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# Climate changes over the past millennium: Relationships with Mediterranean climates(*)

M. E. Mann

*Department of Environmental Sciences, University of Virginia*
*Charlottesville, VA, USA*

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**Summary.** — Evidence is reviewed for climate change and its causes over the interval spanning roughly the past millennium. Particular emphasis is placed on patterns of climate change influencing Mediterranean climates of the Northern Hemisphere. The evidence is taken from studies using high-resolution climate "proxy" data sources, and climate modeling simulations. The available evidence suggests that forced changes in dynamical modes of variability including the North Atlantic Oscillation (NAO) and El Nino/Southern Oscillation (ENSO) have played a key role in the patterns of climate variability in Mediterranean regions over the past millennium.

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I review here evidence for climate change and its causes over the interval spanning roughly the past millennium, with a focus on patterns of climate change influencing Mediterranean climates of the Northern Hemisphere. The evidence is taken from instrumental and high-resolution climate "proxy" data sources, and climate modeling studies. Several research groups have recently developed annually-resolved, hemispheric reconstructions of Northern Hemisphere mean temperature changes over the past 500-2000 years suggesting anomalous late 20th century warmth at hemispheric or global scales (*e.g.* [28, 13, 21, 30, 34, 7]). In addition, a large number of simulations of Northern Hemisphere mean temperature spanning the past millennium or longer have been performed over the past few years using the full hierarchy of available climate models and estimates of past natural and anthropogenic radiative forcing histories [5, 14, 4, 17, 15, 10, 3, 11]. The comparison of empirical reconstructions with model simulations (fig. 1) demonstrates

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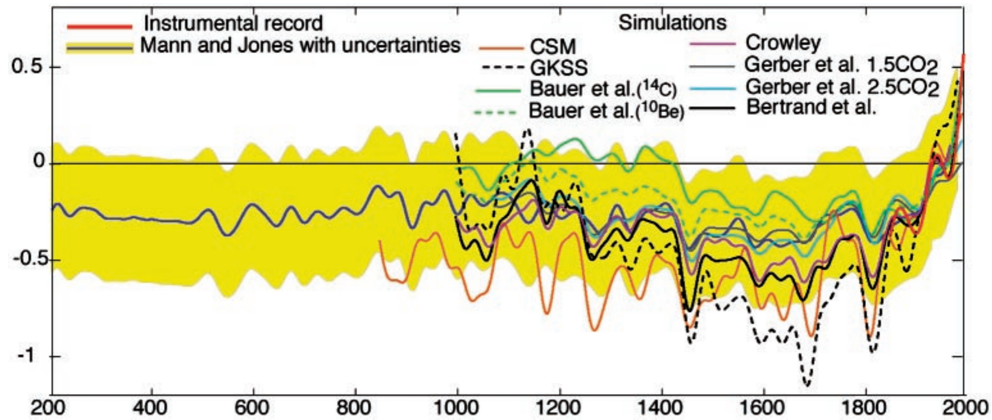


Fig. 1. – Model-based estimates of northern hemisphere temperature variations over the past two millennia (from [22]). Shown are 40 year smoothed series. The simulations are based on varying radiative forcing histories employing a hierarchy of models including one-dimensional energy based models [9], two-dimensional reduced complexity models [4, 5, 14], and full three-dimensional atmosphere-ocean general circulation ("GKSS" [15]; "CSM" [2]). Shown for comparison is instrumental northern hemisphere record 1856-2003, and the proxy-based estimate of [29] extended through 1995 (see [22]) with its 95% confidence interval. Models have been aligned vertically to have the same mean over the common 1856-1980 period as the instrumental series (which is assigned zero mean during the 1961-1990 reference period).

that natural factors appear to explain the major surface temperature changes of the past millennium reasonably well, at least through to the 19th century. Only anthropogenic forcing of climate, however, can explain the recent anomalous large-scale warming in the late-20th century.

The simulations indicate that the modeled late 20th century hemispheric-mean warmth is anomalous in a long-term context, that this anomalous warmth can only be explained by anthropogenic (greenhouse gas plus sulfate aerosol) forcing, and that the modeled natural variability is consistent with long-term proxy-based reconstructions within published uncertainties. Several of the simulations over-predict the net warming that has occurred since the early/mid 19th century as evident from the instrumental record (and reconstructions), leading to the appearance of colder temperatures in past centuries when aligned with the modern instrumental record (fig. 1). Simulations that take into account 19th and 20th century land use changes (see [4] in fig. 1), however, more closely match the observations, suggesting the importance of including land use changes as a significant 19th and 20th century external radiative forcing [16]. One model simulation that produces especially large-amplitude variations (*e.g.*, "GKSS" in fig. 1) assumes an extremely high amplitude solar forcing (nearly 7 W/m$^2$ change in solar constant over the course of the simulation), leading to substantial solar-forced hemispheric mean temperature changes in the past. By contrast, other studies do not support such a substantial solar forcing of hemispheric mean temperature changes (*e.g.* [10, 14], and CSM in fig. 1; see also [17]).

At regional scales, climate variability and change appears m ore closely associated with the behavior of particular modes of climate variability, such as the North Atlantic Oscillation (NAO) and the El Niño/Southern Oscillation (ENSO). These modes of vari-

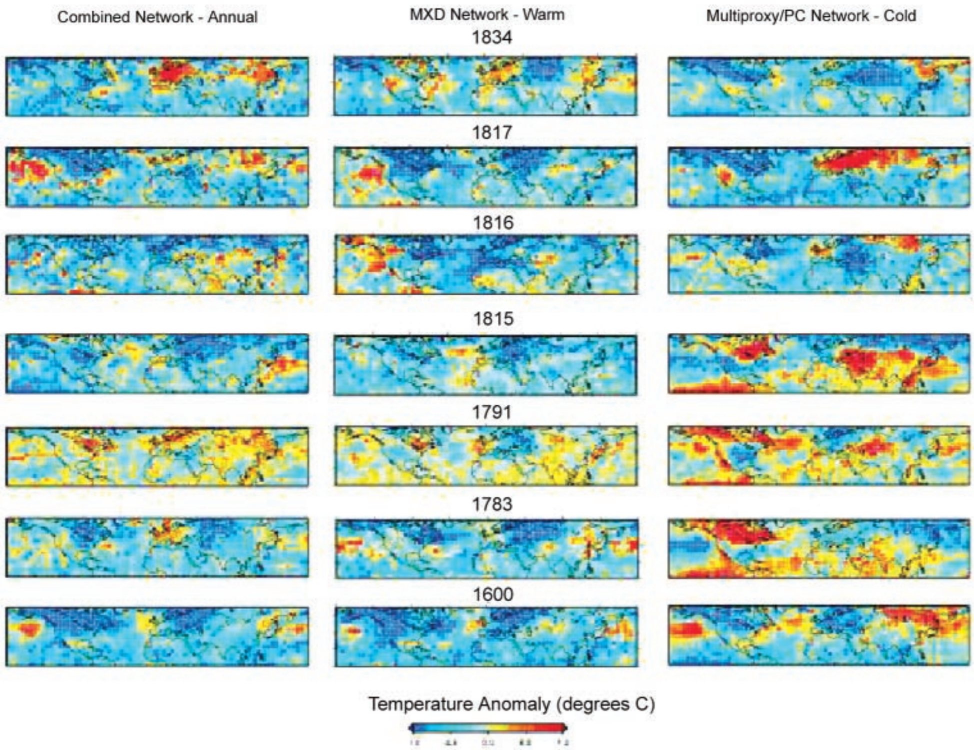


Fig. 2. – Maps of the full field reconstruction for interesting years using the three different proxy networks (multiproxy/PC, MXD and Combined) to reconstruct three seasonal targets. The years shown are the following: 1600, the year of the Huaynaputina (Peru) eruption; 1783, the year of the Laki eruption in Iceland; 1791, an El Niño year [31]; 1816, the "Year Without a Summer" following the Tambora eruption in 1815; and 1834, an exceptionally warm year in Europe [27].

ability may themselves have exhibited late-20th century behavior that is anomalous in a long-term context, but the uncertainties are considerably greater (see [22]). Changes in the NAO and ENSO are especially relevant for understanding the complex patterns of climate change associated with the so-called "Little Ice Age" and "Medieval Warm Period" in Mediterranean regions such as southern Europe, where the NAO exerts a significant influence, and the desert southwest of the United States where ENSO exerts an important influence. The seasonally and regionally complex influences of these patterns is evident in detailed, seasonal spatial reconstructions of surface temperature over the past several centuries (fig. 2).

The substantial cooling in large parts of Europe during the late 17th and early 18th century appear closely related to forced long-term variations in the NAO [23, 24, 35]. A significant component of this variability appears associated with the large-scale dynamical response of the climate system to natural radiative forcing associated with changes in explosive volcanic activity and changes in solar output [35-37]. While solar forcing leads to only moderate changes in hemispheric mean temperature, the reinforcing seasonal patterns of continental summer cooling (due to decreased summer irradiance combined with the lesser thermal inertia over land) and regional temperature changes associated

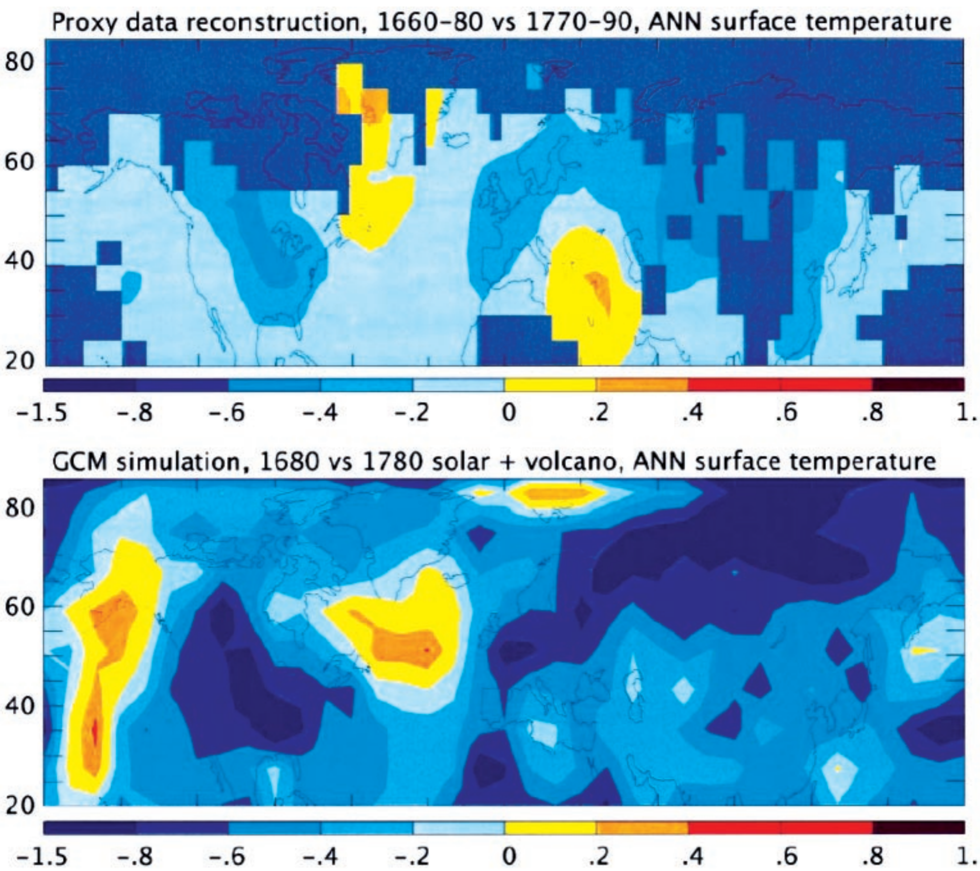


Fig. 3. – Reconstructed (top) and simulated (bottom) annual average temperature difference between 1660-80 and 1770-90. The reconstructed surface temperatures are based on a multiproxy estimate using tree rings, ice cores, corals, and historical data [27]. Model results are based on the sum of the response in two simulations: one incorporating reconstructed solar irradiance changes during this period and one using volcanic forcing scaled to changes over this time.

with a dynamical stratospherically-forced tendency towards the negative phase of the NAO/AO during the Northern winter, leads to a tendency of strong cooling in some regions, such as Europe, but warming in other regions during times of decreased solar irradiance. This prediction matches the spatial pattern of response to solar for c ing estimated from proxy-reconstructed surface temperature patterns [35]. While volcanic forcing exhibits a greater hemispheric-mean temperature influence, due to the substantially greater associated radiative forcing changes, the tendency for seasonally-opposite direct radiative and dynamical responses (see [33,36,37] leads to a muted pattern of spatial variation. The combination of the responses to the two natural forcings matches well observed proxy-reconstructed patterns of temperature change in past centuries (fig.3).

The seasonally-opposing trends over continental regions associated with volcanic forcing appears to explain (see [25,36,34] the greater amplitude variations in surface temperature reconstructions that emphasize continental regions and summer season conditions (*e.g.* [12, 19]. In the "Mediterranean" climatic region of the west coast of the US and

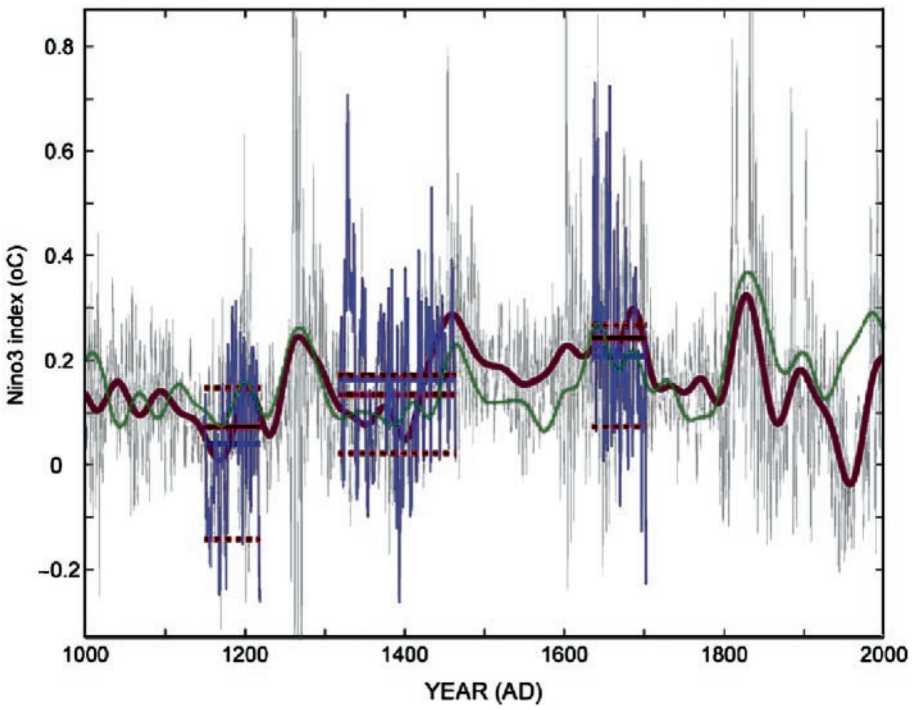


Fig. 4. – (Colours on-line). Comparison (from [30]) of the ensemble annual mean Niño3 response to combined natural radiative forcing (volcanic+solar) over the interval AD 1000-1999 (gray–anomaly in °C relative to AD1950-1980 reference period; 40 year smoothed values shown by thick maroon curve) with reconstructions of ENSO behavior from Palmyra coral oxygen isotopes (blue–the annual means of the published monthly isotope data are shown). The coral data are scaled as described in the text, with warm-event (cold-event) conditions associated with negative (positive) isotopic departures. Thick dashed lines indicate averages of the scaled coral data for the three available time segments (blue) and the ensemble-mean averages from the model (red) for the corresponding time intervals. The associated inter-fourth quartile range for the model means (the interval within which the mean lies for 50% of the model realizations) is also shown. The ensemble mean is not at the center of this range, due to the skewed nature of the underlying distribution of the model Niño3 series. Also shown (green curve) is the 40 year smoothed model result based on the response to volcanic forcing only, with the mean shifted to match that of the coral segments.

parts of the southwestern US, past climate changes appear more closely tied to changes in ENSO in past centuries. These changes may also represent in large part the response to such past changes in radiative forcing [29]. Recent modeling work has focused on the response of the tropical Pacific to natural radiative forcing changes over the past 1000 years. [29] investigated the response of El Niño to natural radiative forcing changes over the past 1000 years based on numerical experiments employing the Zebiak-Cane [40] model of the tropical Pacific coupled ocean-atmosphere system. Previously published empirical results [1] demonstrating a statistically significant tendency towards El Niño conditions in response to past volcanic radiative forcing are reproduced in the model experiments.

A combination of responses to past changes in volcanic and solar radiative forcing closely reproduces (fig. 4) changes in the mean state and interannual variability in El Niño in past centuries recorded from fossil corals [6]. These experiments suggest that the dynamics of El Niño may have played an important role in the response of the global climate to past changes in radiative forcing in past centuries. The ENSO-scale response isolated in this study implies both a decrease in the amplitude of the global or hemispheric-mean warming (cooling) associated with increased (decreased) radiative forcing in past centuries, and a decrease (increase) in the poleward temperature gradient be tween equator and midlatitudes in response to increased (decreased) radiative forcing. Such a response would argue for somewhat lower amplitude variability in actual hemispheric or global mean temperature in past centuries than is predicted by models which either do not resolve at all, or resolve incompletely, the physics underlying ENSO (*e.g.* [32, 9, 15]. This response would furthermore help to explain apparent evidence that extratropical temperature changes in past centuries (*e.g.* [12]) have been greater in amplitude than tropical [18] or full hemispheric-scale (*e.g.* [26]) temperature changes.

The conclusions from [29] of an El Niño-like state during the otherwise generally cold 17th century (*e.g.* [9, 26]) and a La Niña-like state during the otherwise relatively mild 12th/13th centuries [9, 26] appears to be consistent with changes observed in ENSO-sensitive drought regions. [38] provide lake-level evidence in equatorial east Africa (Kenya) for peak wet conditions during the mid-17th to the mid-18th centuries, and dry conditions during the early (11th-13th) centuries of the millennium, reminiscent of anomalies typically associated with El Niño and La Niña conditions, respectively. A similar pattern of drought in earlier centuries and wet conditions in later centuries in the desert southwest of North America [20, 39, 8] favors this interpretation as well.

Further modeling experiments and model/data comparison focusing on the relationship between past radiative forcing of climate, and the behavior of important dynamic al modes of variability such as the NAO and ENSO over the past one or more millennia, should increasingly help elucidate the factors that may be responsible for important changes in climate in past centuries in Mediterranean regions such as the south of Europe and Middle East, and the desert southwest in North America.

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