Climatic volatility, agricultural uncertainty, and the formation, consolidation and breakdown of preindustrial agrarian states

Douglas J. Kennett¹ and Norbert Marwan²

¹Department of Anthropology, The Pennsylvania State University, University Park, PA 16802, USA
²Potsdam Institute for Climate Impact Research, PO Box 601203, Potsdam 14412, Germany

The episodic formation, consolidation and breakdown of preindustrial states occurred in multiple contexts worldwide during the last 5000 years and are contingent upon interacting endogenous economic, demographic and political mechanisms. In some instances, there is support for climate change stimulating integration or inducing sociopolitical fragmentation in these complex systems. Here, we build upon this paradigm and introduce the hypothesis that stable climatic conditions favour the formation of agrarian states, while persistently volatile climatic conditions can contribute to the episodic collapse of these complex societies. It is generally recognized that agrarian economies underwrite preindustrial state-level societies. In these contexts, the economic uncertainty associated with highly volatile climatic regimes makes it difficult for individuals or institutions to determine the costs and benefits of one agricultural strategy over another. We argue that this fosters sociopolitical instability and decentralization. As a first test of this hypothesis, we examine the historical dynamics of state formation and decline in the Mexican and Andean highlands within the last 2000 years. The available data in these regions are consistent with the hypothesis that the formation and consolidation of regional polities and empires is favoured in stable climatic regimes and that political decentralization can be stimulated and perpetuated by highly volatile climatic conditions.
1. Introduction

Climate change on decadal and centennial time scales is now recognized to play a role in the rise and fall of some preindustrial societies [1–11]. Persistently warm centuries in Europe in the last millennium fostered geometric population growth and the aggregation of populations, whereas cooling resulted in declining population, the spread of disease, political instability and war [3]. Comparable sociopolitical dynamics are associated with wet and dry cycles in the tropics with extended wet intervals followed by multi-decadal droughts having the greatest impact on populations and the integrity of political systems [2,6]. The historical dynamics of the rise and fall of economic, social and political institutions are complex [12], and climate change is one possible mechanism stimulating change. The historical record provides the long-term perspective required to understand the human dimensions of climate change that are necessary to project future human response scenarios and constrain the best adaptive pathways for this century [5,13–15]. Models predict greater climatic variability with global warming, including more extreme and extensive droughts and flooding in low-lying regions. The health implications of climate change alone warrant further study [16,17], but of greater concern is the potential for sudden unwanted shifts in our increasingly inter-connected global economic, social and political systems [18].

Here, we explore how the changing frequency and duration of climatic events may have influenced human response and collective action in preindustrial civilizations [19,20]. Humans adapt to the mean of long-term climatic trends (e.g. cooling or drying) or relatively predictable decadal-scale climatic variability (e.g. El Niño Southern Oscillation (ENSO) cycles of 7–10 years [21]) with a variety of risk minimization strategies. People cannot predict the future, but they can sometimes constrain possible outcomes based on life experience and historical information. The exact outcome is unpredictable because of variability that is known to exist based on direct observations or learning [22,23]. Hunter–gatherer societies use mobility to respond to the changing distribution of wild resources [24,25]. Slash and burn agriculturalists decide when to plant crops before the rainy season based on environmental cues and past experience. The diversification of economic activities by agriculturalists provides buffers against unpredictable yields caused by climate variability (e.g. mix of livestock [26]; various combinations of agriculture with hunting or fishing [27]; a diverse set of target domesticates [28]). Agricultural populations embedded in more complex societies, where mobility is often limited because of territorial constraints, use field scattering techniques, irrigation, terracing, grain storage and more elaborate socioeconomic institutions and political networks to minimize risks associated with climate change or other perturbations [29–32]. Individual actors in complex societies may be more risk prone or averse based on their interpretation of different environmental and economic cues.

Competition within complex institutional settings constrains the options available to adapt to climatic change and complex interactions between individual actors in institutions can result in maladaptive solutions [19]. Populations with a variety of independent strategies to minimize risk will be more flexible and have the adaptive capacity to change more gradually [18]. Complex societies are more vulnerable to catastrophic reorganization if mechanisms for minimizing risk are homogeneous and strongly inter-connected economically. In other words, some complex societies are more vulnerable to exogenous perturbations, like climate change, than others. Relatively, predictable changes or trends in climate lead to risk minimization strategies (e.g. multi-cropping or dispersed field systems) and gradual changes in adaptive strategies. In complex societies, it is expected that there would be both household and institutional responses to climatic perturbations and potential conflicts between the two strategies. Change in complex socioecological systems is inevitable and abrupt changes are more likely when innovation is suppressed and institutions become rigid and homogeneous [18,33].

In economic terms, uncertainty presents a very different type of adaptive problem for individuals [23,34] and institutions [35]. Outcomes cannot be assigned probabilities and individuals and the leaders of institutions are left to speculate about possible outcomes. In other words, under conditions of extreme uncertainty, it is impossible for people to evaluate the
costs and benefits of one strategy or another. We argue that the uncertain conditions related to unpredictable climatic conditions and related crop yields are more likely to lead to abrupt changes or tipping points in preindustrial states [18]. Civil conflicts and war stimulated by climate change contributes to societal instability and can greatly magnify socioecological and agricultural uncertainty [2,36]. Constraining the uncertainty of climate change moving into the future has major implications for societal well-being [37–40] and the long-term historical perspective provides context for these decisions. We now turn to the general observation that the rise and fall of civilizations is episodic in nature and then consider the role of climatic volatility in destabilizing these complex systems.

2. Climate volatility and the episodic rise and fall of civilizations

The episodic nature of the rise and fall of preindustrial agrarian civilizations on the continental scale is well recognized and described in multiple regions [41–44]. The generation, fragmentation and regeneration of regional polities are best documented in Mesopotamia, Egypt, Europe, Southeast Asia, Andes, and in both the highlands and lowlands of Mesoamerica [42–49]. The cultural evolutionary framework of the twentieth century over-emphasized the origins, rise and expansion of complex societies [50,51]. In recent years, this has been replaced by an overemphasis on societal collapse ([52]; also [53]). Increasingly, there has been greater emphasis on modelling complex socionatural systems [54,55] and the historical dynamics associated with the rise and fall of complex societies [12,20,56,57]. Indeed, it has been hypothesized that the cyclical nature of political centralization and decentralization may have a ratcheting effect that is central to our understanding of greater societal integration in subsequent political systems when they occur [58].

The large regional political systems that characterize agrarian states or civilizations are composed of multiple political centres (nodes) embedded within large economic, social and political networks. Sometimes these political centres were roughly equivalent in size and influence (e.g. peer-polities [59]). Over 44 polities of varying size and complexity existed during the Classic Maya Period (300–800 CE [60]) and were connected through a variety of cooperative and antagonistic networks [61]. Hierarchical relationships periodically developed in the region with one polity dominating another to form more regional states [42,43]. Historical texts carved on stone monuments indicate that these networks were dynamic and that one centre was never able to integrate these polities into a single entity, but a series of major oscillations occurred with larger centres featuring prominently in the administrative hierarchy of these systems [62]. However, there were intervals of greater and lesser centralization [43]. In other parts of the world, single centres managed to dominate political networks to create regionally expansive polities. Rome is the best example in the Old World [63–65] and Teotihuacan is one of the clearest examples in the New World [66,67]. Both of these large centres dominated large regional polities and then went into decline, breaking up into smaller constituent units. In the case of the highlands of Mexico, these smaller regional polities were eventually reintegrated into the Toltec State and eventually the Aztec Empire from the city of Tenochtitlan (see below).

Changes in the size and distribution of populations are known to occur with the rise and fall of civilizations and these have been linked to climatic variability in some instances. Wet and warm periods in Europe during the last 2500 years were times of prosperity and population growth (e.g. Roman Prosperity and expansion between 400 BCE to 250 CE [68]). The Roman Empire was at its height during this interval and went into decline after 250 CE during an interval of climate cooling and drying that undermined agricultural productivity, stimulated conflict and destabilized sociopolitical systems [68]. Deteriorating human health occurred in this context and resulted in population dispersal and decline [17]. Population growth in Europe peaked again in the tenth and eleventh centuries CE during another salubrious interval of warm and wet conditions that was followed by a major population collapse during the fourteenth century CE known as the ‘Great Famine’ associated with climatic deterioration [3]. Declining populations occurred in the context of food shortages, famine, war and the proliferation of epidemic disease (Black Death [69,70]).
Similar cycles of human prosperity and suffering occurred in the Maya lowlands during wet and dry intervals, respectively, with multi-year droughts associated with inter-polity warfare, political balkanization/decentralization and population decline/dispersal [2].

Sanders [71] introduced the idea that the formation of large regional polities was associated with environmental circumstances favourable to intensive agricultural systems (e.g. irrigation agriculture). Preindustrial agrarian states developed irrigation agricultural systems to support growing populations and to reduce the risks associated with short-term agricultural shortfalls [28,72]. These often developed in conjunction with storage systems or distribution networks and for storing wealth. For example, expansive irrigation canals on the north coast of Peru supported large populations integrated into the Chimu Empire. These systems were vulnerable to failure in the face of extended drought and from catastrophic flooding during ENSO events in the fifteenth century CE that made them vulnerable to Inka military expansion [21]. The water control systems of Angkor (Cambodia) provide another example. These systems sustained a large urban complex that served as the capital of the Khmer Empire from the ninth to fifteenth century CE [73,74]. During the fourteenth and fifteenth centuries CE, these systems were compromised, in part, by multi-decadal drought interspersed with periodic flooding that damaged infrastructure [6]. In both the Chimu and Angkor cases, these were unusually unstable intervals that damaged water control systems and undermined regional political integrity. In both instances, these societies went into decline. These observations underlie our interest in examining climatic volatility as a stressor on agrarian civilizations more generally. We explore the uncertainty associated with transient climatic events and the potential effects of volatile climate conditions on human decision-making and changes in the structure of preindustrial agrarian states in the long-term. As test cases, we examine the rise and fall of complex political institutions in the highlands of Mexico and the Andes. These regions were selected because they are well studied by archaeologists and both have high-resolution climate records nearby where inter-annual volatility can be examined.

3. Measuring climatic volatility

We define volatility as the degree of changeability or variance in ambient climatic conditions over time. High volatility means that climate conditions can change dramatically over a short period of time, whereas lower volatility means that climate conditions do not oscillate dramatically in the short-term. Agricultural uncertainty and risk are higher during more volatile climatic intervals. From an adaptive standpoint, gradual changes in mean conditions over a century (e.g. from wet to dry conditions) present a very different set of challenges than dramatic inter-annual or decadal changes between extreme wet and dry conditions. Our primary argument is that highly volatile climate conditions make it difficult for individuals or institutions to determine the costs and benefits of one agricultural strategy over another. This fosters or amplifies existing tensions within complex socioeconomic systems and can contribute to the decentralization and fragmentation of complex agrarian states.

To evaluate the impact of climatic volatility on the rise and fall of preindustrial states, we examined published climate records for the central Mexican highlands and the Andes [75,76]. Regional polities developed, disintegrated and regenerated multiple times in both these regions over the last 2000 years. We measure climatic volatility in these two records through time by using the empirical dispersion index, \( F = (Q_3 - Q_1)/(Q_3 + Q_1) \), where \( Q_1 \) is the first and \( Q_3 \) is the third quartile of the data vector \( x \). This index was calculated in overlapping 50-year windows (i.e. in an interval of 1–50 years at the measurement point) with an overlap of 8 years. The dispersion index calculated is also called the Quartile dispersion coefficient. Higher \( F \)-values indicate greater climatic volatility. In order to justify the variability in \( F \), a simple bootstrap procedure was applied for each window. From the entire time series, we draw randomly \( N_{\text{loc}} \) samples (with replacement), where \( N_{\text{loc}} \) is the number of samples in the current window. The measure \( F \) was then calculated from this bootstrap series. By repeating this bootstrap procedure 2000 times, an empirical test distribution for the measure \( F \) can be created. The 0.9-quantile of this distribution provides the
one-sided 90% confidence level. If $F$ exceeds this level, the variability of the time series in the corresponding window is higher than the general variability in the climate record.

4. Climatic volatility and uncertainty in the central Mexican highlands

The central Mexican highlands provide a first test of the impact of climate volatility for the episodic development, disintegration and regeneration of regional states. Three large regional polities developed sequentially in this semi-arid region between 100 BCE-650 CE (Teotihuacan), 900–1150 CE (Tula) and 1400–1519 CE (Mexica-Aztec) [77]. Intervening intervals were characterized by the decentralization of these larger political systems and the formation of smaller competing political units. All three of these highly centralized political systems were reliant upon intensive forms of agriculture and the maintenance of extensive regional exchange networks. Starting with the development of Teotihuacan in the northern basin, it is clear that the control of water was vital for sustaining large populations in these urban systems. Water was impounded in reservoirs, springs were tapped for irrigation and systems were developed for capturing rainwater and run-off [78–82]. Populations became increasingly reliant upon these water control systems and sustainable agriculture depended on persistent rainfall and therefore became more vulnerable to drought and climatic volatility.

The central Mexican climate record examined here comes from a stalagmite collected deep within Juxtlahuaca Cave in the highlands of Guerrero (JX-6; Sierra Madre del Sur [75], 17°29′49″N, 99°03′04″W, 2150 m.a.s.l., see figure 1 for location). Oxygen isotope ($\delta^{18}O$) measurements ($n = 1230$) of incremental stalagmite growth record changes in rainfall amount over the last 2400 years. The high-resolution record is precisely dated with 20 uranium series measurements. This translates to a precise rainfall estimate every 1–5 years for the central Mexican highlands. Rainfall amount was calibrated using data collected for this region during the last century. Episodically wet and dry intervals are evident in this record. Extended wet intervals (above 700 mm yr$^{-1}$) occurred between 450–325 BCE, 1–200 CE and 1350–1500 CE. Drying trends are evident between BCE 325–1 CE, 200–850 CE and 1500–2000 CE. Climate was most volatile between 375–400 CE, 600–700 CE, 1050–1100 CE and 1400–1500 CE with the greatest and most persistent volatility in the seventh century CE. The climate volatility index is shown in figure 2 relative to the historical dynamics in the central highlands of Mexico.

Teotihuacan emerged as the first regional state in the central Mexican highlands between 100 BCE and 100 CE [67,85,86]. The rise of this large city follows on the heels of Cuicuilco’s demise, a competing political centre that went into decline approximately 50 BCE and was ultimately covered by volcanic flows approximately 250 CE [87,88]. The fluorescence and expansion of Teotihuacan as a regional power between 100 and 500 CE occurred during an interval of persistent rainfall [75]. The chronological precision of the ceramics sequence limits a clear understanding of the timing of these events, but it appears that populations in the Basin of Mexico became concentrated in the Teotihuacan Valley and the adjacent northern Basin of Mexico between 100 and 500 CE [79]. Successive monumental constructions occurred in the city through this interval [89]. At its peak, Teotihuacan was composed of multiple ethnic groups from different parts of Mesoamerica and maintained strong linkages with other polities in the central Mexican highlands and more distant locations [90–92] (C. García-Des Lauriers 2007, unpublished thesis). There is clear architectural and artefactual evidence for strong connections with early Classic Maya polities between 300 and 600 CE [93]. Populations occupying apartment complexes in the city peaked in the sixth century CE (approx. 125 000 people) and were sustained by rich alluvial soils irrigated with springs flowing out of the surrounding highlands. This large city dominated the political scene in the central highlands and maintained a variety of diplomatic exchanges, trade relations and strategic interventions with more distant polities. Teotihuacan’s interactions with more distant regions started to wane between 450 and 550 CE and there is evidence for the desecration and burning of major buildings sometime between 550 and 650 CE [67,92,94]. The city continued to be occupied during this time, but the population was in decline after 600 CE with existing political tensions amplified by some of the most volatile climate conditions evident in the
Juxtlahuaca Cave climate record between approximately 600 and 700 CE. This was followed by extended drought after 700 CE (figure 2, based on [75]).

The fragmentation and decline of Teotihuacan coincided with greater regionalization and the establishment of multiple competing political centres between 600 and 700 CE [95]. A cult of militarism and human sacrifice spread widely in Mesoamerica at this time. Rapid population loss at Teotihuacan coincided with evidence for widespread burning and the destruction of
monuments in the city centre [66, 94]. This suggests that the volatility evident in the climate record was matched with sociopolitical instability, population reorganization and migration. Residual populations persisted in the area surrounding the city centre, and ceramic evidence indicates greater influence from west Mexico and possibly a movement of people from this region [95]. It is argued that this was associated with the migration of people out of west Mexico, as suggested by the appearance of Coyotlatelco ceramics in many parts of the central Mexican highlands [96]. Persistently, dry conditions peaked in the ninth century CE and undermined agricultural productivity further [75].

Within this unstable sociopolitical context, several competing centres were established on fortified hilltops between 700 and 1100 CE. The best examples come from Cacaxtla in Tlaxcala and Xochicalco in Morelos where murals and monuments suggest the existence of a highly specialized military complex [97, 98]. Teotihuacan may have remained as one of several competing centres, but the population was greatly reduced and the core of the city was largely abandoned. Several hilltop centres appeared in the Tula region with influences from the Bajio region of west Mexico (architectural and ceramic [95]; see figure 1 for location). These hilltop centres were quickly abandoned in the eighth century CE as the centre of Tula was established and emerged as a
dominant regional polity during the early tenth century CE. Conditions during this interval were
colder and more stable compared to the seventh century CE and favoured irrigated agricultural
production surrounding the city. Tula’s influence was more limited compared to Teotihuacan [77],
but it served as a major hub of trade and interaction that extended from as far away as Nicaragua
and Costa Rica to the Western USA. This included clear, yet poorly defined [99], connections with
the Yucatec Maya and Chichén Itzá [100].

Questions linger regarding the chronology of Tula’s emergence and decline [99]. The
traditional view is that Tula developed as a regional polity between 900 and 1150 CE [84,101,102],
but Cowgill’s [103] suggestion that this important centre was thriving earlier, from 800 to 1000
CE, has received recent support [99]. In either case, it appears that Tula was established during a
relatively stable climatic interval and went into decline as climatic conditions became more
volatile in the eleventh century CE. Although additional chronological work is needed, there is
some support for the hypothesis that stable climatic conditions favoured political centralization
and that unstable climatic conditions contributed to sociopolitical instability and decentralization.

Smaller centres controlled a more segmented political landscape left by Tula’s decline and
this pattern was favoured by greater climatic instability between 1150 and 1300 CE. Climatically
stable conditions in the fourteenth century CE coincide with the formation of the Azcapotzalco
State that controlled portions of the Basin of Mexico [43]. The Mexica (Aztec) city of Tenochtitlán
also emerged at this time and by the early fifteenth century CE was one of several large
competing polities in the basin. In 1428 CE, Tenochtitlán formed an alliance with Texcoco to
defeat Azcapotzalco and emerged as the dominant regional power (with Texcoco and Tlacopan,
Triple Alliance [77,104]). At its height, there were 200 000 people living in Tenochtitlán. The Aztecs
developed a sophisticated water control system along the margins of Lake Texcoco that involved
the creation of artificial fields and canals (Chinampas [105]). Terracing and irrigation was also
extensive in the surrounding mountainsides and valleys [79]. How resilient these systems would
have been to the highly volatile conditions of the late fifteenth and early sixteenth century CE is
unknown because the Aztec expansion was truncated by the Spanish arrival in 1519 CE.

The available archaeological and palaeoclimatic data for the central Mexican highlands suggest
that the formation and consolidation of regional states was favoured in stable climatic regimes. It
also appears that highly volatile climatic conditions contributed to the breakup of larger political
entities. This is evident in the case of both Teotihuacan and Tula. These data are consistent
with the hypothesis that climatic volatility promulgates agricultural uncertainty, sociopolitical
fragmentation and competition between smaller political units.

5. Climatic volatility and uncertainty in the Andean highlands

Multiple regional polities and expansionistic states also developed in the Andean highlands
during the Middle (approx. 600–1000 CE, Tiwanaku and Wari) and Late (approx. 1350–1540
CE, Inka) Horizons. Tiwanaku and Wari states emerged in the central and southern highlands,
respectively, within the context of small competing polities during the Early Intermediate Period
(200 BCE–600 CE). The intervening period between the Middle and Late Horizons (approx. 1000–
1350 CE; Late Intermediate Period) was characterized by decentralization and the breakdown
of regional polities into competing groups. Wari, Tiwanaku and Inka originated as high-
elevation agrarian states with dense populations dependent upon sophisticated forms of intensive
agriculture (e.g. irrigation, terracing and raised fields in the case of Tiwanaku [28,72,106]).
The high elevations involved constrained agricultural production that was sensitive to changes in
temperature and precipitation [107].

The regional climate record analysed here comes from the Quelccaya icecap located in the
Cordillera Vilcanota (Peru; 13°56′ S; 70°50′ W, 5670 m.a.s.l. [76,108]; figure 3). This location is
highly sensitive to the position of the Intertropical Convergence Zone and the delivery of
precipitation from the Amazon Basin. The source of this precipitation is ultimately the tropical
Atlantic. The record is also sensitive to sea surface temperature in the eastern Pacific controlled
by ENSO. Annual ice layers are preserved in this ice sheet extending back to 1800 years ago
Figure 3. Map of the Andes region showing geographical approximations of Wari, Tiwanaku and Inka influence. The locations of the Quelccaya icecap and key archaeological sites are also shown. The date ranges in panel (b) are the ages for Inka imperial expansion in the fifteenth and sixteenth centuries CE [109]. (Online version in colour.)

and provide a high-resolution (annual) climate record to evaluate climatic volatility. Changing ice accumulation rates serve as a proxy for the amount of highland precipitation, and oxygen isotopic ratios ($\delta^{18}O$) supply a high-resolution ENSO record that reflects both variability in temperature and precipitation. Climatic volatility ($\delta^{18}O$) was lowest in the early part of the record (200–1000 CE) with a trend towards increasing volatility after 1000 CE that culminated between 1600 and 1800 CE. The intervals of greatest volatility in climate (ENSO) were 1000–1100 CE, 1200–1300 CE and 1550–1800 CE (figure 4).

Wari and Tiwanaku seemingly co-emerged as contemporaneous competing regional polities in the Andes after approximately 600 CE. Wari dominated the central Andes and Tiwanaku held sway over the southern Andes. Both polities influenced, and in some instances, controlled territories well beyond their respective heartlands ([28,110,111]; figure 3). Tiwanaku was a large urban centre positioned on the southern margin of Lake Titicaca at an elevation of 3850 m [112]. The monumental core of this city was moated and comprised several large platform mounds and associated plazas. It is also well known for its elaborately carved stone monoliths [113]. People in the surrounding arid high-elevation environments combined camelid pastoralism with the cultivation of potatoes, quinoa and other domesticated plants, in raised fields along the margin of Lake Titicaca [72,114]. Raised fields and canal systems were fed by streams and springs and reached their maximal extent between 600 and 1000 CE. These field systems had thermal properties that protected crops from frost damage in these high-elevation environments [115].

Wari was centred in the Ayacucho Valley at an elevation of 2770 m. It emerged in parallel with Tiwanaku as a regional polity in the central Andes between 600 and 700 CE [116]. The city was
strategically positioned to take advantage of multiple resource zones. Terraces were constructed in the region to expand the range of maize cultivation [116]. The steep slopes of this region were susceptible to erosion and crop loss without terraces. Terracing also provided a sculpted landscape that was more easily irrigated, where springs were available, and the radiant heat from terrace walls created microenvironments that made maize agriculture more viable at these high elevations. Fortified Wari enclosures (enclaves or administrative centres) were established as far north as the La Libertad region of northern Peru (Viracocha Pampa) and as far south as Cuzco (Pikillacta [110,117,118]) and the Moquegua Valley in southern Peru (Cerro Baúl [119]). Wari ceramics are found at smaller sites throughout this same range [116].

The agricultural systems sustaining Wari and Tiwanaku developed during warm and wet conditions in the highlands from 600 to 1000 CE [76]. Under these conditions populations expanded. Climatic conditions were relatively stable through this interval and became volatile from 1000 to 1300 CE. The shift to more volatile climatic conditions, between 1000 and 1100 CE coincided with a shift towards drier conditions in the highlands that peaked approximately 1200 CE and persisted until 1400 CE (based on ice accumulation rates, figure 4). Lake Titicaca dropped more than 12 m after 1100 CE and this drop adversely affected the viability of raised
field systems [115,120,121]. A nonlinear mathematical simulation suggests that the core Tiwanaku population decreased from 45 000 to 2000 people [122]. Dry and unstable climatic conditions in the eleventh century CE correspond with archaeological evidence for sociopolitical fragmentation. Monumental construction ceased at both Wari and Tiwanaku at this time [112]. Doorways at several Wari centres were purposely sealed (e.g. Pikillacta [117]) and at least one Tiwanaku elite residence was likely sacked and burned during this interval [123].

Agricultural populations persisted in both regions, but became more dispersed and less reliant upon intensive agricultural systems [124]. This was particularly the case with Tiwanaku, because lowered lake levels undermined the use of raised fields. Smaller competing polities emerged in the highlands with the decline of Wari and Tiwanaku after 1000 CE. Hilltop fortifications indicate unstable sociopolitical conditions and the persistent threat of war [125,126]. Widespread evidence for cranial trauma during the Late Intermediate Period (1000–1400 CE) supports this interpretation [127–129]). Highly volatile climatic conditions therefore correspond with the decentralization of regional polities in the Andean highlands and the persistence of sociopolitical instability through much of the Late Intermediate Period.

Wari influences waned in the Cuzco region after 1000 CE and the region was characterized by a high degree of ethnic diversity during the Late Intermediate Period [28]. Inka were one of multiple competing polities in the highlands at this time [130]. Starting as early as 1200 CE, early Inka populations in this region were adopting and developing technologies to increase agricultural productivity at high elevations. Irrigation technologies provided year-round water supply from snow melt and terraces offered microclimates that extended the growing season and expanded the range of maize agriculture (e.g. Valley of the Kings, [28]), as was the case in the Ayacucho region during the Middle Horizon [116]. These systems flourished between 1300 and 1500 CE during a relatively stable climatic regime. The Inka consolidated power in the Cuzco region during this interval and a series of military campaigns between 1438 and 1533 CE expanded the reaches of this empire from as far north as Colombia to as far south as Patagonia (figure 3b; [109]). The Inka used a variety of strategies to control these far-flung territories [131,132]. In some regions, the Inka established provincial capitals and populations were purposely reorganized to minimize resistance [132]. Inka expansion was terminated by the arrival of the Spanish in 1534–1537 CE. The consolidation and expansion of the Inka Empire coincided with one of the least volatile climatic intervals of the last 1000 years.

Striking similarities are evident in the cycling of regional states in the Mexican and Andean highlands [43]. Similar to Teotihuacan and Tula in the Mexican highlands, the formation and expansion of Wari and Tiwanaku between 600 and 1000 CE occurred during a stable climatic interval. This was also the case for the Inka in the fourteenth century CE. Highly volatile climatic conditions characterized the intervening period (Late Intermediate Period, 1000–1350 CE) and undoubtedly enhanced the uncertainties inherent in agricultural production at high elevations. Wari and Tiwanaku went into decline within the context of increasing societal instability and the formation of smaller competing political units throughout the Andes. Many of these smaller polities were fortified and bioarchaeological data indicate a high degree of endemic warfare. The available data suggest that these unstable sociopolitical conditions persisted until the expansion of the Inka Empire in the fourteenth and early fifteenth centuries CE.

6. Conclusion

Highly volatile climatic regimes periodically occurred in both highland Mexico and the Andes during the last 2000 years. These regions also witnessed the sequential formation, consolidation and disintegration of centralized regional polities or states. Political fragmentation, sociopolitical instability and warfare occurred between these more stable intervals. Our work suggests that the formation and rejuvenation of centralized regional states was favoured during stable climatic regimes. The most volatile climatic conditions correspond, in both instances, with the breakdown of regional polities, as in the case of Teotihuacan, or the persistence of decentralized political systems as evident during the Late Intermediate Period in the Andean highlands. In certain
instances, highly volatile conditions co-occur with significant changes in the mean climate state (e.g. drought). The best example of this is associated with the collapse of Tiwanaku and Wari extended drought contributed to societal decline. However, the longer term cyclical trends in the formation, fragmentation, collapse and regeneration of agrarian states appear to be more in sync with cycles of increasing and decreasing climate volatility. We argue that the uncertainties associated with these transient and unpredictable climate conditions favoured decentralization and the emergence of multiple adaptive pathways. Future models should focus on human response to both transient and long-term climate change when simulating the complexity of socionatural systems [133]. This will help constrain the range of human response to climate uncertainty in long-term global environmental impact and response scenarios moving into the next century.

Authors’ contributions. D.J.K. designed the study, conducted the background research, interpreted the data and drafted the paper. N.M. analysed the climate data, interpreted the data, wrote the Material and methods section and edited the paper.

Competing interests. We have no competing interests.

Funding. This research was supported by the National Science Foundation of the United States (grant nos. HSD-0827275 and BCS-0940744 to D.J.K.) and the Leibniz Association (Project no. SAW-2013-IZW-2, N.M.).

Acknowledgements. We thank Stephan Lewandowsky and Tim Ballard for inviting us to participate in this special issue and the associated conference. We are grateful to T. Harper for assistance with the figures and references. Joyce Marcus, Bruce Winterhalder, James Kennett, David Carballo, Rebecca Bliege-Bird, Doug Bird, Sarah B. McClure and Gina Buckley-Yost provided helpful comments on previous drafts of this manuscript, and we thank Stephan Lewandowsky and two anonymous reviewers for valuable feedback that improved the paper.

References


83. Millon R. 1973 Urbanization of Teotihuacan, Mexico, vol. 1, the Teotihuacan map. Austin, TX: University of Texas Press.


95. Cowgill GL. 2013 Possible migrations and shifting identities in the central Mexican epiclassic. Anc. Mesoam. 24, 131–149. (doi:10.1017/S0956536113000060)


