drought, which our dendroclimatic evidence has demonstrated. Regarding the potential impact of the AMO, the precipitation anomalies in our region showed positive association, especially with the SSTs off West Africa (Fig. DR4). However, paleoceanographic data suggest that the SSTs were warmer in these regions during medieval time than they are today (deMenocal et al., 2000). Since this would provide an argument for wetter conditions during the MCA in the study region, it would be reasonable to deduce that the climatic influences due to the AMO may have been somewhat negligible during these times, possibly due to the suggested NAO–ENSO forcing (Fraedrich, 1994; Emile-Geay et al., 2007; Graham et al., 2007).

DISCUSSION AND CONCLUSIONS

Recent studies agree with the general picture that the ENSO has influenced winter and spring precipitation variations, on interannual scales, in Europe over the instrumental period. Meanwhile, several non-European proxy records have identified multicentennial medieval droughts that have also occurred in various other regions of our planet. Our dendroclimatic reconstruction enhances the documentary view that this period was much drier than the following centuries. The medieval megadrought that we recorded was coeval to, and very likely affected by, the coinciding ENSO–NAO anomaly. While past and current climate changes may proceed as shifts between preferred modes of atmospheric circulation patterns (Palmer, 1999), it could be speculated that the present-day warming may alter the association in a manner similar to that of previous changes. Major changes in the past ENSO conditions were related to natural variation, but future changes may be due to anthropogenic forcings. Likewise, large-scale climate change may cause current and future regional droughts (Seager et al., 2007b), similar to droughts in medieval time. Our results underscore the pressing need for a body of millennial precipitation reconstructions in Europe, to better understand the temporal and spatial variability of the late Holocene droughts. Only such reconstructions will detail the spatial picture of the medieval hydrological anomalies in Europe and adjacent areas, and they will enable validation of spatial patterns produced by multicentury model simulations.

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REFERENCES CITED

Alexandre, P., 1987, Le climat en Europe au Moyen Age: Contribution à l'histoire des variations climatiques de 1000 à 1425, d'après les sources narratives de l'Europe occidentale: Paris, Ecole des Hautes Etudes en Sciences Sociales, v. 24, p. 1–827.

Benito, G., Díez-Herrero, A., and Fernández de Villalta, M., 2003, Magnitude and frequency of flooding in the Tagus Basin (central Spain) over the last millennium: Climatic Change, v. 58, p. 171–192, doi: 10.1023/A:1023417102053.

Bjerknes, J., 1969, Atmospheric teleconnections from the equatorial Pacific: Monthly Weather Review, v. 97, p. 163–172, doi: 10.1175/1520–0493(1969)097<0163:ATFTEP>2.3.CO;2.

Box, G.E.P., and Jenkins, G.M., 1970, Time series analysis: Forecasting and control: San Francisco, Holden-Day, 553 p.

Briffa, K.R., Jones, P.D., Bartholin, T.S., Eckstein, D., Schweingruber, F.H., Karlén, W., Zetterberg, P., and Eronen, M., 1992, Fennoscandian summers

from A.D. 500: Temperature changes on short and long timescales: Climate Dynamics, v. 7, p. 111–119, doi: 10.1007/BF00211153.
Brönnimann, S., Xoplaki, E., Casty, C., Pauling, A., and Luterbacher, J., 2007, ENSO influence on Europe during the last centuries: Climate Dynamics, v. 28, p. 181–197, doi: 10.1007/s00382–006–0175-z.
Cane, M.A., 2005, The evolution of El Niño, past and future: Earth and Planetary Science Letters, v. 230, p. 227–240, doi: 10.1016/j.epsl.2004.12.003.
Cobb, K.M., Charles, C.D., Cheng, H., and Edwards, R.L., 2003, El Niño/Southern Oscillation and tropical Pacific climate during the last millennium: Nature, v. 424, p. 271–276, doi: 10.1038/nature01779.
Cook, E.R., Woodhouse, C.A., Eakin, C.M., Meko, D.M., and Stahle, D.W., 2004, Long-term aridity changes in the western United States: Science, v. 306, p. 1015–1018, doi: 10.1126/science.1102586.
Cook, E.R., Seager, R., Cane, M.A., and Stahle, D.W., 2007, North American droughts: Reconstructions, causes and consequences: Earth-Science Reviews, v. 81, p. 93–134, doi: 10.1016/j.earscirev.2006.12.002.
deMenocal, P., Ortiz, J., Guilderson, T., and Sarnthein, M., 2000, Coherent high- and low-latitude climate variability during the Holocene Warm Period: Science, v. 288, p. 2198–2202, doi: 10.1126/science.288.5474.2198.
Emile-Geay, J., Cane, M., Seager, R., Kaplan, A., and Almasi, P., 2007, El Niño as a mediator of the solar influence on climate: Paleoceanography, v. 22, PA3210, doi: 10.1029/2006PA001304.
Fraedrich, K., 1994, An ENSO impact on Europe: A review: Tellus, v. 46A, p. 522–541.
Fritts, H.C., 1976, Tree rings and climate: London, Academic Press, 567 p.
Graham, N., Hughes, M.K., Ammann, C.M., Cobb, K.M., Hoerling, M.P., Kennett, D.J., Kennett, J.P., Rein, B., Stott, L., Wigand, P.E., and Xu, T., 2007, Tropical Pacific–mid-latitude teleconnections in medieval times: Climatic Change, v. 83, p. 241–285, doi: 10.1007/s10584–007–9239–2.
Herweijer, C., and Seager, R., 2008, The global footprint of persistent extra-tropical drought in the instrumental era: International Journal of Climatology, doi: 10.1002/joc.1590 (in press).
Herweijer, C., Seager, R., and Cook, E.R., 2006, North American droughts of the mid to late nineteenth century: History, simulation and implications for Medieval drought: The Holocene, v. 16, p. 159–171, doi: 10.1191/0959683606hl917rp.
Herweijer, C., Seager, R., Cook, E.R., and Emile-Geay, J., 2007, North American droughts of the last millennium from a gridded network of tree-ring data: Journal of Climate, v. 20, p. 1353–1376, doi: 10.1175/JCLI4042.1.
Hoerling, M.P., Hurrell, J.W., and Xu, T., 2001, Tropical origins for recent North Atlantic climate change: Science, v. 292, p. 90–92, doi: 10.1126/science.1058582.
Hurrell, J.W., 1995, Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation: Science, v. 269, p. 676–679, doi: 10.1126/science.269.5224.676.
Kiladis, G.N., and Diaz, H.F., 1989, Global climatic anomalies associated with extremes in the Southern Oscillation: Journal of Climate, v. 2, p. 1069–1090, doi: 10.1175/1520–0442(1989)002<1069:GCAAWE>2.0.CO;2.
Kremenetski, K.V., Boettger, T., MacDonald, G.M., Vaschalova, T., Sulerzhitsky, L., and Hiller, A., 2004, Medieval climate warming and aridity as indicated by multiproxy evidence from the Kola Peninsula, Russia: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 209, p. 113–125, doi: 10.1016/j.palaeo.2004.02.018.
Lamb, H.H., 1965, The Early Medieval Warm Epoch and its sequel: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 1, p. 13–37, doi: 10.1016/0031–0182(65)90004–0.
Lamb, H.H., 1977, Climate: Present, past and future. Volume 2: Climatic history and the future: London, Methuen, 837 p.
Lamb, H.H., 1982, Climate, history and the modern world: London, Methuen, 387 p.
Lloyd-Hughes, B., and Saunders, M.A., 2002, Seasonal prediction of European spring precipitation from El Niño–Southern Oscillation and local sea-surface temperatures: International Journal of Climatology, v. 22, p. 1–14, doi: 10.1002/joc.723.
Mann, M.E., Cane, M.A., Zebiak, S.E., and Clement, A., 2005, Volcanic and solar forcing of the tropical Pacific over the past 1000 years: Journal of Climate, v. 18, p. 447–456, doi: 10.1175/JCLI-3276.1.
Osborn, T.J., Briffa, K.R., and Jones, P.D., 1997, Adjusting variance for sample size in tree-ring chronologies and other regional mean time series: Dendrochronologia, v. 15, p. 89–99.
Palmer, T.N., 1999, A nonlinear dynamical perspective on climate prediction: Journal of Climate, v. 12, p. 575–591, doi: 10.1175/1520–0442(1999)012<0575:ANDPOC>2.0.CO;2.
Pozo-Vázquez, D., Gámiz-Fortis, S.R., Tovar-Pescador, J., Esteban-Parra, M.J., and Castro-Díez, Y., 2005, El Niño–Southern oscillation events and associated European winter precipitation anomalies: International Journal of Climatology, v. 25, p. 17–31, doi: 10.1002/joc.1097.
Proctor, C.J., Baker, A., and Barnes, W.L., 2002, A three thousand year record of North Atlantic climate: Climate Dynamics, v. 19, p. 449–454, doi: 10.1007/s00382–002–0236-x.
Rein, B., Lückge, A., and Sirocko, F., 2004, A major Holocene ENSO anomaly during the Medieval period: Geophysical Research Letters, v. 31, L17211, doi: 10.1029/2004GL020161.
Rind, D., Shindell, D., Perlwitz, J., Lerner, J., and Lonergan, P., 2004, The relative importance of solar and anthropogenic forcing of climate change between the Maunder Minimum and the present: Journal of Climate, v. 17, p. 906–929, doi: 10.1175/1520–0442(2004)017<0906:TRIOSA>2.0.CO;2.
Russell, J.M., and Johnson, T.C., 2005, A high-resolution geochemical record from Lake Edward, Uganda Congo and the timing and causes of tropical African drought during the late Holocene: Quaternary Science Reviews, v. 24, p. 1375–1389, doi: 10.1016/j.quascirev.2004.10.003.
Russell, J.M., and Johnson, T.C., 2007, Little Ice Age drought in equatorial Africa: Intertropical Convergence Zone migrations and El Niño–Southern Oscillation variability: Geology, v. 35, p. 21–24, doi: 10.1130/G23125A.1.
Seager, R., Graham, N., Herweijer, C., Gordon, A.L., Kushnir, Y., and Cook, E., 2007a, Blueprints for Medieval hydroclimate: Quaternary Science Reviews, v. 26, p. 2322–2336, doi: 10.1016/j.quascirev.2007.04.020.
Seager, R., and 12 others, 2007b, Model projections of an imminent transition to a more arid climate in southwestern North America: Science, v. 316, p. 1181–1184, doi: 10.1126/science.1139601.
Shindell, D.T., Miller, R.L., Schmidt, G.A., and Pandolfo, L., 1999, Greenhouse gas forcing of Northern Hemisphere winter climate trends: Nature, v. 399, p. 452–455, doi: 10.1038/20905.
Shindell, D.T., Schmidt, G.A., Miller, R.L., and Mann, M.E., 2003, Volcanic and solar forcing of climate change during the pre-Industrial period: Journal of Climate, v. 16, p. 4094–4107, doi: 10.1175/1520–0442(2003)016<4094:VASFOC>2.0.CO;2.
Solanki, S.K., Usoskin, I.G., Kromer, B., Schüssler, M., and Beer, J., 2004, Unusual activity of the Sun during recent decades compared to the previous 11,000 years: Nature, v. 431, p. 1084–1087, doi: 10.1038/nature02995.
Stager, J.C., Ryves, D., Cumming, B.F., Meeker, L.D., and Beer, J., 2005, Solar variability and the levels of Lake Victoria, East Africa, during the last millennium: Journal of Paleolimnology, v. 33, p. 243–251, doi: 10.1007/s10933–004–4227–2.
Stine, S., 1994, Extreme and persistent drought in California and Patagonia during medieval time: Nature, v. 369, p. 546–549, doi: 10.1038/369546a0.
Sutton, R.T., and Hodson, D.L.R., 2005, Atlantic ocean forcing of North American and European summer climate: Science, v. 309, p. 115–118, doi: 10.1126/science.1109496.
Tol, R.S.J., and Langen, A., 2000, A concise history of Dutch river floods: Climatic Change, v. 46, p. 357–369, doi: 10.1023/A:1005655412478.
Tuomenvirta, H., 2004, Reliable estimation of climatic variations in Finland: Finnish Meteorological Institute Contributions, v. 43, p. 1–79.
Väliranta, M., Korhola, A., Seppä, H., Tuittila, E.-S., Sarmaja-Korjonen, K., Laine, J., and Alm, J., 2007, High-resolution reconstruction of wetness dynamics in a southern boreal raised bog, Finland, during the late Holocene: A quantitative approach: The Holocene, v. 17, p. 1093–1107, doi: 10.1177/0959683607082550.
van Oldenborgh, G.J., and Burgers, G., 2005, Searching for decadal variations in ENSO precipitation teleconnections: Geophysical Research Letters, v. 32, L15701, doi: 10.1029/2005GL023110.
van Oldenborgh, G.J., Burgers, G., and Klein Tank, A., 2000, On the El Niño teleconnection to spring precipitation in Europe: International Journal of Climatology, v. 20, p. 565–574, doi: 10.1002/(SICI)1097–0088(200004)20:5<565:AID-JOC488>3.0.CO;2–5.
Verschuren, D., Laird, K.R., and Cumming, B.F., 2000, Rainfall and drought in equatorial East Africa during the past 1,100 years: Nature, v. 403, p. 410–414, doi: 10.1038/35000179.
Wigley, T.M.L., Briffa, K.R., and Jones, P.D., 1984, On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology: Journal of Applied Meteorology, v. 23, p. 201–213, doi: 10.1175/1520–0450(1984)023<0201:OTAVOC>2.0.CO;2.
Zebiak, S.E., and Cane, M.A., 1987, A model El Niño/Southern Oscillation: Monthly Weather Review, v. 115, p. 2262–2278, doi: 10.1175/1520–0493(1987)115<2262:AMENO>2.0.CO;2.

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