Dark Ages Cold Period: a literature review and directions for future research

#### Abstract

Several late Quaternary studies have recorded cold and disturbed climates centred during the mid-first millennium AD and discussed these conditions under the term 'Dark Ages Cold Period' (DACP). A review of 114 palaeoclimate papers indicated that cold climates were common in the Northern Hemisphere between AD 400 and 765. There are also suggestions that some regions may have been relatively wet during the DACP while those around the Mediterranean and the China/Tibetan Plateau indicate coinciding droughts. A set of environmental responses, on the other hand, indicate a delayed DACP interval (AD 509-865) postdating the actual climate signal. Previously, the DACP has been linked with the North

Atlantic ice-rafting event at about 1400 years ago while some evidence suggests an involvement of the North Atlantic Oscillation and/or El Niño-Southern Oscillation. More recently another proposed phase of widespread cooling, the Late Antique Little Ice Age (LALIA), overlaps with the DACP, and has been tentatively linked with volcanic aerosol and solar irradiance variations reinforcing the climatic downturn since AD 536. Importantly, a higher number of proxy records extending over the first millennium AD is required for more rigorous assessments of climate variability and the forcing during these centuries, and to disentangle the DACP and LALIA fingerprints in the proxy data, particularly to determine whether the DACP and the LALIA are distinct features. Also a richer network of both climate

and environmental proxies is needed to evaluate the human-environment interactions, during the historical Migration Period, and thus through the DACP.

Keywords: palaeoclimatology, North Atlantic Oscillation, El Niño-Southern Oscillation, ice rafted debris events, Late Antique Little Ice Age, volcanic forcing

Dark Ages Cold Period – key issues

Much has been written about late Holocene climate variability. An increasingly large number of proxy datasets have been analysed to reduce the uncertainties in estimating pre-industrial climate variability (Jones et al., 2001; Jones and Mann, 2004; Mann et al., 2009; Neukom et al., 2014; Wilson et al., 2016). Placing these variations in the context of ongoing change and

determining their relative magnitudes shows a large representation of long-term climate features such as a putative 'Medieval Warm Period' (MWP) and a cooler 'Little Ice Age' (LIA), at least for Northern Hemisphere. Less attention has been paid to climate variability during the first millennium AD. Existing analyses show evidence for markedly variable climate through this millennium with greater proxy indications for cold events and glacier advances (Wanner et al., 2008, 2011). Magnitude and geographical spread of these variations remain, however, more poorly understood than those that took place during the later MWP and LIA. Yet, there is a growing interest to explore the first millennium AD human-environmental interactions (Büntgen et al., 2011, 2016). Probably the most frequently discussed climate anomaly of the

first millennium is that commonly identified as the 'Dark Ages Cold Period' (DACP). Collectively, there seems to be a number of proxy indications for perturbed climates at some time before the MWP. But when exactly have these climatic events been recorded and where? Was the DACP characterized by changes only in temperature? And what are the possible forcings behind this period?

Here we aim to present a perspective on climate variability during the DACP based on literature published in international English-language peer-reviewed journals. In this context, a total of 114 palaeoclimate papers (a search was performed for 'Dark Ages Cold Period' and, separately, for 'Dark Age Cold Period' by Google Scholar (http://scholar.google.com/), accessed June 1st, 2016) were found to specify some sort of climatic and/or environmental changes during the DACP (Supplementary Appendix 1 and Table S1, available online). This

approach enabled evaluation of the DACP with respect to its proxy indications. At first glance, the review of these papers appears to support the premise of the DACP. Consistent with expectations, a majority of these papers suggests a change to a colder climatic regime (Figure 1a), with no restriction to any certain geographical region (Figure 1b) or proxy type (Figure 1c), recorded in the mid-first millennium AD (Figure 1d). This first look appears to support the idea of the DACP as a climate anomaly with generally lowered temperatures and potentially wide-

geographical spread, albeit with a strong emphasis towards European and North Atlantic studies, which is partly related to the greater amount of evidence and studies from these

areas. A more precise analysis reveals, however, several interesting aspects that complement, and some that contrast with this picture of the DACP.

Origins of the DACP concept

Some of the early accounts of anomalous climate conditions during the mid-first millennium

AD were made by H.H. Lamb. Combining various types of proxy indications, Lamb (1982, 1995) identified "generally rather colder and more disturbed climate" especially in Europe. He placed these changes in the timeline of the written historical period referred to as Dark Ages, broadly between AD 400 and 900, with tangible evidence indicating advancing glaciers having cut an old Roman route in the Alps. In fact, the works by Lamb (1965, 1977, 1982, 1985, 1995) appear most often cited (17 out of 114 papers) when referring to the DACP. Among other

investigators, Blackford and Chambers (1991) studied peat stratigraphy in the British Isles and showed multi-site indications towards wet/cold conditions around AD 550. Proxy evidence of cold climates was also found by Hass (1996) in his palaeoceanographic study in the North Sea between AD 400 and 700. Later, McDermott et al. (2001) described temperature-driven changes in an Irish speleothem  $\delta^{18}$ O record showing a cold phase bracketed by relatively warmer Roman and Medieval periods (Figure 1d), for which they used the term 'Dark Ages Cold Period' but gave no detailed age ranges for the period. Yet another study, commonly cited for the DACP, appears that of Ljungqvist (2010) who compiled multi-proxy evidence around the extra-tropical Northern Hemisphere for the past two millennia (Figure 2a). In all, 37

out of 114 papers cite at least one of the foregoing papers when referring to the DACP. Even a larger proportion of papers (39 out of 114), however, make no citation to any previous literature when discussing the DACP, an approach that is also common to discussions of the MWP and the LIA. This situation is likely reflected in those viewpoints that classify DACP as an event for which chronology and wider significance are not yet well defined anywhere but are still a matter of debate (e.g. Eiríksson et al., 2006). Clearly, there is a need for studies combining evidence on the specifics of the DACP, such as this study.

# Characterising the DACP climates

The DACP event has been generally regarded as cold, in more than half of the papers (55 percent), these findings representing studies around Europe, in addition to North Atlantic,

Arctic regions, North America, China/Tibetan Plateau, and the northern Pacific (Figure 3). DACP conditions have been attributed not only to cold climates (Figure 1a), but in 20 percent of papers the event has also been linked with hydroclimatic changes (wet, dry, or unspecified change), most often with wet or moist conditions (11 percent). The majority of these wet events (79 percent) originated from various locations in Europe or North Africa. Dry conditions (7 percent), on the other hand, were demonstrated equivalently for the Mediterranean and the China/Tibetan Plateau (Figure 3).

More detailed chronological examination of DACP indications showed an average (median) starting and ending dates of AD 410 (AD 450) and AD 775 (AD 800) for the event, respectively (Figure 1e). Similarly, the DACP was found to have lasted, on average, for 366 (350) years. In a limited set of papers providing a date for the most extreme phase of the DACP an average (median) was given as AD 625 (650). We note that these age estimates, especially the onset dates, fall fairly close to the historically-based ranges already outlined from a less extensive set of observations by Lamb (1982, 1995).

Dividing the data into climatic (n = 96) and environmental (n = 16) indications suggested an earlier climatic start to the event, with a mean year of AD 395, in comparison to that of AD 509 as evident in palaeoenvironmental data (Figure 1e). A parallel difference was observed for the terminal years of the event, with mean years of AD 764 and AD 865, for palaeoclimate and

environmental data, respectively. Both of these differences were found to be significant (*t*test, p < 0.05). In these comparisons the environmental changes included glacial expansions, aeolian, coastal, and soil processes, in addition to changes in forested and aquatic ecosystems. It is possible that this delay represents the lag in these responses to an actual climatic change.

Making similar comparisons between the temperature and hydroclimate indications suggested an earlier starting year for hydroclimate (AD 356) than temperature proxies (AD 414). This difference did not, however, show statistical significance at any reasonable level. Also the difference between the terminal years was relatively unremarkable (Figure 1e).

#### Ocean-atmospheric interactions

Palaeoceanographic proxy data (e.g. foraminifera, alkenone) are well represented amongst DACP studies (Figure 1c), implying that DACP climates may involve ocean-atmosphere interactions. In fact, the DACP phase has been frequently (Berglund, 2003; Reimann et al.,

2011; Oliva and Gómez-Ortiz 2012; Cui and Chang, 2013; Ülgen et al., 2012; Zhong et al., 2014; Li et al. 2016; Rudaya et al., 2016; Ruiz-Fernández et al., 2016) interpreted in the context of a North Atlantic event of ice-rafting debris (IRD) at about 1400 years ago (Figure 2b) (Bond et al., 1997), during which cooler surface waters had advected southward. According to this evidence, the IRD event at about 1400 years ago belongs to a series of similar events and climatic shifts through the Holocene with a cyclicity close to 1470 ± 500 years. The most recent

such cycle being broadly in accord with the MWP and LIA phases (Bond et al., 2001). Solar forcing of these events was initially suggested, with a potential amplification mechanism through thermohaline circulation (Bond et al., 1997, 2001).

Solar proxy data (Steinhilber et al., 2009) consistently illustrate low activity between AD 400 and 700, with a notable seventh-century solar minimum (Figure 2c), the millennial-scale solar changes culminating over these centuries and thus during the DACP (Scafetta, 2012). Interestingly, there is multiple proxy evidence showing that reduced solar activity may modulate the North Atlantic Oscillation (NAO) towards its negative phase (Gray et al., 2010).

Since the NAO is a leading pattern of climate variability in the global atmosphere, and the negative NAO phase is generally associated with cooler temperatures particularly over western Europe and eastern North-America for both the winter (Wanner et al., 2001; Hurrell and Deser, 2010) and summer seasons (Folland et al., 2009), a prolonged negative NAO phase could thus result in cold temperatures at least over some parts of the Northern Hemisphere continents.

The only indications of warm DACP climates appear to originate from Greenland (Figure 3) and thus from a region central to the NAO temperature seesaw (Andresen et al., 2010; Ribeiro et al., 2012) whereby cooling over western Europe is associated with warming over Greenland (van Loon and Rogers, 1978), especially during the winter half of the year as also observed for instrumental temperature trends since the mid-nineteenth century (Jones et al., 2014). These

findings would generally agree with the suggestion of negative NAO phase during the DACP. Alternative explanatory mechanisms (Krawczyk et al., 2010) are required to explain the coinciding proxy indications of cold and warm DACP conditions off the West Greenland margin. However, we note that the longest existing reconstructions of the NAO-index (Olsen et al., 2012; Baker et al., 2015; Faust et al., 2016) do not illustrate any striking agreement over the DACP period but they do exhibit negative indices at some point during the DACP (Figure 2d, e,

f).

Coexisting cold/wet conditions at European sites during the DACP (Figure 3) are consistent with the earlier studies of peat humification from the British Isles (Blackford and Chambers, 1991). When the seasonal sensitivity of these proxy records is specifically stated, the wet DACP conditions appear to reflect spring and summer seasons (Helama et al., 2009; Swierczynski et al., 2012; Grauel et al., 2013). The NAO effects during the warm-season are less extensively studied than those for the winter-season (Hurrell, 1995; Jones et al., 1997), however, highly negative correlations between the instrumentally based NAO-index and precipitation prevail largely for the British Isles and northern Europe, in contrast to weaker, negative correlations for the southern part of the continent (Folland et al., 2009). These issues raise the critical question of seasonality in proxy responsiveness, especially regarding the NAO-reconstructions (Jones et al., 2014). While the longest NAO-reconstructions are indicative of variations in the winter season (Olsen et al., 2012; Baker et al., 2015; Faust et al., 2016), the existing

reconstructions of summer-NAO-index (Linderholm et al., 2008; Folland et al., 2009) remain too short to extend over the DACP interval. Consequently, there is a need for developing longer and seasonally specific reconstructions for the winter and summer half years (Jones et al., 2014).

A range of DACP indications of Pacific origin (Figure 1b; Figure 3) suggests that the event may have extended to areas quite distant from the key regions of the NAO. Climatic oscillations similar to that of IRD cyclicity of 1470-years in the North Atlantic (Bond et al., 1997, 2001) have been reported in the North Pacific Gyre system (Isono et al., 2009), with a possibility of a

climatic link between the North Pacific Gyre Oscillation (NPGO; Di Lorenzo et al., 2008) and the North Atlantic component of the thermohaline circulation (Isono et al., 2009). The lowfrequency NPGO is driven by the central tropical Pacific El Niño mode of sea surface temperatures (SST) and affects the climate variability over Eurasia and North America (Di Lorenzo et al., 2008, 2010). A recently produced 2000-year-long reconstruction of El Niño-Southern Oscillation (ENSO) variability suggests La Niña-like SST mean state (basin-wide

cooling of the tropical Pacific) during the DACP (Figure 2g) (Yan et al., 2011). This would be qualitatively consistent with observation of Conroy et al. (2008) in a set of independent ENSOsensitive proxy records showing higher ENSO frequency and longer, stronger El Niño events (warming of the tropical Pacific), between 2000 and 1500 years ago,, i.e. the centuries predating the DACP event. Moreover, in one of these records (Moy et al., 2002) the periods of low ENSO activity were seen to follow the events in the North Atlantic (Bond et al., 1997,

2001). Despite this broad acceptance, the hardships of reconstructing the low-frequency band of ENSO variability have been recognised (Wilson et al., 2009; Yan et al., 2011). As a result, a pressing need remains for extending the network of proxy records, sensitive to a range of climate/environmental parameters (temperature, precipitation, salinity) reflecting the various aspects of ENSO effects at local/regional scale, spanning not only the second but also the first millennium AD.

Late Antique Little Ice Age

Recently, a collection of multi-proxy evidence illustrated a cooling phase around the Northern Hemisphere which was tree-ring dated to AD 536-660 and termed the Late Antique Little Ice Age (LALIA) (Büntgen et al., 2016). This event was shown to follow a multitude of large unknown volcanic eruptions in AD 536, 540 and 547, for which evidence was derived from bipolar ice-core timescales and sulphur records (Figure 2h) (Sigl et al., 2015). The cooling, having once initiated from volcanic aerosol forcing (Larsen et al. 2008), may have been

sustained over extended intervals possibly because of the coinciding solar minimum and through sea-ice/ocean feedback mechanisms (Büntgen et al., 2016; Matskovsky and Helama, 2016), analogous to findings from equivalent proxy data (Gennaretti et al., 2014) and transient climate model simulations (Miller et al., 2012) during the LIA. Despite there being no mention of the DACP given by Büntgen et al. (2016), both the common signal of large-scale cooling and the overlap of the LALIA (i.e. AD 536-660) and the DACP (i.e. AD 410-775) climatic episodes are

eye-catching. It seems odd therefore to invoke a new cold period such as the LALIA within a previously defined cold period, the DACP! Whereas the DACP has frequently been deduced in the context of North Atlantic ice rafted debris events representing, if true, a continuum of natural variability through the Pleistocene and Holocene climates, the LALIA has been suggested as being triggered by volcanic forcing and would represent an episodic phase of abrupt cooling. It is likely that all these signals are superimposed within the palaeoclimatic archive, so it is important to combine the diverse proxy records as opposed to looking at just one type of proxy record (trees in this case) when considering large-scale averages. Obviously, there remains a pressing need for more detailed analyses of climate variability over these

centuries, taking into account the hypothesised forcings behind both the LALIA and DACP. Such work is necessary to determine the nature of the climate during these events and the effect this may have caused on a series of societal unrest and humanitarian crises in both the western and eastern zones of Eurasia (Büntgen et al., 2011, 2016). Additionally, both the LALIA and DACP overlap with the Migration Period, the years AD 400-600 being regarded as one the 'hinges' of human history (Randsborg, 1991). The role of climatic perturbations in these multifaceted societal events remains, however, largely undiscussed (Haldon, 2016).

### From past to future DACP studies

The first millennium AD was characterised by cold and disturbed climates. Climatic events discussed under the term 'Dark Ages Cold Period' represent various geographical regions and types of palaeoclimate information (Figure 1). Yet, these variations remain far less studied in comparison to the second millennium AD climate cooling, the LIA (Bradley and Jones, 1992, 1993; Matthews and Briffa, 2005). Interestingly, the DACP and LIA have both been characterised by predominantly cool climates, hydroclimatic changes, glacier advances, and may be tentatively linked with reduced solar activity, changes in ocean-atmospheric circulation patterns (i.e. NAO, ENSO), and the North Atlantic ice rafted debris events. Moreover, tree-ring evidence suggests increases in volcanic forcing at least during the mid-sixth century AD. Similar to the LIA evidence (Bradley and Jones, 1992), however, the DACP literature shows no evidence for a synchronous multi-centennial coldness prevailing around the Northern

Hemisphere and the globe. This evidence notwithstanding, there appears no consensus in the literature about which of the forcings may have dominated in triggering/sustaining the climatic changes, nor even the chronology of the event. As with the LIA, it is likely to be a combination of a number of factors, particularly volcanic and solar forcing. In this paper, we have specifically assessed proxy evidence from palaeoclimate literature for climatic events referred to as DACP. As a result, the intervals AD 400-765 and AD 509-865 were defined for climatic and environmental DACP representations, respectively, from a wide variety of proxy data. We are under no illusion that the approach is perfect. The results, however, outline and categorise the characteristics of the anomalies that palaeoclimatologists have identified as DACP climates with implications for those factors that may have influenced the climatic/environmental changes as their forcings.

Continuing needs for developing proxy datasets over the first millennium AD are evident for more rigorous examination of the DACP (and LALIA) signals, their coherence and spatial structure in palaeoclimate analyses at regional, hemispheric and global scales. Dating accuracy is an important issue in the development of these concepts. Oceanic links are almost certainly needed to help explain the solar influence behind the climatic changes, yet, the proxy records from these archives should be dated to similar accuracy as the terrestrial records indicative of DACP and LALIA signals. Environmental proxies are needed to evaluate the human-

environmental interactions during the historical Migration Period. Some weight should be assigned in particular in the developing network of proxy records (also non-temperature) to

differentiate the winter and summer half years for the key regions of the NAO and ENSO. Only more extensive data will detail the variable nature of these circulation modes on large-scale averages, particularly their low-frequency phases, to enable validations of their roles behind the first millennium AD climate anomalies.

Acknowledgements

The authors acknowledge helpful comments from anonymous referees.

Funding

The manuscript was written while the first author (S.H.) was supported by Grant 288267 from the Academy of Finland.

### References

Andresen CA, McCarthy DJ, Dylmer CV et al. (2010) Interaction between subsurface ocean waters and calving of the Jakobshavn Isbræ during the late Holocene. *The Holocene* 21: 211–

224.

Baker A, Hellstrom JC, Kelly BFJ et al. (2015) A composite annual-resolution stalagmite record of North Atlantic climate over the last three millennia. *Scientific Reports* 5: 10307. DOI: 10.1038/srep10307.

Berglund BE (2003) Human impact and climate changes—synchronous events and a causal link? *Quaternary International* 105: 7–12.

Blackford JJ and Chambers FM (1991) Proxy records of climate from blanket mires: evidence for a Dark Age (1400 BP) climatic deterioration in the British Isles. *The Holocene* 1: 63–67.

Bond G, Kromer B, Beer J et al. (2001) Persistent solar influence on North Atlantic climate during the Holocene. *Science* 294: 2130–2136.

Bond G, Showers W, Cheseby M et al. (1997) A pervasive millennial-scale cycle in North Atlantic Holocene and Glacial climates. *Science* 278: 1257–1266.

Bradley RS and Jones PD (1992) When was the Little Ice Age. In Mikami, T, editor, *Proceedings* of the International Symposium on the Little Ice Age Climate, Department of Geography, Tokyo Metropolitan University, pp. 1–4.

Bradley RS and Jones PD (1993) 'Little Ice Age' summer temperature variations: their nature and relevance to recent global warming trends. *The Holocene* 3: 367–376.

Büntgen U, Tegel W, Nicolussi K et al. (2011) 2500 Years of European climate variability and human susceptibility. *Science* 311: 578–582.

Büntgen U, Myglan VS, Ljungqvist FC et al. (2016) Cooling and societal change during the Late Antique Little Ice Age from 536 to around 660 AD. *Nature Geoscience* 9: 231–236.

Conroy JL, Overpeck JT, Cole JE et al. (2008) Holocene changes in eastern tropical Pacific climate inferred from a Galápagos lake sediment record. *Quaternary Science Reviews* 27: 1166–1180.

Cui J and Chang H (2013) The possible climate impact on the collapse of an ancient urban city in Mu Us Desert, China. *Regional Environmental Change* 13: 353–364.

Di Lorenzo E, Cobb KM Furtado JC et al. (2010) Central Pacific El Niño and decadal climate change in the North Pacific Ocean. *Nature Geoscience* 3: 762–765.

Di Lorenzo E, Schneider N, Cobb KM et al. (2008) North Pacific Gyre Oscillation links ocean climate and ecosystem change. *Geophysical Research Letters* 35: L08607. DOI: 10.1029/2007GL032838.

Eiríksson J, Bartels-Jonsdóttir HB, Cage AG et al. (2006) Variability of the North Atlantic Current during the last 2000 years based on shelf bottom water and sea surface temperatures along an open ocean/shallow marine transect in western Europe. *The Holocene* 16: 1017–1029.

Faust JC, Fabian K, Milzer G et al. (2016) Norwegian fjord sediments reveal NAO related winter temperature and precipitation changes of the past 2800 years. *Earth and Planetary Science Letters* 435:84–93.

Folland CK, Knight J, Linderholm HW et al. (2009) The summer North Atlantic Oscillation: past, present, and future. *Journal of Climate* 22: 1082–1103.

Gennaretti F, Arseneault D, Nicault A et al. (2014) Volcano-induced regime shifts in millennial tree-ring chronologies from northeastern North America. *Proceedings of the National Academy of Science of the United States of America* 111: 10077–10082.

Grauel A-L, Goudeau M-LS, de Lange GJ et al. (2013) Climate of the past 2500 years in the Gulf of Taranto, central Mediterranean Sea: A high-resolution climate reconstruction based on  $\delta^{18}$ O and  $\delta^{13}$ C of *Globigerinoides ruber* (white). *The Holocene* 23: 1440–1446.

Gray LJ, Beer J, Geller M et al. (2010) Solar influences on climate. *Reviews of Geophysics* 48: RG4001. DOI: 10.1029/2009RG000282.

Haldon J (2016) Cooling and societal change. Nature Geoscience 9: 191–192.

Hass HC (1996) Northern Europe climate variations during late Holocene: evidence from marine Skagerrak. *Palaeogeography, Palaeoclimatology, Palaeoecology* 123: 121–145.

Helama S, Meriläinen J, Tuomenvirta H (2009) Multicentennial megadrought in northern Europe coincided with a global El Niño–Southern Oscillation drought pattern during the Medieval Climate Anomaly. *Geology* 37: 175–178.

Hurrell JW (1995) Decadal trends in the North Atlantic Oscillation: regional trends and precipitation. *Science* 269: 676–679.

Hurrell JW and Deser C (2010) North Atlantic climate variability: The role of the North Atlantic Oscillation. *Journal of Marine Systems* 79: 231–244.

Isono D, Yamamoto M, Irino T et al. (2009) The 1500-year climate oscillation in the midlatitude North Pacific during the Holocene. *Geology* 37: 591–594.

Jones PD and Mann ME (2004) Climate over past millennia. *Reviews in Geophysics* 42: RG2002. DOI: 10.1029/2003RG000143.

Jones PD, Harpman C and Vinther BM (2014) Winter-responding proxy temperature reconstructions and the North Atlantic Oscillation. *Journal of Geophysical Research* 119: 6497–6505.

Jones PD, Jonsson T and Wheeler D (1997) Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland. *International Journal of Climatology* 17: 1433–1450.

Jones PD, Osborn TJ and Briffa KR (2001) The evolution of climate over the last millennium. *Science* 292:662–667.

Krawczyk D, Witkowski A, Moros M et al. (2010) Late-Holocene diatom-inferred reconstruction of temperature variations of the West Greenland Current from Disko Bugt, central West Greenland. *The Holocene* 20: 659–666.

Lamb HH (1965) The early medieval warm epoch and its sequel. *Palaeogeography, Palaeoclimatology, Palaeoecology* 1: 13–37.

Lamb HH (1977) Climate: Present, Past and Future, Vol. 2. London: Methuen & Co.

Lamb HH (1982) Climate, History and the Modern World. Boca Raton: Routledge.

Lamb HH (1985) Climatic History and the Future. New Jersey: Princeton University Press.

Lamb HH (1995) Climate History and The ModernWorld. 2nd Edition. New York: Routledge.

Larsen LB, Vinther BM, Briffa KR et al. (2008) New ice core evidence for a volcanic cause of the A.D. 536 dust veil. *Geophysical Research Letters* 35: L04708, DOI: 10.1029/2007GL032450.

Li G, Dong H, Hou W et al. (2016) Temporal succession of ancient phytoplankton community in Qinghai Lake and implication for paleo-environmental change. *Scientific Repots* 6: 19769. DOI: 10.1038/srep19769.

Linderholm HW, Folland CK and Hurrell JW (2008) Reconstructing Summer North Atlantic Oscillation (SNAO) variability over the last five centuries. *TRACE - Tree Rings in Archaeology, Climatology and* 

*Ecology* 6:6–13.

Ljungqvist FC (2010) A new reconstruction of temperature variability in the extra-tropical Northern Hemisphere during the last two millennia. *Geografiska Annaler: Series A, Physical Geography* 92:339–351.

Mann ME, Zhang Z, Rutherford S et al. (2009) Global signatures and dynamical origins of the Little Ice Age and medieval climate anomaly. *Science* 326: 1256–1260.

Matskovsky VV and Helama S (2016) Direct transformation of tree-ring measurements into palaeoclimate reconstructions in three-dimensional space. *The Holocene* 26: 439-449. DOI: 10.1177/0959683615609748.

Matthews JA and Briffa KR (2005) The 'Little Ice Age': re-evaluation of an evolving concept. Geografiska Annaler 87A: 17–36.

McDermott F, Mattey DP and Hawkesworth C (2001) Centennial-scale Holocene climate variability revealed by a high-resolution speleothem  $\delta^{18}$ O record from SW Ireland. *Science* 294: 1328–1331.

Miller GH, Geirsdóttir Á, Zhong Y et al. (2012) Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks. *Geophysical Research Letters* 39: L02708.

DOI: 10.1029/2011GL050168.

Moy CM, Seltzer GO, Rodbell DT et al. (2002) Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. Nature 420: 162–165.

Neukom R, Gergis J, Karoly DJ et al. (2014) Inter-hemispheric temperature variability over the past millennium. *Nature Climate Change* 4: 362–367.

Oliva M and Gómez-Ortiz A (2012) Late-Holocene environmental dynamics and climate variability in a Mediterranean high mountain environment (Sierra Nevada, Spain) inferred from lake sediments and historical sources. *The Holocene* 22: 915–927.

Olsen J, Anderson NJ and Knudsen MF (2012) Variability of the North Atlantic Oscillation over the past 5,200 years. *Nature Geoscience* 5: 808–812.

Randsborg K (1991) *The first millennium AD in Europe and the Mediterranean*. Cambridge: Cambridge University Press.

Reimann T, Tsukamoto S, Harff J et al. (2011) Reconstruction of Holocene coastal foredune progradation using luminescence dating — An example from the Świna barrier (southern Baltic Sea, NW Poland). *Geomorphology* 132: 1–16.

Ribeiro S, Moros M, Ellegaard M et al. (2012) Climate variability in West Greenland during the past 1500 years: evidence from a high-resolution marine palynological record from Disko Bay. *Boreas* 41:68–83.

Rudaya N, Nazarova L, Novenko E et al. (2016) Quantitative reconstructions of mid- to late Holocene climate and vegetation in the north-eastern altai mountains recorded in lake teletskoye. *Global and Planetary Change* 141: 12–24.

Ruiz-Fernández J, Nieuwendam A, Oliva M et al. (2016) Cryogenic processes and fire activity in a high Atlantic mountain area in NW Iberia (Picos de Europa) during the Mid–Late Holocene. *Science of the Total Environment*  Scafetta N (2012) Multi-scale harmonic model for solar and climate cyclical variation throughout the Holocene based on Jupiter–Saturn tidal frequencies plus the 11-year solar dynamo cycle. *Journal of Atmospheric and Solar-Terrestrial Physics* 80: 296–311.

Sigl M, Winstrup M, McConnell JR et al. (2015) Timing and climate forcing of volcanic eruptions for the past 2,500 years. *Nature* 523: 543–549.

Steinhilber F, Beer J and Fröhlich C (2009) Total solar irradiance during the Holocene. *Geophysical Research Letters* 36, L19704, DOI: 10.1029/2009GL040142.

Swierczynski T, Brauer A, Lauterbach S et al. (2012) A 1600 yr seasonally resolved record of decadal-scale flood variability from the Austrian Pre-Alps. *Geology* 40: 1047–1050.

Ülgen UM, Franz SO, Biltekin D et al. (2012) Climatic and environmental evolution of Lake Iznik (NW Turkey) over the last ~ 4700 years. *Quaternary International* 274: 88–101.

van Loon H and Rogers JC (1978) The seesaw in winter temperatures between Greenland and Northern Europe. Part I: General description. *Monthly Weather Review* 106: 296–310.

Wanner H, Brönnimann S, Casty C et al. (2001) North Atlantic Oscillation – concepts and studies. *Surveys in Geophysics* 22: 321–382.

Wanner H, Beer J, Bütikofer J et al. (2008) Mid- to Late Holocene climate change: an overview. *Quaternary Science Reviews* 27: 1791–1828.

Wanner H, Solomina O, Grosjean M et al. (2011) Structure and origin of Holocene cold events. *Quaternary Science Reviews* 30: 3109–3123.

Wilson R, Anchukaitis K, Briffa KR et al. (2016) Last millennium northern hemisphere summer temperatures from tree rings: Part I: The long term context. *Quaternary Science Reviews* 134: 1–18.

Wilson R, Cook E, D'Arrigo R et al. (2009) Reconstructing ENSO: the influence of method, proxy data, climate forcing and teleconnections. *Journal of Quaternary Science* 25: 62–78.

Yan H, Sun L, Wang Y et al. (2011) A record of the Southern Oscillation Index for the past 2,000 years from precipitation proxies. *Nature Geoscience* 4: 611–614.

Zhong W, Xue J, Ouyang J et al. (2014) Evidence of late Holocene climate variability in the western Nanling Mountains, South China. *Journal of Paleolimnology* 52: 1–10.

#### **FIGURE CAPTIONS**

**Figure 1.** Proportions of different climatic and environmental characteristics attributable to Dark Ages Cold Period (DACP) in the palaeoclimate literature (a), with corresponding proportions of geographical regions (b) and proxy type (c), and the temporal distribution of dating placements shown as bars covering a window with average starting and ending dates attributable to corresponding climatic and environmental events (d).

**Figure 2.** Reconstructed extra-tropical Northern Hemisphere (90–30°N) decadal mean temperature relative to the 1961-1990 (Ljungqvist, 2010), the stacked North Atlantic multicore record of percent hematite stained grains (% HSG) indicative of ice-rafted debris (IRD) events corresponding to the Little Ice Age (IRD-0) and Dark Ages Cold Period (IRD-1) (Bond et

al., 2001), the ice-core derived solar forcing as total solar irradiance (ΔTSI) (Steinhilber et al., 2009), the proxy records indicative of the North Atlantic Oscillation (NAO) based on stalagmite band widths (Baker et al. 2015), and lake (NAO<sub>PCA3</sub>) (Olsen et al., 2012), and fjord sediments (NAO<sub>TFJ</sub>) (Faust et al., 2016), the reconstructed Southern Oscillation-index (SOI<sub>pr</sub>) (Yan et al., 2011), and the ice-core derived global volcanic forcing (GVF) (Sigl et al., 2015). The timeframes of the Dark Ages Cold Period (AD 400-765) and the Late Antique Little Ice Age (AD 536-660) are

illustrated as areas of light and dark grey shading, respectively.

**Figure 3.** Geographical distribution of different climatic and environmental characteristics attributable to Dark Ages Cold Period (DACP) in the palaeoclimate literature shown for regions with at least five indications including Mediterranean, China/Tibetan Plateau, NW Europe, Greenland, North Atlantic, Pacific, East Europe, North America, and Alps.

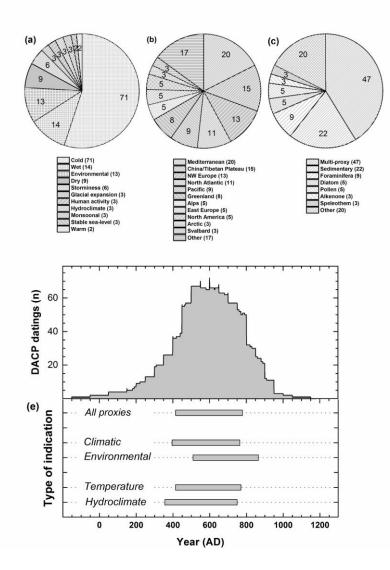


Figure 1. Proportions of different climatic and environmental characteristics attributable to Dark Ages Cold Period (DACP) in the palaeoclimate literature (a), with corresponding proportions of geographical regions (b) and proxy type (c), and the temporal distribution of dating placements shown as bars covering a window with average starting and ending dates attributable to corresponding climatic and environmental events (d).

277x307mm (300 x 300 DPI)

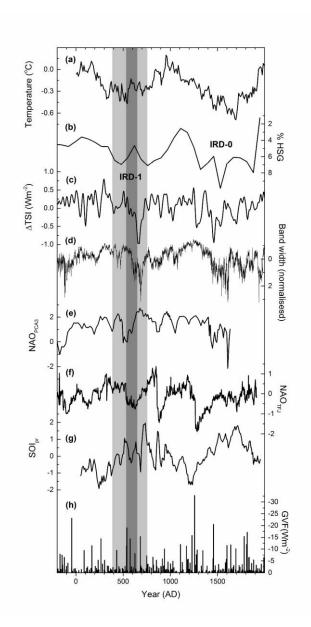


Figure 2. Reconstructed extra-tropical Northern Hemisphere (90–30°N) decadal mean temperature relative to the 1961-1990 (Ljungqvist, 2010), the stacked North Atlantic multi-core record of percent hematite stained grains (% HSG) indicative of ice-rafted debris (IRD) events corresponding to the Little Ice Age (IRD-0) and Dark Ages Cold Period (IRD-1) (Bond et al., 2001), the ice-core derived solar forcing as total solar irradiance (ΔTSI) (Steinhilber et al., 2009), the proxy records indicative of the North Atlantic Oscillation (NAO) based on stalagmite band widths (Baker et al. 2015), and lake (NAOPCA3) (Olsen et al., 2012), and fjord sediments (NAOTFJ) (Faust et al., 2016), the reconstructed Southern Oscillation-index (SOIpr) (Yan et al., 2011), and the ice-core derived global volcanic forcing (GVF) (Sigl et al., 2015). The timeframes of the Dark Ages Cold Period (AD 400-765) and the Late Antique Little Ice Age (AD 536-660) are illustrated as

areas of light and dark grey shading, respectively.

292x505mm (300 x 300 DPI)

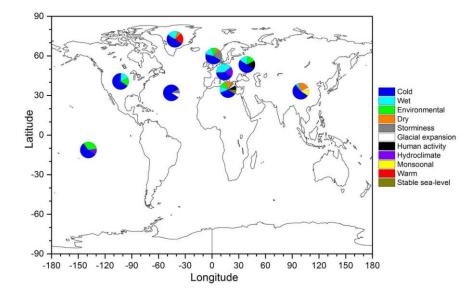


Figure 3. Geographical distribution of different climatic and environmental characteristics attributable to Dark Ages Cold Period (DACP) in the palaeoclimate literature shown for regions with at least five indications including Mediterranean, China/Tibetan Plateau, NW Europe, Greenland, North Atlantic, Pacific, EastEurope, North America, and Alps.

140x92mm (300 x 300 DPI)

Dark Ages Cold Period: a literature review and directions for future research

Samuli Helama, Phil D. Jones, Keith R. Briffa

Supplementary Appendix 1

Palaeoclimate literature

- 1. Andresen CA, McCarthy DJ, Dylmer CV et al. (2010) Interaction between subsurface ocean waters and calving of the Jakobshavn Isbræ during the late Holocene. *The Holocene* 21: 211–224.
- 2. Andresen CS, Björck S, Bennike O et al. (2004) Holocene climate changes in southern Greenland: evidence from lake sediments. *Journal of Quaternary Science* 19: 783–795.
- 3. Azzoug M, Carré M, Chase BM et al. (2012) Positive precipitation–evaporation budget from AD 460 to 1090 in the Saloum Delta (Senegal) indicated by mollusk oxygen isotopes. *Global and Planetary Change* 98–99: 54–62.
- 4. Bakker J, Paulissen E, Kaniewski D et al. (2013) Climate, people, fire and vegetation: new insights into vegetation dynamics in the Eastern Mediterranean since the 1st century AD.

Climate of the Past 9: 57–87.

- 5. Bal M-C, Pelachs A, Perez-Obiol R et al. (2011) Fire history and human activities during the last 3300cal yr BP in Spain's Central Pyrenees: the case of the Estany de Burg. *Palaeogeography, Palaeoclimatology, Palaeoecology* 300:179–190.
- 6. Bjune AE, Seppä J and Birks HJB (2009) Quantitative summer-temperature reconstructions for the last 2000 years based on pollen-stratigraphical data from northern Fennoscandia. *Journal of Paleolimnology* 41: 43–56.
- Björck S and Clemmensen LB (2004) Aeolian sediment in raised bog deposits, Halland, SW Sweden: a new proxy record of Holocene winter storminess variation in southern Scandinavia? *The Holocene* 14: 677–688.
- 8. Boch R and Spötl C (2011) Reconstructing palaeoprecipitation from an active cave flowstone. *Journal of Quaternary Science* 26: 675–687.
- 9. Breitenmoser P, Beer J, Brönnimann S et al. (2012) Solar and volcanic fingerprints in tree-ring chronologies over the past 2000 years. *Palaeogeography, Palaeoclimatology, Palaeoecology* 313-314: 127–139.
- 10. Charman DJ (2010) Centennial climate variability in the British Isles during the mid–late Holocene. *Quaternary Science Reviews* 29: 1539–1554.
- 11. Chen R, Shen J, Li C et al. (2015) Mid-to late-Holocene East Asian summer monsoon variability recorded in lacustrine sediments from Jingpo Lake, Northeastern China. *The Holocene* 25:454-468.
- 12. Chiriloaei F, Rădoane M, Perșoiu I et al. (2012) Late Holocene history of the Moldova River Valley, Romania. *Catena* 93: 64–77.
- 13. Christiansen B and Ljungqvist FC (2012) The extra-tropical Northern Hemisphere temperature in the last two millennia: reconstructions of low-frequency variability. *Climate of the Past* 8:765–786.
- 14. Clemmensen LB, Murray A, Heinemeier J et al. (2009) The evolution of Holocene coastal dunefields, Jutland, Denmark: a record of climate change over the past 5000 years. *Geomorphology* 105: 303–313.
- 15. Corella JP, Brauer A, Mangili C et al. (2012) The 1.5-ka varved record of Lake Montcortès (southern Pyrenees, NE Spain). *Quaternary Research* 78: 323–332.

- 16. Corella JP, Stefanova V, El Anjoumi A et al. (2013) A 2500-year multi-proxy reconstruction of climate change and human activities in northern Spain: The Lake Arreo record. *Palaeogeography, Palaeoclimatology, Palaeoecology* 386:555–568.
- 17. Cristea G, Cuna SM, Fărcaş S et al. (2014) Carbon isotope composition as an indicator of climatic changes during the middle and late Holocene in a peat bog from the Maramureş Mountains (Romania). *The Holocene* 24: 15–23.
- 18. Cui J and Chang H (2013) The possible climate impact on the collapse of an ancient urban city in Mu Us Desert, China. *Regional Environmental Change* 13: 353–364.
- Degeai J-P, Devillers B, Dezileau L et al. (2015) Major storm periods and climate forcing in the Western Mediterranean during the Late Holocene. *Quaternary Science Reviews* 129: 37– 56.
- 20. Détriché S, Bréhéret J-G, Karrat L'h et al. (2013) Environmental controls on the Late Holocene carbonate sedimentation of a karstic lake in the Middle-Atlas Mountains (Lake Afourgagh, Morocco). *Sedimentology* 60: 1231–1256.
- 21. Dinis JL, Henriques V, Freitas MC et al. (2006) Natural to anthropogenic forcing in the Holocene evolution of three coastal lagoons (Caldas da Rainha valley, western Portugal). *Quaternary International* 150: 41–51.
- 22. Dong X, Bennion H, Batterbee RW et al. (2011) A multiproxy palaeolimnological study of climate and nutrient impacts on Esthwaite Water, England over the past 1200 years. *The*

Holocene 22:107-118.

- 23. Eiríksson J, Bartels-Jonsdóttir HB, Cage AG et al. (2006) Variability of the North Atlantic Current during the last 2000 years based on shelf bottom water and sea surface temperatures along an open ocean/shallow marine transect in western Europe. *The Holocene* 16:1017–1029.
- 24. Erbs-Hansen DR, Knudsen KL, Gary AC et al. (2011) Holocene climatic development in Skagerrak, eastern North Atlantic: Foraminiferal and stable isotopic evidence. *The Holocene* 22:301–312.
- 25. Erbs-Hansen DR, Knudsen KL, Olsen J et al. (2013) Paleoceanographical development off Sisimiut, West Greenland, during the mid-and late Holocene: A multiproxy study. *Marine Micropaleontology* 102:79–97.
- 26. Faivre S, Bakran-Petricioli T, Horvatinčić N et al. (2013) Distinct phases of relative sea level changes in the central Adriatic during the last 1500 years—influence of climatic variations? *Palaeogeography, Palaeoclimatology, Palaeoecology* 369:163–174.
- 27. Fleury S, Crosta X, Schneider R et al. (2016) Centennial-scale variations in diatom productivity off Peru over the last 3000 years. *The Holocene* 26: 520–531.
- 28. García-Ruiz JM, Palacois D, de Andrés N et al. (2014) Holocene and 'Little Ice Age'glacial activity in the Marboré Cirque, Monte Perdido Massif, Central Spanish Pyrenees. *The Holocene* 24:1439–1452.
- 29. Ge QS, Zheng JY, Hao ZX et al. (2013) General characteristics of climate changes during the past 2000 years in China. *Science China: Earth Sciences* 56: 321–329.
- 30. Geirsdóttir Á, Miller GH, Larsen DJ et al. (2013) Abrupt Holocene climate transitions in the northern North Atlantic region recorded by synchronized lacustrine records in Iceland. *Quaternary Science Reviews* 70: 48–62.
- 31. Grauel A-L, Goudeau M-LS, de Lange GJ et al. (2013) Climate of the past 2500 years in the

Gulf of Taranto, central Mediterranean Sea: A high-resolution climate reconstruction based on  $\delta^{18}$ O and  $\delta^{13}$ C of *Globigerinoides ruber* (white). *The Holocene* 23: 1440–1446.

32. Guilizzoni, P, Marchetto A, Lami A (2006) Records of environmental and climatic changes during the late Holocene from Svalbard: palaeolimnology of Kongressvatnet. *Journal of Paleolimnology* 36: 325–351.

- Hald M, Salomonsen GR, Husum K et al. (2011) A 2000 year record of Atlantic Water temperature variability from the Malangen Fjord, northeastern North Atlantic. *The Holocene* 21:1049–1059.
- 34. Hanhijärvi S, Tingley MP and Korhola A (2013) Pairwise comparisons to reconstruct mean temperature in the Arctic Atlantic Region over the last 2,000 years. *Climate Dynamics* 41: 2039–2060.
- 35. Hass HC, Kuhn G, Monien P et al. (2010) Climate fluctuations during the past two millennia

as recorded in sediments from Maxwell Bay, South Shetland Islands, West Antarctica. *Geological Society, London, Special Publications* 344: 243–260.

- 36. He Y, Zhao C, Wang Z et al. (2013) Late Holocene coupled moisture and temperature changes on the northern Tibetan Plateau. *Quaternary Science Reviews* 80: 47–57.
- 37. He YX, Liu WG, Zhao C et al. (2013) Solar influenced late Holocene temperature changes on the northern Tibetan Plateau. *Chinese Science Bullelin* 58: 1053–1059.
- 38. Helama S, Meriläinen J and Tuomenvirta H (2009) Multicentennial megadrought in northern Europe coincided with a global El Niño–Southern Oscillation drought pattern during the Medieval Climate Anomaly. *Geology* 37: 175–178.
- Huang Y, Jiang H, Sarnthein M et al. (2009) Diatom response to changes in palaeoenvironments of the northern South China Sea during the last 15000 years. *Marine Micropaleontology* 72:99–109.
- 40. Ilyashuk EA, Ilyashuk BP, Tylmann W et al. (2015) Biodiversity dynamics of chironomid midges in high-altitude lakes of the Alps over the past two millennia. *Insect Conservation and Diversity* 8:547–561.
- 41. Isono D, Yamamoto M, Irino T et al. (2009) The 1500-year climate oscillation in the midlatitude North Pacific during the Holocene. *Geology* 37: 591–594.
- 42. Jakab G, Majkut P, Juhász I et al. (2009) Palaeoclimatic signals and anthropogenic disturbances from the peatbog at Nagybárkány (North Hungary). *Hydrobiologia* 631: 87–106.
- 43. Ji J, Shen J, Balsam W. et al. (2005) Asian monsoon oscillations in the northeastern Qinghai Tibet Plateau since the late glacial as interpreted from visible reflectance of Qinghai Lake sediments. *Earth and Planetary Science Letters* 233: 61–70.
- 44. Jiang H, Shevenell A, Yu S et al. (2015) Decadal-to centennial-scale East Asian summer monsoon variability during the Medieval Climate Anomaly reconstructed from an eastern Tibet lacustrine sequence. *Journal of Paleolimnology* 54: 205–222.
- 45. Keigwin LD and Pickart RS (1999) Slope water current over the Laurentian Fan on interannual to millennial time scales. *Science* 286: 520–523.
- Khider D, Stott LD, Emile-Geay J et al. (2011) Assessing El Niño Southern Oscillation variability during the past millennium. *Paleoceanography*, 26: PA3222. DOI: 10.1029/2011PA002139.
- 47. Kinnard C, Zdanowicz CM, Fisher DA et al. (2011) Reconstructed changes in Arctic sea ice over the past 1,450 years. *Nature* 479: 509–512.
- 48. Kirkbride MP and Winkler S (2012) Correlation of Late Quaternary moraines: impact of climate variability, glacier response, and chronological resolution. *Quaternary Science Reviews* 46:1–29.
- 49. Koizumi I and Yamamoto H (2011) Oceanographic variations over the last 150,000 yr in the Japan Sea and synchronous Holocene with the Northern Hemisphere. *Journal of Asian Earth*

*Sciences* 40: 1203–1213.

- 50. Krawczyk D, Witkowski A and Moros M (2010) Late-Holocene diatom-inferred reconstruction of temperature variations of the West Greenland Current from Disko Bugt, central West Greenland. *The Holocene* 20: 659–666.
- Ladd M, Way RG and Viau AE (2015) The impact of using different modern climate data sets in pollen-based paleoclimate reconstructions of North America. *Quaternary Science Reviews* 112: 78–85.

- 52. Larsen DJ, Miller GH, Geirsdóttir Á et al. (2011) A 3000-year varved record of glacier activity and climate change from the proglacial lake Hvítárvatn, Iceland. *Quaternary Science Reviews* 30:2715–2731.
- 53. Larsen DJ, Miller GH, Geirsdóttir Á et al. (2012) Non-linear Holocene climate evolution in the North Atlantic: a high-resolution, multi-proxy record of glacier activity and environmental change from Hvítárvatn, central Iceland. *Quaternary Science Reviews* 39: 14–25.
- 54. Last FM, Last WM, Fayek M et al. (2013) Occurrence and significance of a cold-water carbonate pseudomorph in microbialites from a saline lake. *Journal of Paleolimnology* 50:
- 505–517.
  55. Lie Z, Henderson ACG and Huang Y (2006) Alkenone-based reconstruction of late-Holocene surface temperature and salinity changes in Lake Qinghai, China. *Geophysical Research Letters* 33: L09707. DOI: 10.1029/2006GL026151.
- 56. Liu X, Herzschuh U, Wang Y et al. (2014) Glacier fluctuations of Muztagh Ata and temperature changes during the late Holocene in westernmost Tibetan Plateau, based on glaciolacustrine sediment records. *Geophysical Research Letters* 41: 6265–6273.
- 57. Liu X, Yu Z, Dong H et al. (2014) A less or more dusty future in the Northern Qinghai-Tibetan Plateau? *Scientific Reports* 4: 6672. DOI: 10.1038/srep06672.
- 58. Liu Z, Henderson ACG and Huang Y (2008) Regional moisture source changes inferred from Late Holocene stable isotope records. *Advances in Atmospheric Sciences* 25: 1021–1028.
- 59. Ljungqvist FC (2009) Temperature proxy records covering the last two millennia: a tabular and visual overview. *Geografiska Annaler: Series A, Physical Geography* 91: 11–29.
- 60. Ljungqvist FC (2010) A new reconstruction of temperature variability in the extra-tropical Northern Hemisphere during the last two millennia. *Geografiska Annaler: Series A, Physical Geography* 92:339–351.
- 61. Margaritelli G, Vallefuoco M, Di Rita F et al. (2016) Marine response to climate changes during the last five millennia in the central Mediterranean Sea. *Global and Planetary Change* 142:53–72.
- 62. Martín-Chivelet J, Muñoz-García MB, Edwards L et al. (2011) Land surface temperature changes in Northern Iberia since 4000 yr BP, based on  $\delta^{13}$ C of speleothems. *Global and Planetary Change* 77: 1–12.
- McDermott F, Mattey DP and Hawkesworth C (2001) Centennial-scale Holocene climate variability revealed by a high-resolution speleothem δ<sup>18</sup>O record from SW Ireland. *Science* 294: 1328–1331.
- 64. Mernild SH, Seidenkrantz M-S, Chylek P (2011). Climate-driven fluctuations in freshwater flux to Sermilik Fjord, East Greenland, during the last 4000 years. *The Holocene* 22: 155–164.
- Millet L, Arnaud F, Heiri O et al. (2009) Late-Holocene summer temperature reconstruction from chironomid assemblages of Lake Anterne, northern French Alps. *The Holocene* 19: 317– 328.
- 66. Moreno J, Fatela F, Leorri E et al. (2014) Marsh benthic Foraminifera response to estuarine hydrological balance driven by climate variability over the last 2000yr (Minho estuary, NW Portugal). *Quaternary Research* 82: 318–330.
- 67. Moreno PI, Vilanova I, Villa-Martínez R (2014) Southern Annular Mode-like changes in southwestern Patagonia at centennial timescales over the last three millennia. *Nature Communications* 5: 4375. DOI: 10.1038/ncomms5375.
- 68. Morley A, Rosenthal Y and deMenocal P (2014) Ocean-atmosphere climate shift during the mid-to-late Holocene transition. *Earth and Planetary Science Letters* 388: 18–26.
- 69. Oliva F, Viau AE, Bjornson J et al. (2016) A 1300 year reconstruction of paleofloods using oxbow lake sediments in temperate southwestern Quebec, Canada. *Canadian Journal of Earth Sciences* 53: 378–386.

- 70. Oliva M and Gómez-Ortiz A (2012) Late-Holocene environmental dynamics and climate variability in a Mediterranean high mountain environment (Sierra Nevada, Spain) inferred from lake sediment and historical sources. *The Holocene* 22: 915–927.
- 71. Oliva M, Schulte L and Gómez Ortiz A (2011) The role of aridification in constraining the elevation range of Holocene solifluction processes and associated landforms in the periglacial belt of the Sierra Nevada. *Earth Surface Processes and Landforms* 36: 1279–1291.
- Orme LC, Davies SJ and Duller GAT (2015) Reconstructed centennial variability of Late Holocene storminess from Cors Fochno, Wales, UK. *Journal of Quaternary Science* 30: 478–
- 488.
  73. Park J, Kim M, Lim HS et al. (2013) Pollen and sediment evidence for late-Holocene human impact at the Seonam-dong archeological site, Gwangju, Korea. *Review of Palaeobotany and Palynology* 193:110–118.
- 74. Patternson WP, Dietrich KA, Holmden C et al. (2010) Two millennia of North Atlantic seasonality and implications for Norse colonies. *Proceedings of the National Academy of Science of the United States of America* 107: 5306–5310.
- 75. Pinto B, Aguiar C and Partidário M (2010) Brief historical ecology of Northern Portugal during the Holocene. *Environment and History* 16: 3–42.
- 76. Rasmussen TL and Thomsen E (2014) Brine formation in relation to climate changes and ice retreat during the last 15,000 years in Storfjorden, Svalbard, 76–78°N. *Paleoceanography* 29:

911–929.

- 77. Rasmussen TL and Thomsen E (2015) Palaeoceanographic development in Storfjorden, Svalbard, during the deglaciation and Holocene: evidence from benthic foraminiferal records. *Boreas* 44: 24–44.
- 78. Reimann T, Tsukamoto S, Harff J et al. (2011) Reconstruction of Holocene coastal foredune progradation using luminescence dating—An example from the Świna barrier (southern Baltic Sea, NW Poland). *Geomorphology* 132: 1–16.
- 79. Ribeiro S, Moros M, Ellegaard M et al. (2012) Climate variability in West Greenland during the past 1500 years: evidence from a high-resolution marine palynological record from Disko Bay. *Boreas* 41:68–83.
- Ricaurte-Villota C, González-Yajimovich O and Sanchez A (2013) Coupled response of rainfall and denitrification to solar forcing during the Holocene in Alfonso Basin. *Ciencias Marinas* 39: 151–164.
- 81. Rudaya N, Nazarova L, Novenko E et al. (2016) Quantitative reconstructions of mid- to late Holocene climate and vegetation in the north-eastern altai mountains recorded in lake teletskoye. *Global and Planetary Change* 141: 12–24.
- 82. Ruiz-Fernández J, Nieuwendam A, Oliva M et al. (2016) Cryogenic processes and fire activity in a high Atlantic mountain area in NW Iberia (Picos de Europa) during the Mid–Late Holocene. *Science of The Total Environment* DOI: 10.1016/j.scitotenv.2016.03.022.
- 83. Rørvik K-L, Grøsfjeld K and Hald M (2009) A late Holocene climate history from Malangen, a north Norwegian Fjord, based on dinocysts. *Norwegian Journal of Geology* 89: 135–147.
- 84. Salvatteci R, Gutiérrez D, Field D et al. (2014) The response of the Peruvian Upwelling Ecosystem to centennial-scale global change during the last two millennia. *Climate of the Past* 10:715–731.
- 85. Sarnthein M, van Kreveld S, Erlenkeuser H et al. (2003) Centennial-to-millennial-scale

periodicities of Holocene climate and sediment injections off the western Barents shelf, 75°N. *Boreas* 32: 447–461.

- 86. Seidenkrantz M-S, Roncaglia L and Fischel A et al. (2008) Variable North Atlantic climate seesaw patterns documented by a late Holocene marine record from Disko Bugt, West Greenland. *Marine Micropaleontology* 68:66–83.
- 87. Seppä H, Bjune AE, Telford RJ et al. (2009) Last nine-thousand years of temperature

- Sha L, Jiang H, Seidenkrantz M-S et al. (2014) A diatom-based sea-ice reconstruction for the Vaigat Strait (Disko Bugt, West Greenland) over the last 5000 yr. *Palaeogeography, Palaeoclimatology, Palaeoecology* 403:66–79.
- 89. Shi F, Yang B, Ljungqvist FC et al. (2012) Multi-proxy reconstruction of Arctic summer temperatures over the past 1400 years. *Climate Research* 54: 113–128.
- Spielhagen R (2012) History of Atlantic Water advection to the Arctic Ocean: a review of 20 years of progress since the "Oden"–"Polarstern" expedition ARCTIC 91. *Polarforschung* 82: 19–36.
- 91. Spielhagen RF, Werner K, Sørensen SA et al. (2011) Enhanced modern heat transfer to the Arctic by warm Atlantic water. *Science* 331: 450–453.
- 92. Stacke V, Pánek T and Sedláček J(2014) Late Holocene evolution of the Bečva River floodplain (Outer Western Carpathians, Czech Republic). *Geomorphology* 206: 440–451.
- 93. Su Y, Liu L, Fang XQ et al. (2016) The relationship between climate change and wars waged between nomadic and farming groups from the Western Han Dynasty to the Tang Dynasty period. *Climate of the Past* 12: 137–150.
- 94. Superson J and Rodzik J and Reder J (2014) Natural and human influence on loess gully catchment evolution: a case study from Lublin Upland, E Poland. *Geomorphology* 212: 28–40.
- 95. Surić M, Korbar T and Juračić M (2014) Tectonic constraints on the late Pleistocene-

Holocene relative sea-level change along the north-eastern Adriatic coast (Croatia). *Geomorphology* 220:93–103.

- 96. Swierczynski T, Brauer A, Lauterbach S et al. (2012) A 1600 yr seasonally resolved record of decadal-scale flood variability from the Austrian Pre-Alps. *Geology* 40: 1047–1050.
- 97. Swierczynski T, Lauterbach S, Dulski P et al. (2013) Mid-to late Holocene flood frequency changes in the northeastern Alps as recorded in varved sediments of Lake Mondsee (Upper Austria). *Quaternary Science Reviews* 80 (2013) 78–90.
- 98. Swindles GT, Lawson IT, Matthews IP et al. (2013) Centennial-scale climate change in Ireland during the Holocene. *Earth-Science Reviews* 126: 300–320.
- 99. Tierney JE, Oppo DW, Rosenthal Y et al. (2010). Coordinated hydrological regimes in the Indo-Pacific region during the past two millennia. *Paleoceanography* 25: PA1102. DOI: 10.1029/2009PA001871.
- 100. Vakulenko NV and Sonechkin DM (2013) Evidence of the upcoming end of the contemporary interglacial. *Doklady Earth Sciences* 452: 926–929.
- 101. van Hengstum PJ, Donnelly JP, Kingston AW et al. (2015) Low-frequency storminess signal at Bermuda linked to cooling events in the North Atlantic region. *Paleoceanography* 30: 52–76.
- 102. Wang T, Surge D and Walker KJ (2011) Isotopic evidence for climate change during the Vandal Minimum from Ariopsis felis otoliths and Mercenaria campechiensis shells, southwest Florida, USA. *The Holocene* 21: 1081–1091.
- 103. Vanniaère B, Magny M, Joannin S et al. (2013) Orbital changes, variation in solar activity and increased anthropogenic activities: controls on the Holocene flood frequency in the Lake Ledro area, Northern Italy. *Climate of the Past* 9, 1193–1209.
- 104. Wei Z, jiayuan C, Jibin X, et al. (2014) Late Holocene monsoon climate as evidenced by proxy records from a lacustrine sediment sequence in western Guangdong, South China.

Journal of Asian Earth Sciences 80: 56–62.

- 105. Viana JCC, Sifeddine A, Turcq B et al. (2014) A late Holocene paleoclimate reconstruction from Boqueirão Lake sediments, northeastern Brazil. *Palaeogeography, Palaeoclimatology, Palaeoecology* 415: 117–126.
- 106. Wilson LJ, Hald M and Godtliebsen F (2011) Foraminiferal faunal evidence of twentieth-century Barents Sea warming. *The Holocene* 21: 527–537.

- 107. Wolf D, Seim A, Diaz Del Olmo F et al. (2013) Late Quaternary fluvial dynamics of the Jarama River in central Spain. *Quaternary International* 302: 20–41.
- 108. Wu W, Tan W, Zhou L et al. (2012) Sea surface temperature variability in southern Okinawa Trough during last 2700 years. *Geophysical Research Letters* 39: L14705. DOI: 10.1029/2012GL052749.
- 109. Yamada K, Kamite M, Saito-Kato M et al. (2010) Late Holocene monsoonal-climate change inferred from Lakes Ni-no-Megata and San-no-Megata, northeastern Japan.

Quaternary International 220: 122–132.

- 110. Yan H, Soon W and Wang Y (2015) A composite sea surface temperature record of the northern South China Sea for the past 2500 years: A unique look into seasonality and seasonal climate changes. *Earth-Science Reviews* 141: 122–135.
- 111. Yan H, Sun L, Wang Y et al. (2011) A record of the Southern Oscillation Index for the past 2,000 years from precipitation proxies. *Nature Geoscience* 4: 611–614.
- 112. Ülgen UM, Franz SO, Biltekin D et al. (2012) Climatic and environmental evolution of Lake Iznik (NW Turkey) over the last ~ 4700 years. *Quaternary International* 274: 88–101.
- 113. Zhang P, Cheng H, Edwards RL et al. (2008) A test of climate, sun, and culture relationships from an 1810-year Chinese cave record. *Science* 322: 940–942.
- 114. Zhong W, Xue J, Ouyang J et al. (2014) Evidence of late Holocene climate variability in the western Nanling Mountains, South China. *Journal of Paleolimnology* 52:1–10.

Dark Ages Cold Period: a literature review and directions for future research

Samuli Helama, Phil D. Jones, Keith R. Briffa

## Supplementary Table

Table S1. Characteristics of the Dark Ages Cold Period (DACP) in 114 palaeoclimate papers (Ref; see Supplementary Appendix 1), with proxy type (MPR – multi-proxy, SED – sedimentary, FOR – foraminifera, DIA – diatom, POL – pollen, ALK – alkenone, SPE – speleothem, OTH – other), geographical regions (MED – Mediterranean, CTP – China/Tibetan Plateau, NWE – NW Europe, GRE – Greenland, PCF – Pacific, ALP – Alps, EAE – East Europe, NAM – North America, ARC – Arctic, SVB – Svalbard, OTH – other), starting date (Year-1), most extreme phase of the DACP (Year-2), ending date (Year-3), and the actual proxy indications.

Ref	Proxy	Region	Year-1	Year-2	Year-3	Indications
1	MPR	GRE	-50	n/a	450	warm
2	MPR	GRE	n/a	n/a	n/a	cold
3	OTH	OTH	n/a	n/a	n/a	wet
4	MPR	MED	650	n/a	950	dry
5	MPR	MED	500	n/a	800	human activity
6	POL	NWE	500	n/a	600	cold
7	SED	NWE	400	n/a	700	cold, wet, storminess
8	OTH	ALP	450	n/a	800	hydroclimate
9	OTH	OTH	450	n/a	950	cold
10	MPR	NWE	350	n/a	820	dry
11	MPR	СТР	400	n/a	700	cold
12	SED	EAE	n/a	n/a	n/a	cold, wet
13	MPR	OTH	300	n/a	800	cold
14	SED	NWE	n/a	n/a	n/a	environmental
15	SED	MED	450	n/a	900	cold
16	MPR	MED	465	n/a	890	cold, wet
17	OTH	EAE	500	n/a	1000	cold, glacial expansion
18	MPR	СТР	420	n/a	550	cold, dry, monsoonal
19	SED	MED	400	n/a	800	storminess
20	SED	OTH	181	n/a	625	wet
21	MPR	MED	450	n/a	950	cold, human activity
22	MPR	NWE	780	n/a	880	cold, storminess
23	MPR	NAT	400	n/a	800	cold
24	MPR	NAT	n/a	n/a	n/a	cold
25	MPR	GRE	350	n/a	800	cold
26	OTH	MED	550	n/a	770	stable sea-level
27	DIA	PCF	600	n/a	800	environmental
28	MPR	MED	600	n/a	800	glacial expansion
29	MPR	СТР	221	n/a	580	dry
30	MPR	NAT	n/a	500	n/a	cold
31	FOR	MED	500	n/a	750	wet
32	MPR	SVB	600	n/a	800	environmental

33	FOR	NAT	400	n/a	800	cold
34	MPR	ARC	600	n/a	900	cold
35	SED	OTH	300	n/a	400	cold
36	SED	CTP	50	n/a	700	wet
37	ALK	CTP	50	n/a	700	cold
38	OTH	NWE	n/a	800	n/a	wet
39	DIA	PCF	150	n/a	600	cold
40	OTH	ALP	n/a	n/a	n/a	cold
41	ALK	PCF	n/a	500	n/a	cold
42	OTH	EAE	n/a	n/a	n/a	cold
43	SED	СТР	-150	n/a	150	dry
44	MPR	СТР	n/a	n/a	n/a	cold
45	FOR	NAT	n/a	n/a	n/a	cold
46	FOR	PCF	450	n/a	750	environmental
47	MPR	ARC	600	n/a	900	cold
48	SED	OTH	700	n/a	900	environmental
49	DIA	PCF	310	n/a	650	cold
50	DIA	GRE	450	n/a	650	cold
51	POL	NAM	350	n/a	650	cold
52	SED	NWE	550	n/a	900	cold
53	MPR	NAT	n/a	600	n/a	cold
55	OTH	NAM	n/a	n/a	n/a	cold
55	ALK	CTP	450	n/a	850	cold
56	SED	СТР	250	n/a	830 880	glacial expansion
57	SED	СТР	350	n/a	600	cold
58	MPR	СТР	450	n/a	850	cold
59 60	MPR	OTH	300	n/a	800	cold
60 61	MPR	OTH	300	n/a	800	cold
61 62	MPR	MED	550	n/a	860	cold
62	SPE	MED	300	n/a	600	cold
63	SPE	NWE	n/a	n/a	n/a	cold
64	OTH	GRE	440	n/a	910	cold, dry
65	OTH	ALP	400	n/a	680	cold
66	FOR	MED	400	n/a	700	cold
67	MPR	OTH	200	n/a	900	wet
68	FOR	NAT	n/a	700	n/a	cold
69	SED	NAM	300	n/a	800	cold, wet
70	MPR	MED	600	n/a	800	cold
71	MPR	MED	450	n/a	950	environmental
72	OTH	NWE	450	n/a	950	storminess
73	MPR	OTH	400	n/a	800	cold
74	OTH	NAT	400	n/a	600	cold
75	OTH	MED	450	n/a	950	environmental
76	OTH	SVB	450	n/a	850	cold
77	FOR	SVB	450	n/a	850	cold
78	MPR	NWE	470	n/a	760	cold, storminess
79	POL	GRE	500	n/a	1050	warm
80	SED	NAM	n/a	n/a	n/a	environmental

1							
2 3	81	POL	ОТН	600	n/a	700	cold
4	82	MPR	MED	n/a	800	n/a	environmental
5	83	OTH	NWE	500	n/a	790	cold, environmental
6	83 84	MPR	PCF	500	-		
7					n/a	900	environmental
8	85	FOR	OTH	350	n/a	950	cold
9	86	SED	GRE	450	n/a	650	cold
10	87	POL	NWE	450	n/a	550	cold
11	88	DIA	GRE	440	n/a	830	cold
12	89	MPR	ARC	630	n/a	770	cold
13	90	MPR	NAT	500	n/a	800	cold
14 15	91	SED	NAT	n/a	n/a	n/a	cold
16	92	MPR	EAE	350	n/a	750	human activity
17	93	MPR	СТР	201	n/a	550	cold
18	94	OTH	EAE	n/a	n/a	n/a	environmental
19	95	MPR	MED	n/a	n/a	n/a	stable-sea level
20	96	SED	ALP	250	n/a	600	wet
21	97	SED	ALP	450	n/a	750	wet
22	98		NWE		-		
23		MPR		550	n/a	n/a	wet
24	99	OTH	OTH	n/a	n/a	n/a	hydroclimate
25	100	OTH	OTH	n/a	n/a	n/a	cold
26	101	MPR	NAT	150	n/a	650	storminess
27	102	MPR	NAM	500	n/a	800	cold
28 29	103	MPR	MED	n/a	n/a	n/a	wet
30	104	SED	CTP	450	n/a	1150	cold
31	105	MPR	OTH	n/a	n/a	n/a	environmental
32	106	FOR	OTH	n/a	700	n/a	cold
33	107	SED	MED	n/a	400	n/a	cold, dry
34	108	OTH	PCF	400	n/a	550	cold
35	109	MPR	OTH	n/a	n/a	n/a	monsoonal
36	110	MPR	PCF	400	n/a	800	cold
37	110	MPR	PCF	500	n/a	900	hydroclimate
38	111			650	-	900	
39 40		SED	MED		n/a		dry
40 41	113	SPE	CTP	190	n/a	850	monsoonal
41	114	MPR	СТР	250	n/a	950	cold, dry
42							