Forum Article

The Holocene
1–4

DOI: 10.1177/0959683615622552
hol.sagepub.com
SAGE

The Medieval Quiet Period

Raymond S Bradley,[1] Heinz Wanner[2] and Henry F. Diaz[3]

Abstract

For several centuries in early Medieval times the climate system was relatively unperturbed by natural forcing factors, resulting in a unique period of climate stability. We argue that this represents a reference state for the Common Era, well before anthropogenic forcing became the dominant driver of the climate system.

Keywords

Paleoclimate, solar forcing, volcanic forcing, Medieval climate

Received 26 July 2015; revised manuscript accepted 6 November 2015

Introduction

The notion of a "Medieval Warm Period" (MWP) has become a basic paradigm in the literature on climate variations of recent millennia, though the timing and duration of that interval is ill-defined (Lamb, 1965). Numerous articles have compared the average temperature in recent decades, with paleotemperature estimates for different intervals of time during the Medieval period *sensu lato* (from the Fall of Rome in 476 CE to the beginning of the Renaissance, ~1500 CE) (Hughes and Diaz, 1994; Bradley et al., 2003; Diaz et al., 2011). Such comparisons have assumed particular significance in terms of the role of greenhouse gases in recent decades. Critics have argued that, if temperatures were as warm or warmer than current conditions before the onset of anthropogenic forcing, this would provide evidence that "natural" fluctuations alone could explain current conditions, since greenhouse gases were only ~280 ppmv during Medieval time (versus 400 ppmv today). Hence the debate about the timing, extent and exact level of global temperature in the past has raged on, a hostage to the conflicting views about the nature and magnitude of anthropogenic climate change.

There are many papers that have used the phrase, "Medieval Warm Period" (defined by Lamb (1965) as a time of "warm climate" between 1000 and 1200 C.E.) or "Medieval Climate Anomaly" (MCA), a term chosen by Stine (1994) to refer to regional hydrological anomalies in the 12th and 14th centuries. However, in many studies that use these terms the period of time to which they refer is commonly not defined; indeed, they may only be vaguely alluded to when an anomaly in a time series roughly falls within the interval from A.D. 500-1500. Consider, for example, recent studies of "Medieval" Pacific SST anomalies and droughts by Seager et al. (2008) and Burgman et al. (2010), who selected the period AD1320-1462 as their "Medieval" climate anomaly, a time that many other studies would place in the "Little Ice Age". By contrast, the major Medieval tropical droughts identified by Haug et al. (2003) were centered around A.D. 760, 810, 860, and 910 A.D. In short, there is a plethora of studies that selectively, and inconsistently, use the term MWP or MCA. Rather, than attempt to reconcile these different views, in this study we focus on two important forcing factors in Medieval time, to identify the period during which they were relatively stable and unlikely to have resulted in major climatic disruptions. We will argue that for several centuries during early Medieval time (from ~725-1025 CE), there was a prolonged period with both minimal explosive volcanic activity, and no significant perturbations in solar forcing, either positive or negative. The world was thus in a period of relative stability, in terms of radiative forcing—an "unperturbed" state that we term the "Medieval Quiet Period" (MQP). The lack of significant forcing would have allowed global surface temperatures to reach a state of quasi-equilibrium that was not possible either before or after that interval, due to large variations in volcanic forcing and solar variability, or both. The MQP thus represents a reference climate state, or baseline, to which other periods can be compared to better assess the role of natural and anthropogenic forcing.

Climate forcing factors

Global temperature is affected by a range of forcing factors, but in recent decades greenhouse gases have become the dominant drivers (Myhre et al., 2013). In contrast, throughout Medieval time greenhouse gases were close to levels that had prevailed over previous millennia. There was no stratospheric ozone depletion from industrial gases, and no significant tropospheric air pollution from urbanization. Land use changes were extensive in some

[1]Climate System Research Center, University of Massachusetts, Amherst, USA
[2]Oeschger Centre for Climate Change Research, University of Bern, Switzerland
[3]NOAA/ERL/CIRES, Boulder, Colorado, USA

Corresponding author:
Raymond S. Bradley, CSRC, Department of Geosciences, University of Massachusetts, Amherst, MA 01003, USA.
Email: rbradley@geo.umass.edu

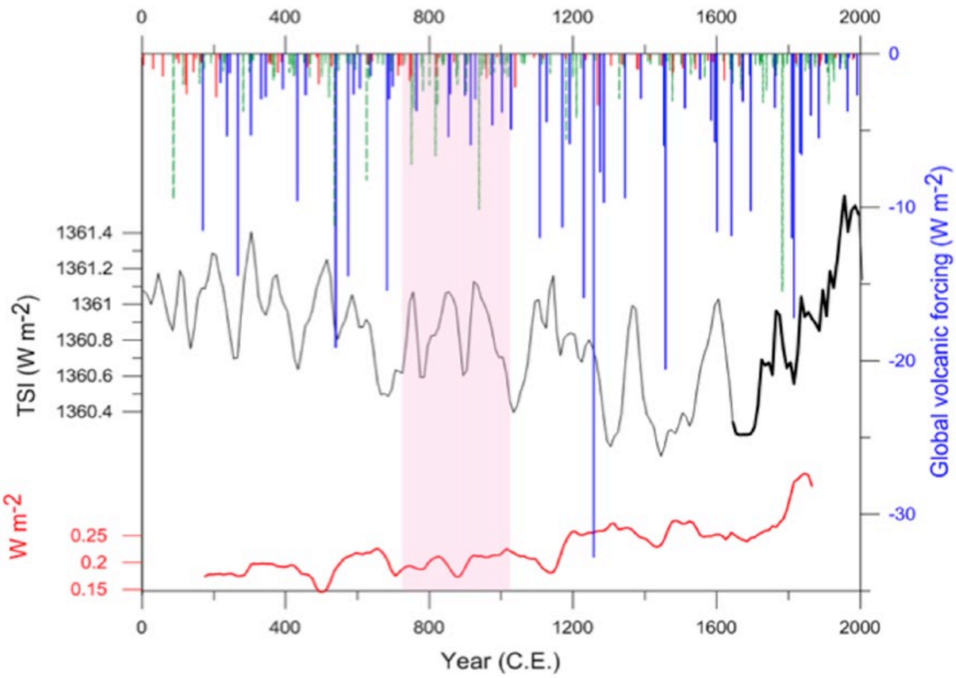

Figure 1. Variations in total solar irradiance based on a physically based model of cosmogenic ^{14}C production changes (Vieira et al., 2011) adjusted to satellite-derived values for the most recent solar cycle 23, 1996-2008 (Kopp and Lean, 2011). Estimates post-1640 CE (bold line) are based on the SATIRE-T model (Krivova et al., 2010) and before that on the SATIRE-H model (Vieira et al., 2011). Bars show estimates of global volcanic forcing (Sigl et al., 2015) from explosive eruptions that occurred in the Tropics (blue), affecting both hemipheres, or in the northern hemisphere (green dashed) or southern hemisphere (red), which had only regional climatic impacts. Estimates are based on a set of exceptionally well dated Antarctic and Greenland ice cores (Sigl et al., 2014; 2015). The lower red line shows the 300-year running standard deviation of solar forcing. Pink shading identifies a prolonged period (~725–1025 CE) when total solar irradiance was close to the long-term mean, and relatively constant, and when volcanic loading of the atmosphere was also minimal, relative to other intervals. This long period of relative stability, the Medieval Quiet Period, was a unique interval within the last two millennia, with minimal forcing from either irradiance changes or volcanism, and no anthropogenic forcing.

regions, but on a global scale the impacts related to land clearance and agriculture were minimal. Thus, all of the radiative anthropogenic forcings that now dominate the climate system were close to zero. Whatever forcing factors influenced climate in Medieval time, they were entirely "natural" (non-anthropogenic), principally volcanic aerosols (negative forcing) and solar variability (either positive or negative), with a minor contribution from orbital forcing.

What is the evidence for perturbations in these forcing factors during the MQP? Changes in the output of energy from the sun result in variations in the solar wind, which affect the production of cosmogenic isotopes in the upper atmosphere. Thus, paleorecords of isotopes such as ^{10}Be and ^{14}C, adjusted for geomagnetic field variations and modulations within the climate system, provide a measure of past heliomagnetic activity (Vieira et al., 2011; Steinhilber et al., 2012). However, estimating how such variability relates to changes in total solar irradiance (TSI) requires calibration of the cosmogenic isotope record, which has proven to be extremely difficult, and results vary (Vieira et al., 2011). In part, this is because the period of (satellite-based) measurements of solar irradiance is quite limited (~35 years) and TSI during that interval (3 Schwabe cycles) has only varied within each solar cycle by ~0.1% (solar maximum to solar minimum), which has had no discernible effect on global temperatures (Lean, 2010). Historical records indicate that solar activity has varied considerably more in the past than in recent decades, but current estimates place the range of solar cycle-averaged TSI variability over the last millennium (from the Maunder Minimum, 1645-1715, to present) at <0.1% (Wang et al., 2005; Krivova et al., 2010). The most stable period of irradiance during the last 1500 years was in early Medieval time, from ~725-1025 A.D. The variability of total solar irradiance was unusually low during this period; decadal mean TSI did not deviate from the average for the last 2,000 years by more than 0.03% (Vieira et al., 2011) (Figure 1). Therefore, we have no evidence to suggest that solar irradiance forcing was anomalous during the MQP: rather, the evidence from cosmogenic isotopes indicates that irradiance was exceptionally steady during that period.

What about volcanoes? Explosive volcanic eruptions produce particulates, gases (principally SO_2) and water vapor that may be carried to high altitudes and dispersed around the globe by stratospheric winds. Oxidation of the SO_2 to H_2SO_4 has a significant radiative effect, reducing the flux of solar radiation to the lower troposphere, leading to a drop in surface temperature (Robock, 2000). Major tropical volcanic eruptions can produce negative radiative forcing on a global scale, whereas the effect of high latitude eruptions is much more limited. The record of past volcanism is only available from ice cores, mainly in remote polar regions and so may be biased by nearby high latitude eruptions, and it may underestimate the role of near-equatorial eruptions if material from such events does not penetrate to polar latitudes, or is not deposited evenly on ice sheets. Thus, the history of global volcanism is imperfect, but historical data indicate that ice cores do capture a record of all major events that are known to have occurred, and a network of sites can capture the geographical variations in deposition. A major difficulty in producing a record of globally significant volcanic forcing has been the requirement that events be precisely dated. This is an essential requirement to determine if events recorded in Greenland and Antarctica were synchronous, which provides evidence that the eruption event was probably tropical or equatorial in origin, and thus likely to have had a globally significant climatic impact. Until recently, ice cores were not sufficiently well-dated to make that determination, with chronological errors accumulating the further the record extended back in time. However, this problem has been largely overcome in recent ice core studies by Sigl et al. (2013, 2014, 2015), which have allowed a very accurate chronology of volcanic events to be constructed. These annually-resolved records from Antarctica and Greenland indicate that the 8th–11th centuries were unusually free of major explosive eruptions within the last 1500 years. In fact, there were no major tropical eruptions at all for over 400 years, between 682 and 1108 CE, and only one large northern hemisphere (Icelandic) eruption (in 939 CE), which would have had a very limited impact on global temperatures (Figure 1). Explosive events during this long period of quiescence produced minimal anomalies in radiative forcing globally; the average forcing from the few eruptions that did occur was only ~12% of that from Tambora in 1815 (Sigl et al., 2015). This relatively unperturbed state was brought to a sudden end by several large equatorial eruptions in the 12th and 13th centuries (in 1108, 1171, 1230 and, most notably, the cataclysmic eruption of Samalas (Indonesia) in 1257 CE) that had a significant impact on global surface temperatures (Lavigne et al., 2013; Sigl et al., 2015). This sequence of events heralded a period of more frequent large explosive eruptions over the following 7 centuries, which only diminished in the early 20th century.

Discussion

For several centuries in early Medieval time, the atmosphere had minimal contamination from explosive eruptions, and minimal variations in solar irradiance for at least 300 years. There was no other period in the last 2 millennia with such a low level of perturbations from natural climatic forcing factors. We note that the period of minimal volcanic forcing actually began earlier, following a major low latitude eruption in 682 C.E., and lasted longer, until 1108 CE, but these earlier and later intervals both coincided with solar minima. We therefore characterize the interval from ~725-1025 C.E. as the *Medieval Quiet Period*, which can be viewed as a natural baseline, or reference climate for the Common Era. Solar irradiance declined abruptly in the 11th century (the "Oort Minimum"), followed by a succession of minima that were among the lowest TSI values of the last 8000 years, before steadily increasing following the Maunder Minimum (~1645–1715 CE). Explosive volcanism also increased in frequency after the 12th century. With the increase in irradiance and a decline in explosive volcanism in the early 20th century, global temperatures might then have returned to an unperturbed level similar to that of the MQP, but the rapid rise in anthropogenic greenhouse gases propelled temperatures well beyond that level, as positive anthropogenic radiative forcing overwhelmed natural variability (Myhre et al., 2013). Unfortunately, there are currently no well-constrained global temperature reconstructions that extend back into the 8th century, though the limited regional data that do exist show that temperatures in this period were indeed relatively high (Jones and Mann, 2004; Mann et al., 2009; PAGES 2K Consortium, 2013; McGregor et al., 2015). With such a long period of minimal disturbance from external forcing during the MQP, the upper ocean would have had time to equilibrate with the atmosphere, and global climate may have reached a quasi-stable state with respect to the principal modes of atmospheric circulation (ENSO, PDO, NAO, AMO etc.).

It is interesting to consider the possible causes of earlier multi-decadal to century-scale periods that were relatively warm or cold (on a hemispheric or global scale). Earlier warm periods were likely driven by orbital forcing (which has been steadily declining over the Common Era during northern hemisphere summers) and/or by episodes of persistently higher TSI, during intervals without major explosive eruptions. Colder periods in the past could have resulted from times of lower solar output, perhaps reinforced by the co-occurrence of major explosive eruptions (as happened in the mid-13th and mid-15th centuries). Associated feedbacks (principally snow cover and sea-ice expansion) would have reinforced the overall negative radiative forcing (Zhong et al., 2011; Miller et al., 2012). But unless the magnitude of TSI reduction during solar minima is much greater than current models indicate, with the higher irradiance due to orbital forcing, we view earlier cold periods as most likely the result of periods of major explosive volcanism. Additional uncertainty is introduced by processes internal to the climate system, but they are unlikely to have made a significant contribution on these hemispheric to global-scale, and multi-decadal to centennial timescales (Goosse et al., 2005). A possible exception to that might be related to long-term changes in the Atlantic Meridional Overturning Circulation (AMOC), and related oceanic connections, but the current evidence for such changes on the timescale considered here is weak and contradictory.

Acknowledgements

We thank Andrew Schurer for suggesting the descriptive phrase "MQP" to describe this time interval.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

References

Bradley RS, Hughes MK and Diaz HF (2003) Climate in Medieval time. *Science*, 302: 404–405.

Burgman R, Seager R, Clement A and Herweijer C (2010) Role of tropical Pacific SSTs in global medieval hydroclimate: A modeling study. *Geophysical Research Letters* 37: doi:10.1029/2009GL042239.

Diaz HF, Trigo R, Hughes MK et al. (2011) Spatial and temporal characteristics of climate in medieval times revisited. *Bulletin of the American Meteorological Society* 92: 1487–1500.

Goosse H, Renssen H, Timmermann A and Bradley RS (2005) Internal and forced climate variability during the last millennium: a model-data comparison using ensemble simulations. *Quaternary Science Reviews* 24: 1345–1360.

Haug G, Günther D, Peterson LC et al. (2003) Climate and the collapse of the Maya civilization. *Science* 299: 1731–1735.

Hughes MK and Diaz HF (1994) Was there a 'Medieval Warm Period', and if so, where and when? *Climatic Change* 26: 109–142.

Jones PD and Mann ME (2004) Climate over past millennia. *Reviews of Geophysics* 42: RG2002.

Kopp G and Lean JL (2011) A new, lower value of total solar irradiance: evidence and climate significance. *Geophysical Research Letters* 38: L01706, doi:10.1029/2010GL045777.

Krivova NA, Vieira LEA and Solanki SK (2010) Reconstruction of solar spectral irradiance since the Maunder minimum. *Journal of Geophysical Research*, 115: A12112, doi:10.1029/2010JA015431.

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

Lavigne F, Degeai JP, Komorowski J-C et al. (2013) Source of the great A.D. 1257 mystery eruption unveiled, Samalas volcano, Rinjani Volcanic Complex, Indonesia. *Proceedings of the National Academy of Sciences* 110: 14742–14748.

Lean JL (2010) Cycles and trends in solar irradiance and climate. *WIREs Climate Change* 1: 111–122.

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.

McGregor HV, Evans MN, Goosse H et al. (2015) Robust global ocean cooling trend for the pre-industrial Common Era. *Nature Geoscience*, 8: 671–677.

Miller GH, Geirsdóttir A, 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.

Myhre G, Shindell D, Bréon F-M et al. (2013) Anthropogenic and natural radiative forcing. In: Stocker TF, Qin D, Plattner G-K et al. (eds) *Climate Change 2013: The Physical Science Basis*. Cambridge, Cambridge University Press, pp. 659–740.

PAGES 2k Consortium (2013) Continental-scale temperature variability during the past two millennia. *Nature Geoscience* 6: 339-346.

Robock A (2000) Volcanic eruptions and climate. *Reviews of Geophysics* 38: 191–219.

Seager R, Burgman R, Kushner Y et al. (2008) Tropical Pacific forcing of North American Medieval Megadroughts: testing the concept with an atmosphere model forced by coral-reconstructed SSTs. *J. Climate* 21: 6175–6190.

Sigl M, McConnell JR, Layman L et al. (2013) A new bipolar ice core record of volcanism from WAIS Divide and NEEM and implications for climate forcing of the last 2000 years. *Journal of Geophysical Research Atmospheres* 118: 1151–1169.

Sigl M, McConnell JR, Toohey M et al. (2014) Insights from Antarctica on volcanic forcing during the Common Era. *Nature Climate Change* 4: 693–697.

Sigl M, Winstrup M, McConnell JR et al. (2015) Timing and climate forcing of volcanic eruptions for the past 2,500 years. *Nature* 523: doi:10.1038/nature14565.

Steinhilber F, Abreu JA, Beer J et al., (2012) 9400 years of cosmic radiation and solar activity from ice cores and tree rings. *Proceedings of the National Academy of Sci*ences 109: 5967–5971.

Stine S (1994) Extreme and persistent drought in California and Patagonia during mediaeval time. *Nature* 369: 546–549.

Vieira LEA, Solanki SK, Krivova NA and Usoskin I (2011) Evolution of the solar irradiance during the Holocene. *Astronomy and Astrophysics*, 531: A6, doi: 10.1051/0004–6361/201015843.

Wang Y-M, Lean JL and Sheeley Jr JR (2005) Modeling the sun's magnetic field and irradiance since 1713. *Astrophysical Journal* 625: 522–538.

Zhong Y, Miller GH, Otto-Bliesner BL, Holland MM, Bailey DA, Schneider DP and Geirsdóttir Á (2011) Centennial-scale climate change from decadally-paced explosive volcanism: A coupled sea ice-ocean mechanism. *Climate Dynamics* 37: 2373–2387.