Title
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Journal
Cliodynamics, 12(0)

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Publication Date
2021

DOI
10.21237/C7clio12054304

Cliodynamics: The Journal of Quantitative History and Cultural Evolution

Human Social Complexity Was Significantly Lower during Climate Cooling Events of the Past 10 Millennia

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Human civilizations depend on the climate. Changes in climate affect the production of food and other resources that support populations and their economies. We asked whether the millennium-scale climate cooling events identified by Gerard Bond predicted social complexity in the Seshat cross-cultural database. The results show that social complexity was significantly lower during the coldest two centuries of Bond cooling events. Reductions in complexity are evident in regions north of the tropics adjacent to the Atlantic or Arctic, particularly in North Africa, Europe, and Central Eurasia.

Introduction

Like all living systems, human societies depend fundamentally on metabolism, the uptake and transformation of energy that supports a population and its activities. The food available to a population relies on the productivity of the plant and animal food species that it harvests. The productivity of these species depends on human effort, ecology, and climate, particularly in terms of temperature and precipitation (Tainter 1988; Brown et al. 2011; Burger et al. 2012; Hooper et al. 2014; Putnam et al. 2016).

Climate cooling events that occurred during the Holocene on a roughly millennial timescale were identified by Bond et al. (1997, 2001) on the basis of drift ice indices in the North Atlantic. We hypothesized that these climate events would have had a discernable impact on the extent of social complexity in human societies over time. Studies of specific regions and time periods indicate links between climate and social organization; the collapse of the Akkadian Empire and Egyptian Old Kingdom during the 4.2-kiloyear event are notable examples (Cookson et al. 2019; see Table 1). However, it has remained difficult to test relationships between climate and social variables in a global longitudinal sample. The Seshat dataset published by Turchin et al. (2015, 2018)—a sample of 30 locations in 10 world regions spanning from 9600 BCE to 1900 CE—now allows such a test.

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Citation: Hooper, Paul L. 2021. "Human Social Complexity Was Significantly Lower during Climate Cooling Events of the Past 10 Millennia. *Cliodynamics* 12: Report 1, 1-12.

We asked whether the cooling events reflected in North Atlantic drift ice indices (Bond et al. 1997, 2001) predict the extent of social complexity as quantified by Turchin et al. (2018). Table 1 lists the seven Bond events that overlap in time with the Seshat data. We analyzed the principal component of social complexity (PC1) calculated by Turchin et al. (2018). PC1 reflects a constellation of traits associated with social complexity, including population size, government, religious hierarchy, writing, currency, and urbanization.

Table 1. Bond climate cooling events.

Bond event	Approx. date	Related phenomenon	References
6	7400 BCE	9.2-kiloyear event	Bond et al. (2001); Dobrowolski et al. (2016); Zielhofer et al. (2019)
5	6200 BCE	8.2-kiloyear event	Kobashi et al. (2007); Nicolussi and Schlüchter (2012); Yalçın et al. (2021)
4	3600 BCE	Piora Oscillation	Pèlachs et al. (2011); Cheng et al. (2015); Bevan et al. (2017)
3	2200 BCE	4.2-kiloyear event	Dalfes et al. (2013; Kawahata (2019); Cookson et al. (2019)
2	800 BCE	Iron Age cold epoch	Gutiérrez-Elorza and Peña-Monné (1998); Fensterer et al. (2013); Yu et al. (2018)
1	500 CE	Late Antique Little Ice Age	Allen et al. (2002); Büntgen et al. (2016); Peregrine (2020)
0	1500 CE	Little Ice Age	Grove (2004); Putnam et al. (2016); Zerboni et al. (2020)

Methods

We predicted that social complexity would be lowest in the last centuries of a cooling event, the period of maximum cold before productivity begins to improve again due to warming. To test this prediction, we employed a multilevel regression model estimating Turchin et al.'s (2018) measure of social complexity, PC1. This measure is calculated by taking the principal component of 51 variables associated with social complexity across locations and timepoints. We took the mean of the 20 values of PC1 imputed by Turchin et al. (2018) for each observation. PC1 ranges from -5.67 to 3.98, with a mean of 0.00 and standard deviation of 2.63. In the Middle Yellow River Valley in China, for example, PC1 is 1.69 near the end of the Western Zhou Dynasty in 800 BCE, and 2.36 near the end of the Han Dynasty in 200 CE.

The Turchin et al. (2018) dataset includes a total of 414 observations in 30 locations (a.k.a. natural geographic areas) across 10 world regions (North America, South America, Africa, Europe, Central Eurasia, East Asia, Southwest Asia, South Asia, Southeast Asia, and Australia-Oceania). The regression model included a random effect for location to represent stable differences in complexity across locations. A 0-1 dummy variable was used to demarcate locations in the Old World (Africa, Europe, and Asia) to represent the distinctive sociopolitical trajectory of this macro-region (Kohler et al. 2017).

To control for long-term trends in social complexity, the regression included terms for year of observation and location "age" (years from earliest observation). Year and age were both divided by 1,000, and can therefore be interpreted in units of millennia (e.g., 1000 BCE = -1.0). Linear and quadratic terms for year and age, and the interaction between year and age were considered for inclusion in best-fit models. AIC criteria favored including a linear term for year of observation, linear and quadratic terms for age of location, and a year × age interaction term (Table 2).

The effect of Bond cooling events was represented by a 0-1 dummy variable set to 1 for observations occurring during the last two centuries of a cooling event (i.e., the 200 years prior to and including the dates in Table 1). Understanding that the interpretation of Bond event 0 around 1500 CE may be controversial, models were fit with both the full sample of observations (N = 414) and the subsample of observations that excludes the last millennium (≤1000 CE; N = 284).

We first tested the hypothesis that cooling events are associated with lower social complexity in the global sample (Table 2), then examined estimates for specific regions. Because Bond events were described in the context of the North Atlantic, we tested whether locations north of the tropics and in one of the six regions adjacent to the Atlantic or Arctic—North America, Europe, North Africa, Central Eurasia, East Asia, and Southwest Asia—exhibit stronger signals of cooling events compared to other regions. These models included fixed effects for region and cooling × region interaction terms. We estimated the effects of cooling for northern regions as a group (Table 3), then for each region individually (Table 4). The rows corresponding to the hypothesized effects of cooling in Tables 2–4 are highlighted in gray.

Models were estimated using the lmer function in R (Bates et al. 2015; R Core Team 2021). Best-fit models were evaluated based on AIC minimization. Statistical significance was judged based on 95% confidence intervals (CI).
The code and dataset used in the analysis can be downloaded from github.com/systemsscience/climate. The original data are available from the Seshat Databank (seshatdatabank.info).

Table 2. Regression estimating the effect of cooling events on social complexity in the global sample.

	A. Full Sample			B. Sample ≤ 1000 CE		
Fixed effects	*B*	*2.5%*	*97.5%*	*B*	*2.5%*	*97.5%*
Intercept	-4.478	-5.295	-3.661	-4.938	-6.161	-3.718
Year	0.505	0.344	0.667	0.517	0.285	0.750
Age	1.333	1.090	1.569	1.370	1.007	1.715
Age^2	-0.107	-0.132	-0.081	-0.114	-0.146	-0.078
Year × Age	0.097	0.058	0.134	0.134	0.080	0.181
Old World	2.363	1.329	3.391	3.036	1.493	4.577
Cooling event	-0.278	-0.528	-0.029	-0.384	-0.712	-0.063
Random effects	*SD*	*2.5%*	*97.5%*	*SD*	*2.5%*	*97.5%*
SD(Location)	1.144	0.804	1.467	1.324	0.847	1.766
SD(Residual)	1.090	1.012	1.166	1.096	1.002	1.189

Table 3. Regression estimating the effect of cooling events on social complexity in northern versus southern regions.

	A. Full Sample			B. Sample ≤ 1000 CE		
Fixed effects	*B*	*2.5%*	*97.5%*	*B*	*2.5%*	*97.5%*
Intercept	-4.468	-5.307	-3.630	-4.855	-6.077	-3.631
Year	0.495	0.329	0.662	0.487	0.251	0.725
Age	1.338	1.088	1.577	1.410	1.036	1.756
Age^2	-0.106	-0.130	-0.080	-0.114	-0.146	-0.078
Year × Age	0.094	0.055	0.131	0.133	0.080	0.180
Old World	2.475	1.445	3.510	3.282	1.724	4.839
Southern region	-	-	-	-	-	-
Northern region	-0.260	-1.214	0.694	-0.672	-1.996	0.658
Cooling event × Southern region	0.133	-0.337	0.612	-0.013	-0.747	0.723
Cooling event × Northern region	-0.431	-0.723	-0.142	-0.467	-0.832	-0.111
Random effects	*SD*	*2.5%*	*97.5%*	*SD*	*2.5%*	*97.5%*
SD(Location)	1.141	0.782	1.433	1.331	0.827	1.712
SD(Residual)	1.086	1.008	1.161	1.096	0.999	1.186

Table 4. Regression estimating the effect of cooling events on social complexity in each northern region.

	A. Full Sample			B. Sample ≤ 1000 CE		
Fixed effects	*B*	*2.5%*	*97.5%*	*B*	*2.5%*	*97.5%*
Intercept	-4.452	-5.163	-3.758	-4.545	-5.385	-3.637
Year	0.611	0.457	0.777	0.701	0.498	0.900
Age	1.276	1.044	1.484	1.241	0.922	1.516
Age^2	-0.116	-0.141	-0.090	-0.123	-0.152	-0.086
Year × Age	0.107	0.068	0.145	0.143	0.088	0.187
Old World	2.450	1.563	3.428	3.163	1.910	4.281
Southern region	-	-	-	-	-	-
North America	-0.705	-2.174	0.707	-1.907	-3.763	-0.083
Europe	-0.675	-1.865	0.465	-1.334	-2.489	-0.000
North Africa	1.591	-0.176	3.349	1.526	-0.123	3.248
Central Eurasia	-1.148	-2.321	0.018	-1.106	-2.378	0.273
East Asia	0.870	-0.304	2.042	0.706	-0.568	2.077
Southwest Asia	1.669	-0.107	3.478	2.086	0.239	3.867
Cooling event × Southern region	0.132	-0.325	0.616	-0.031	-0.758	0.684
Cooling event × North America	-0.889	-2.237	0.325	-0.620	-2.343	1.100
Cooling event × Europe	-0.544	-1.175	0.081	-0.863	-1.657	-0.096
Cooling event × North Africa	-0.905	-1.711	-0.098	-0.502	-1.465	0.443
Cooling event × Central Eurasia	-0.536	-1.259	0.183	-1.326	-2.230	-0.353
Cooling event × East Asia	-0.434	-1.075	0.227	-0.446	-1.272	0.374
Cooling event × Southwest Asia	0.112	-0.473	0.698	0.262	-0.403	0.907
Random effects	*SD*	*2.5%*	*97.5%*	*SD*	*2.5%*	*97.5%*
SD(Location)	0.970	0.488	1.058	1.035	0.379	1.039
SD(Residual)	1.088	1.005	1.159	1.088	0.986	1.171

Results

The analyses show that social complexity is detectably lower during the last two centuries of Bond cooling events. The model in Table 2A indicates that the social complexity measure PC1 is 0.28 (0.03–0.53 CI) units lower during cooling periods relative to other centuries. This effect is evident independent of the Little Ice Age: the model in Table 2B, which only includes observations prior to last millennium, also estimates a significant reduction in complexity (0.38 units; 0.06–0.71 CI) during cooling periods.

The time controls in Table 2 suggest that—all else equal—there is a roughly linear increase in complexity over historical time, and that complexity increases at a decreasing rate with the age of the location. There is also a positive interaction between time and location age. Around the mean observation year (120 BCE) and location age (3,545 yrs), the time terms in Table 2A suggests that PC1 increases at a rate of 0.001409 units per year, or 1.409 units per millennium. This number provides a sense of scale for the other parameter estimates: the estimated effect of cooling for the full sample (0.28) equates to a loss of 197 "equivalent years" of accumulated complexity; the effect for the subsample ≤ 1000 CE (0.38) equates to a loss of 273 years. The geographic controls indicate that there is significant heterogeneity in complexity across locations, and that mean complexity is higher in Old World locations.

The models in Table 3 show that reductions in complexity occur specifically in regions north of the tropics adjacent to the Atlantic and Arctic Oceans. Grouped together, these northern regions are estimated to experience an average loss of 0.43 (0.14–0.72 CI) units of complexity during periods of cooling (Table 3A); this equates to a loss of 306 years of accumulated complexity. Prior to 1000 CE, the estimated loss associated with cooling in northern regions is 0.47 (0.11–0.83 CI), or 331 equivalent years (Table 3B). The estimate for the effect of cooling in southern regions is indistinguishable from zero in both models.

Table 4 breaks down losses in complexity north of the tropics by region. In the full sample (Table 4A), the estimated effects of cooling are greatest in North Africa (0.91 ~ 642 equivalent yrs) and North America (0.89 ~ 631 yrs), followed by Europe (0.54 ~ 386 yrs), Central Eurasia (0.54 ~ 380 yrs), and East Asia (0.43 ~ 308 yrs). The estimate for the effect of cooling in North Africa is statistically significant. Unexpectedly, Southwest Asia does not follow the pattern of the other northern regions, showing a slightly positive estimate indistinguishable from zero.

In the ≤1000 CE subsample (Table 4B), the estimated losses during cooling events are greatest in Central Eurasia (1.33 ~ 941 equivalent yrs) and Europe (0.86 ~ 612 yrs), followed by North America (0.62 ~ 440 yrs), North Africa (0.50 ~ 356 yrs), and East Asia (0.45 ~ 317 yrs). The estimates for the effects of cooling in Central Eurasia and Europe are statistically significant in this earlier subsample.

Discussion

These results suggest a fundamental relationship between climate and the organization of human societies. Societies north of the tropics near the North Atlantic and Arctic exhibit lower social complexity during the most punishing years of cold events that have occurred every millennium or so throughout the Holocene. This linkage between climate and human civilization will remain salient as the climate continues to change (Brown et al. 2011; Xu et al. 2020).

These global results complement finer-scale analyses of regional trajectories and time periods, such as the population trajectories of the Sahara (Manning and Timpson 2014) and China (Wang et al. 2014) across the Holocene; the collapse of the Akkadian Empire (Cookson et al. 2019), Old Egyptian Kingdom (Krom et al. 2002) and Neolithic civilizations in China (Liu and Feng 2012; Li et al. 2018) around 2200 BCE; and the rise and fall of the Classic Maya (Haug et al. 2003; Kennett et al. 2012) and Puebloan polities (Schwindt et al. 2016; Crabtree et al. 2017) before 1500 CE.

It will be important to understand the proximate pathways by which sunlight, temperature, precipitation, seasonality, and sea levels affect energetic and cultural productivity, and consequentially social organization. Nomadic pastoralists, for example, appear to fare relatively better than agriculturalists during cooling periods, an asymmetry that may have precipitated the nomadic expansions that occurred around 200–500 CE and 1200–1500 CE (Pei and Zhang 2014; Putnam et al. 2016). Past work has also emphasized the destabilizing effects of aridity that commonly accompanies cold periods (deMenocal 2001; Li et al. 2007). In some environments, aridity may also favor more social hierarchy by increasing environmental circumscription (Kennett and Kennett 2006; Hooper et al. 2018).

This analysis represents an initial foray into understanding relationships between climate change and societal variables in the Seshat Databank. Future work with this and other datasets should leverage a variety of climate proxies to evaluate the effects of climate on multiple dimensions of social organization (Guedes et al. 2016; Peregrine 2020). While the Turchin et al. (2018) dataset is sizeable by cross-cultural standards, the power of the current analysis remains limited by sample size. More comprehensive tests will be possible when high-resolution longitudinal studies have been integrated into larger comparative datasets.

Acknowledgments

Gratitude to Elizabeth Meyer, Philip Hooper, Amy Anderson, Timothy Kohler, and the reviewers for helpful input and discussion.

References

Allen, J. R. M., W. A. Watts, E. McGee, and B. Huntley. 2002. "Holocene Environmental Variability—the Record from Lago Grande di Monticchio, Italy." *Quaternary International* 88 (1): 69–80. doi: 10.1016/S1040-6182(01)00074-X.

Bates, D., M. Machler, B. Bolker, and S. Walker. 2015. "Fitting Linear Mixed-effects Models Using lme4." *Journal of Statistical Software* 67 (1): 1–48. doi: 10.18637/jss.v067.i01.

Bevan, A., S. Colledge, D. Fuller, R. Fyfe, S. Shennan, and C. Stevens. 2017. "Holocene Fluctuations in Human Population Demonstrate Repeated Links to Food Production and Climate." *Proceedings of the National Academy of Sciences* 114 (49): E10524–31. doi: 10.1073/pnas.1709190114.

Bond, G., B. Kromer, J. Beer, R. Muscheler, M. N. Evans, W. Showers, S. Hoffmann, R. Lotti-Bond, I. Hajdas, and G. Bonani. 2001. "Persistent Solar Influence on North Atlantic Climate during the Holocene." *Science* 294 (5549): 2130–36. doi: 10.1126/science.1065680.

Bond, G., W. Showers, M. Cheseby, R. Lotti, P. Almasi, P. deMenocal, P. Priore, H. Cullen, I. Hajdas, and G. Bonani. 1997. "A Pervasive Millennial-scale Cycle in North Atlantic Holocene and Glacial Climates." *Science* 278 (5341): 1257–66. doi: 10.1126/science.278.5341.1257.

Brown, J. H., W. R. Burnside, A. D. Davidson, J. P. DeLong, W. C. Dunn, M. J. Hamilton, N. Mercado-Silva, J. C. Nekola, J. G. Okie, W. H. Woodruff, and W. Zuo. 2011. "Energetic Limits to Economic Growth." *BioScience* 61 (1): 19–26. doi: 10.1525/bio.2011.61.1.7.

Büntgen, U., V. S. Myglan, F. C. Ljungqvist, M. McCormick, N. Di Cosmo, M. Sigl, J. Jungclaus, et al. 2016. "Cooling and Societal Change during the Late Antique Little Ice Age from 536 to around 660 AD." *Nature Geoscience* 9 (3): 231–36. doi: 10.1038/ngeo2652.

Burger, J. R., C. D. Allen, J. H. Brown, W. R. Burnside, A. D. Davidson, T. S. Fristoe, M. J. Hamilton, N. Mercado-Silva, J. C. Nekola, J. G. Okie, and W. Zuo. 2012. "The Macroecology of Sustainability." *PLoS Biology* 10 (6): p.e1001345. doi: 10.1371/journal.pbio.1001345.

Cheng, H., A. Sinha, S. Verheyden, F. H. Nader, X. L. Li, P. Z. Zhang, J. J. Yin, et al. 2015. "The Climate Variability in Northern Levant over the Past 20,000 Years." *Geophysical Research Letters* 42 (20): 8641–50. doi: 10.1002/2015GL065397.

Cookson, E., D. J. Hill, and D. Lawrence. 2019. "Impacts of Long term Climate Change during the Collapse of the Akkadian Empire." *Journal of Archaeological Science* 106: 1–9. doi: 10.1016/j.jas.2019.03.009.

Crabtree, S. A., R. K. Bocinsky, P. L. Hooper, S. C. Ryan, and T. A. Kohler. 2017. "How to Make a Polity (in the Central Mesa Verde Region)." *American Antiquity* 82 (1): 71–95. doi: 10.1017/aaq.2016.18.

Dalfes, H. N., G. Kukla, and H. Weiss, eds. 2013. *Third Millennium BC Climate Change and Old World Collapse*. Berlin: Springer.

deMenocal, P. B. 2001. "Cultural Responses to Climate Change during the Late Holocene." *Science* 292 (5517): 667–73. doi: 10.1126/science.1059827.

Dobrowolski, Radosław, K. Bałaga, A. Buczek, W. P. Alexandrowicz, M. Mazurek, S. Hałas, and N. Piotrowska. 2016. "Multi-Proxy Evidence of Holocene Climate Variability in Volhynia Upland (SE Poland) Recorded in Spring-Fed Fen Deposits from the Komarów Site." *The Holocene* 26 (9): 1406–25. doi: 10.1177/0959683616640038.

Fensterer, C., D. Scholz, D. L. Hoffmann, C. Spötl, A. Schröder-Ritzrau, C. Horn, J. M. Pajón, and A. Mangini, 2013. "Millennial-scale Climate Variability during the Last 12.5 ka Recorded in a Caribbean Speleothem." *Earth and Planetary Science Letters* 361: 143–51. doi: 10.1016/J.EPSL.2012.11.019.

Grove, J. M. 2004. *Little Ice Ages: Ancient and Modern*. 2nd ed. London: Routledge.

Guedes, J. A. A., S. A. Crabtree, R. K. Bocinsky, and T. A. Kohler. 2016. "Twenty-First Century Approaches to Ancient Problems: Climate and Society." *Proceedings of the National Academy of Sciences* 113 (51): 14483–91. doi: 10.1073/pnas.1616188113.

Gutiérrez-Elorza, M. and J. L. Peña-Monné. 1998. "Geomorphology and Late Holocene Climatic Change in Northeastern Spain." *Geomorphology* 23 (2–4): 205–17. doi: 10.1016/S0169-555X(98)00004-X.

Haug, G. H., D. Günther, L. C. Peterson, D. M. Sigman, K. A. Hughen, and B. Aeschlimann. 2003. "Climate and the Collapse of Maya Civilization." *Science* 299 (5613): 1731–35. doi: 10.1126/science.1080444.

Hooper, P. L., M. Gurven, and H. S. Kaplan. 2014. "Social and Economic Underpinnings of Human Biodemography." In *Sociality, Hierarchy, Health: Comparative Biodemography*, edited by M. Weinstein and M. A. Lane, 169-95. Washington, DC: National Academies Press. doi: 10.17226/18822

Hooper, P. L., E. A. Smith, T. A. Kohler, H. T. Wright, and H. S. Kaplan. 2018. "Ecological and Social Dynamics of Territoriality and Hierarchy Formation." In *The Emergence of Premodern States: New Perspectives on the Development of Complex Societies*, edited by J. A. Sabloff and P. Sabloff, 105–30. Santa Fe: SFI Press. doi: 10.37911/9781947864030.05.

Kawahata, H. 2019. “Climatic Reconstruction at the Sannai-Maruyama Site between Bond Events 4 and 3—Implication for the Collapse of the Society at 4.2 ka Event.” *Progress in Earth and Planetary Science* 6 (1): 1–18. doi: 10.1186/s40645-019-0308-8.

Kennett, D. J., S. F. Breitenbach, V. V. Aquino, Y. Asmerom, J. Awe, J. U. Baldini, P. Bartlein, B. J. Culleton, C. Ebert, C. Jazwa, and M. J. Macri. 2012. “Development and Disintegration of Maya Political Systems in Response to Climate Change.” *Science* 338 (6108): 788–91. doi: 10.1126/science.1226299.

Kennett, D. J., and J. P. Kennett. 2006. “Early State Formation in Southern Mesopotamia: Sea Levels, Shorelines, and Climate Change.” *Journal of Island & Coastal Archaeology* 1 (1): 67–99. doi: 10.1080/15564890600586283.

Kobashi, T., J. P. Severinghaus, E. J. Brook, J. M. Barnola, and A. M. Grachev. 2007. “Precise Timing and Characterization of Abrupt Climate Change 8200 Years Ago from Air Trapped in Polar Ice.” *Quaternary Science Reviews* 26 (9–10): 1212–22. doi: 10.1016/j.quascirev.2007.01.009.

Kohler, T. A., M. E. Smith, A. Bogaard, G. M. Feinman, C. E. Peterson, A. Betzenhauser, M. Pailes, E. C. Stone, A. M. Prentiss, T. J. Dennehy, and L. J. Ellyson. 2017. “Greater Post-Neolithic Wealth Disparities in Eurasia than in North America and Mesoamerica.” *Nature* 551 (7682): 619–22. doi: 10.1038/nature24646.

Krom, M. D., J. D. Stanley, R. A. Cliff, and J. C. Woodward. 2002. “Nile River Sediment Fluctuations over the Past 7000 yr and Their Key Role in Sapropel Development.” *Geology* 30 (1): 71–74. doi: 10.1130/0091-7613(2002)030<0071:NRSFOT>2.0.CO;2.

Li, C., Y. X. Li, Y. Zheng, S. Y. Yu, L. Y. Tang, B. B. Li, and Q. Y. Cui. 2018. “A High-Resolution Pollen Record from East China Reveals Large Climate Variability near the Northgrippian-Meghalayan Boundary (around 4200 Years Ago) Exerted Societal Influence.” *Palaeogeography Palaeoclimatology Palaeoecology* 512 (December): 156–65. doi: 10.1016/j.palaeo.2018.07.031.

Li, Y. X., Z. Yu, and K. P. Kodama. 2007. “Sensitive Moisture Response to Holocene Millennial-Scale Climate Variations in the Mid-Atlantic Region, USA.” *The Holocene* 17 (1): 3–8. doi: 10.1177/0959683606069386.

Liu, F., and Z. Feng. 2012. “A Dramatic Climatic Transition at ~4000 Cal. yr BP and Its Cultural Responses in Chinese Cultural Domains.” *The Holocene* 22 (10): 1181–97. doi: 10.1177/0959683612441839.

Manning, K., and A. Timpson. 2014. “The Demographic Response to Holocene Climate Change in the Sahara.” *Quaternary Science Reviews* 101 (October): 28–35. doi: 10.1016/j.quascirev.2014.07.003.

Nicolussi, K., and C. Schlüchter. 2012. “The 8.2 Ka Event—Calendar-Dated Glacier Response in the Alps.” *Geology* 40 (9): 819–22. doi: 10.1130/G32406.1.

Pei, Q., and D. Zhang. 2014. "Long-Term Relationship between Climate Change and Nomadic Migration in Historical China." *Ecology and Society* 19 (2): 68. doi: 10.5751/ES-06528-190268.

Pèlachs, A., R. Julià, R. Pérez-Obiol, J. M. Soriano, M.-C. Bal, R. Cunill and J. Catalan. 2011. "Potential Influence of Bond Events on mid-Holocene Climate and Vegetation in Southern Pyrenees as Assessed from Burg Lake LOI and Pollen Records." *The Holocene* 21 (1): 95-104. doi: 10.1177/0959683610386820.

Peregrine, P. N. 2020. "Climate and Social Change at the Start of the Late Antique Little Ice Age." *The Holocene* 30 (11): 1643–8. doi: 10.1177/0959683620941079.

Putnam, A. E., D. E. Putnam, L. Andreu-Hayles, E. R. Cook, J. G. Palmer, E. H. Clark, C. Wang, et al. 2016. "Little Ice Age Wetting of Interior Asian deserts and the Rise of the Mongol Empire." *Quaternary Science Reviews* 131 (January): 33–50. doi: 10.1016/j.quascirev.2015.10.033.

R Core Team, 2021. *R: A Language and Environment for Statistical Computing*. Version 4.0.5. Vienna: R Foundation for Statistical Computing. URL: www.R-project.org.

Schwindt, D. M., R. K. Bocinsky, S. G. Ortman, D. M. Glowacki, M. D. Varien, and T. A. Kohler. 2016. "The Social Consequences of Climate Change in the Central Mesa Verde Region." *American Antiquity* 81 (1): 74–96. doi: 10.7183/0002-7316.81.1.74.

Tainter, J., 1988. *The Collapse of Complex Societies*. Cambridge, UK: Cambridge University Press.

Turchin, P., R. Brennan, T. Currie, K. Feeney, P. François, D. Hoyer, J. Manning, et al. 2015. "Seshat: The Global History Databank." *Cliodynamics* 6 (1): 77–107. doi: 10.21237/C7clio6127917.

Turchin, P., T. E. Currie, H. Whitehouse, P. François, K. Feeney, D. Mullins, D. Hoyer, et al. 2018. "Quantitative Historical Analysis Uncovers a Single Dimension of Complexity That Structures Global Variation in Human Social Organization." *Proceedings of the National Academy of Sciences* 115 (2): E144–51. doi: 10.1073/pnas.1708800115.

Wang, C., H. Lu, J. Zhang, Z. Gu, and K. He. 2014. "Prehistoric Demographic Fluctuations in China Inferred from Radiocarbon Data and Their Linkage with Climate Change over the Past 50,000 Years." *Quaternary Science Reviews* 98 (August): 45–59. doi: 10.1016/j.quascirev.2014.05.015.

Xu, C., T. A. Kohler, T. M. Lenton, J.-C. Svenning and M. Scheffer. 2020. "Future of the Human Climate Niche." *Proceedings of the National Academy of Sciences* 117 (21): 11350-5. doi: 10.1073/pnas.1910114117.

Yalçın, M. N., H. Wilkes, and B. Plessen. 2021. "Organic Geochemical Characterization of Early-Mid-Holocene Swamp Deposits near the Neolithic Settlement in Yenikapı-Istanbul: Assessment of Environmental Variability and Anthropogenic Impacts." *The Holocene* 31 (11–12): 1690–704. doi: 10.1177/09596836211033197.

Yu, S. Y., X. Chen, X. Liu, Z. Fang, J. Guo, S. Zhan, H. Fang, and F. Chen. 2018. "Ancient Water Wells Reveal a Prolonged Drought in the Lower Yellow River Area about 2800 Years Ago." *Science Bulletin* 63 (20): 1324–7. doi: 10.1016/j.scib.2018.09.017.

Zerboni, A., G. S. Mariani, L. Castelletti, E. S. Ferrari, M. Tremari, F. Livio, and R. Amit. 2020. "Was the Little Ice Age the Coolest Holocene Climatic Period in the Italian Central Alps?" *Progress in Physical Geography: Earth and Environment* 44 (4): 495–513. doi: 10.1177/0309133319881105.

Zielhofer, C., A. Köhler, S. Mischke, A. Benkaddour, A. Mikdad, and W. J. Fletcher. 2019. "Western Mediterranean Hydro-Climatic Consequences of Holocene Ice-Rafted Debris (Bond) Events." *Climate of the Past* 15 (2): 463–75. doi: 10.5194/cp-15-463-2019.