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

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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.

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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_{loc} samples (with replacement), where N_{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 (δ^{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

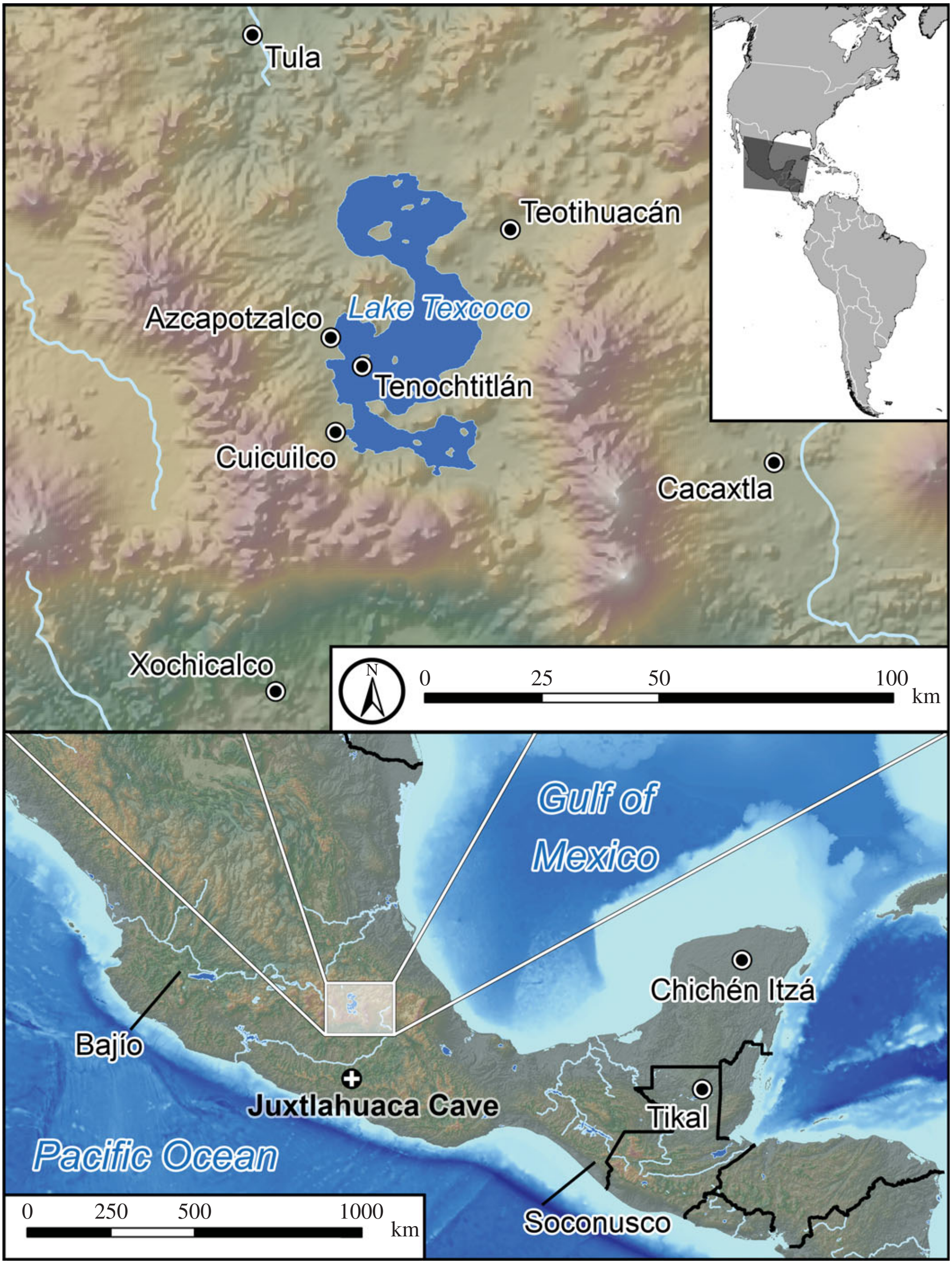

Figure 1. Map of Mesoamerica and the central Mexican highlands showing locations mentioned in text. (Online version in colour.)

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

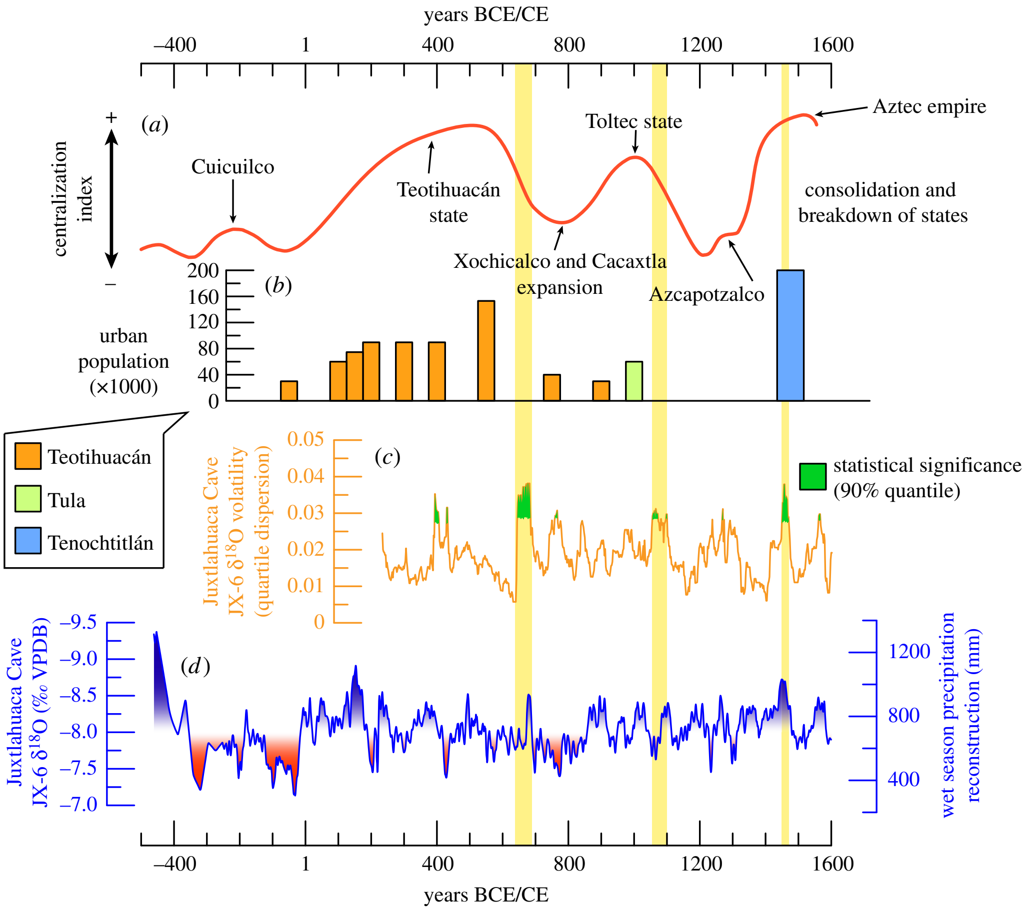

Figure 2. (*a*) Temporal estimates for the formation, consolidation and breakdown of regional polities in the central Mexican highlands (adapted from [43]; see text for more detail). These are qualitative estimates based on archaeological interpretations of population size and societal complexity. (*b*) Population estimates for Teotihuacán [66,83], Tula [84] and Tenochtitlán [79] based on site size and complexity. (*c*) Climate volatility index with statistically significant unstable intervals highlighted in green. (*d*) $\delta^{18}O$ time series and wet season precipitation reconstruction from stalagmite JX-6 collected from Juxtlahuaca Cave, Guerrero [75]. Intervals shaded in blue are wet and those shaded red are drought intervals. (Online version in colour.)

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 wetter 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 Tenochtitlan 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

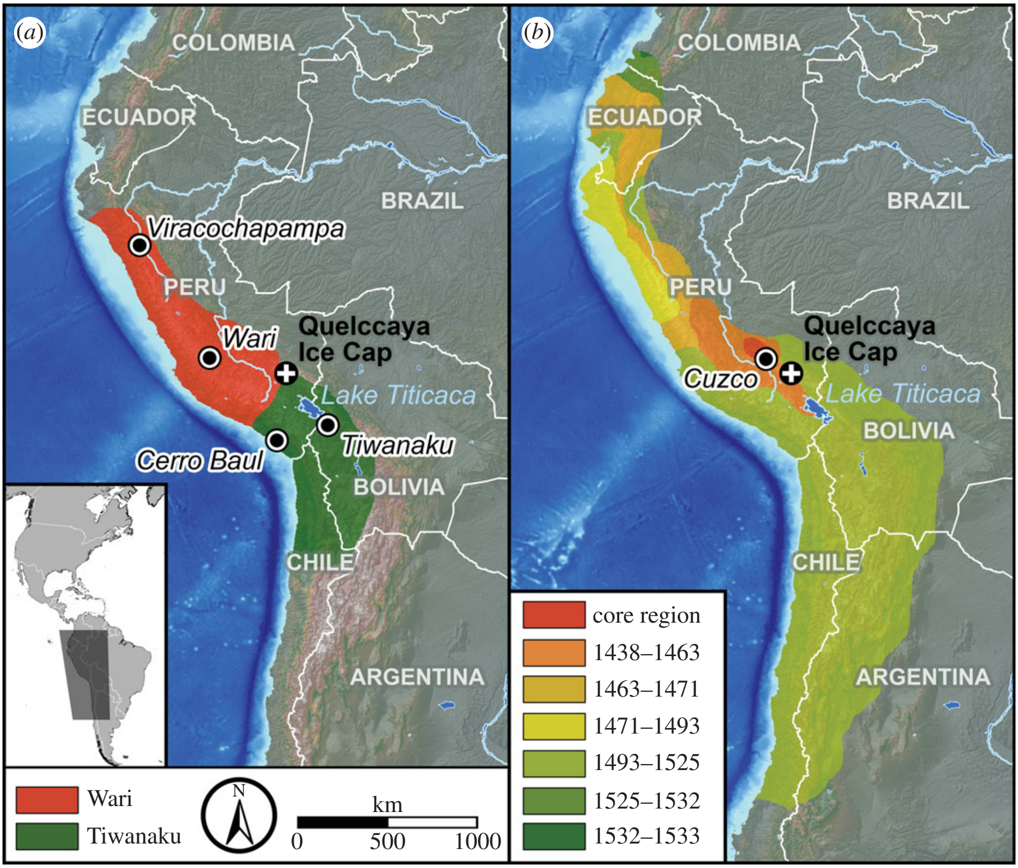

Figure 3. Map of the Andes region showing geographical approximations of Wari, Tiwanaku and Inka influence. The locations of the Quelccaya icecap and key archaeological sites are also shown. The date ranges in panel (*b*) are the ages for Inka imperial expansion in the fifteenth and sixteenth centuries 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

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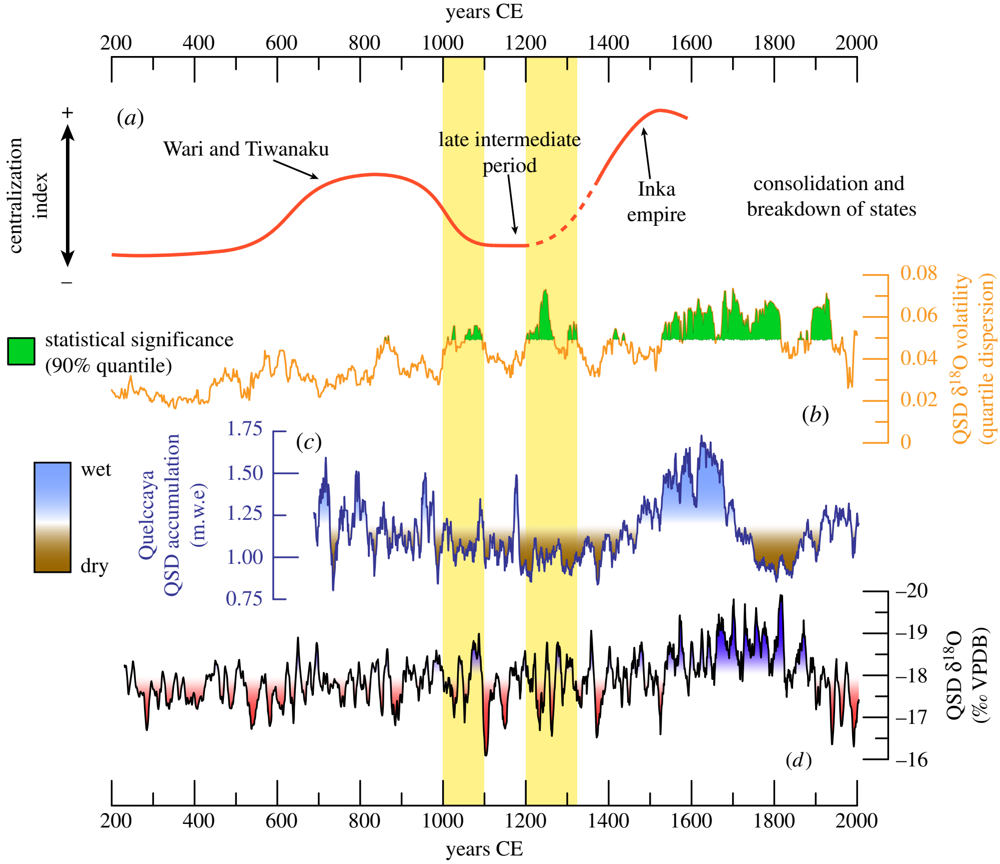

Figure 4. (*a*) Temporal estimates for the formation, consolidation and breakdown of regional polities in the Andean highlands (adapted from [43]; see text for more detail). These are qualitative estimates based on archaeological interpretations of population size and societal complexity. (*b*) Climate volatility index with statistically significant unstable intervals highlighted in green. (*c*) Ice accumulation record from the Quelccaya icecap as a highland precipitation record [110]. Drought intervals are shown in brown and wet intervals are highlighted blue. (*d*) δ^{18}O time series from the Quelccaya icecap as a measure of ENSO variability [110]. This isotope record reflects both temperature and precipitation and reflects overall variability in the climate system. (Online version in colour.)

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 3*b*; [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.

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References

1. deMenocal PB. 2001 Cultural responses to climate change during the late Holocene. *Science* **292**, 667–673. (doi:10.1126/science.1059287)
2. Kennett DJ *et al.* 2012 Development and disintegration of Maya political systems in response to climate change. *Science* **338**, 788–791. (doi:10.1126/science.1226299)
3. Lima M. 2014 Climate change and the population collapse during the 'Great Famine' in pre-industrial Europe. *Evol. Ecol.* **4**, 284–291. (doi:10.1002/ece3.936)
4. Hsiang SM, Burke M, Miguel E. 2013 Quantifying the influence of climate on human conflict. *Science* **341**, 1235367. (doi:10.1126/science.1235367)
5. Barnes J *et al.* 2013 Contribution of anthropology to the study of climate change. *Nat. Clim. Change* **3**, 541–544. (doi:10.1038/nclimate1775)
6. Buckley BM *et al.* 2010 Climate as a contributing factor in the demise of Angkor, Cambodia. *Proc. Natl Acad. Sci. USA* **107**, 6748–6752. (doi:10.1073/pnas.0910827107)
7. Weiss H, Bradley R. 2001 What drives societal collapse? *Science* **291**, 609–610. (doi:10.1126/science.1058775)
8. Weiss H, Courty MA, Wetterstrom W, Guichard F, Senior L, Meadow R, Curnow A. 1993 The genesis and collapse of third millennium north Mesopotamian civilization. *Science* **291**, 995–1088. (doi:10.1126/science.261.5124.995)
9. Kennett DJ, Kennett JP. 2006 Early state formation in Mesopotamia: sea levels, shorelines, and climate change. *J. Island Coast. Archaeol.* **1**, 67–99. (doi:10.1080/15564890600586283)
10. Hodell DA, Curtis JH, Brenner M. 1995 Possible role of climate in the collapse of Classic Maya civilization. *Nature* **375**, 391–394. (doi:10.1038/375391a0)
11. Brenner MW *et al.* 2001 Abrupt climate change and pre-Columbian cultural collapse. In *Interhemispheric climate linkages* (ed. V Markraf), pp. 87–103. New York, NY: Academic Press.
12. Turchin P. 2003 *Historical dynamics: why states rise and fall*. Princeton, NJ: Princeton University Press.
13. Palmer PI, Smith MJ. 2014 Model human adaptation to climate change. *Nature* **512**, 365–366. (doi:10.1038/512365a)
14. Riede F. 2014 Climate models: use archaeology data. *Nature* **513**, 315. (doi:10.1038/513315c)
15. Freeman MC, Groom B, Zeckhauser RJ. 2015 Better predictions, better allocations: scientific advances and adaptation to climate change. *Phil. Trans. R. Soc. A* **373**, 20150122. (doi:10.1098/rsta.2015.0122)

16. Patz JA, Campbell-Lendrum D, Holloway T, Foley J. 2005 Impact of regional climate change on human health. *Nature* **438**, 310–318. (doi:10.1038/nature04188)
17. McMichael AJ. 2012 Insights from past millennia into climatic impacts on human health and survival. *Proc. Natl Acad. Sci. USA* **109**, 4730–4737. (doi:10.2307/530502)
18. Scheffer M *et al.* 2012 Anticipating critical transitions. *Science* **338**, 344–348. (doi:10.1126/science.1225244)
19. Smithers J, Smit B. 1997 Human adaptation to climatic variability and change. *Globl. Environ. Change* **7**, 129–146. (doi:10.1016/S0959-3780[97]00003-4)
20. Carballo DM, Roscoe P, Feinman GM. 2014 Cooperation and collective action in the cultural evolution of complex societies. *J. Archaeol. Method Theory* **21**, 98–133. (doi:10.1007/s10816-01209147-2)
21. Dillehay TD, Kolata AL. 2004 Long-term human response to uncertain environmental conditions in the Andes. *Proc. Natl Acad. Sci. USA* **101**, 4325–4330. (doi:10.1073/pnas.0400538101)
22. Stephens DW. 1989 Variance and the value of information. *Am. Nat.* **134**, 128–140. (doi:10.1086/284969)
23. Winterhalder B, Lu F, Tucker B. 1999 Risk-sensitive adaptive tactics: models and evidence from subsistence studies in biology and anthropology. *J. Archaeol. Res.* **7**, 301–348.
24. Kaplan H, Hill K. 1985 Food sharing among Ache foragers: tests of explanatory hypotheses. *Cur. Anthropol.* **26**, 223–246. (doi:10.1086/203251)
25. Wiessner P. 1982 Risk, reciprocity and social influences on Kung economics. In *Politics and history in band societies* (eds E Leacock, R Lee), pp. 61–84. New York, NY: Cambridge University Press.
26. Mace R, Houston A. 1989 Pastoralist strategies for survival in unpredictable environments: a model of herd composition that maximizes household survival. *Agric. Syst.* **31**, 185–204. (doi:10.1016/0308-521X(89)90020-6)
27. O'Shea J. 1989 The role of wild resources in small-scale agricultural systems: tales from the lakes and the plains. In *Bad year economics: cultural responses to risk and uncertainty* (eds P Halstead, J O'Shea), pp. 57–67. Cambridge, UK: Cambridge University Press.
28. Covey RA. 2006 *How the Incas built their heartland: state formation and the innovation of imperial strategies in the Sacred Valley, Peru*. Ann Arbor, MI: The University of Michigan Press.
29. Zimmerer KS. 1996 *Changing fortunes: biodiversity and peasant livelihood in the Peruvian highlands*. Berkeley, CA: University of California Press.
30. Goland C. 1993 Field scattering as agricultural risk management: a case study from Cuyo Cuyo, Department of Puno, Peru. *Mt Res. Dev.* **3**, 317–338. (doi:10.2307/3673760)
31. Winterhalder B. 1994 The ecological basis of water management in the central Andes: rainfall and temperature in southern Peru. In *Irrigation at high altitutdes: the social organization of water control systems in the Andes* (eds WP Mitchell, DW Guillet), pp. 21–67. Washington, DC: American Anthropological Association.
32. Evans TP, Winterhalder B. 2000 Modified solar insolation as an agronomic factor in terraced environments. *J. Land Degrad. Environ.* **11**, 273–287. (doi:10.1002/1099-145X(200005/06)11:3<273::AID-LDR384>3.0.CO;2-J)
33. Hegmon M, Peeples MA, Kinzig AP, Kulow S, Meegan CM, Nelson MD. 2008 Social transformations and its human costs in the Prehispanic U.S. *Southwest*. *Am. Anthropol.* **110**, 313–324. (doi:10.1111/j.1548-1433.2008.00041.x)
34. Cashdan E. 1990 *Risk and uncertainty in tribal and peasant economies*. Boulder, CO: Westview Press.
35. Knight FH. 1921 *Risk, uncertainty and profit*. Boston, MA: Houghton Mifflin.
36. Hsiang SM, Meng K, Cane MA. 2011 Civil conflicts are associated with global climate. *Nature* **476**, 438–441. (doi:10.1038/nature10311)
37. Freeman MC, Wagner G, Zeckhauser RJ. 2015 Climate sensitivity uncertainty: when is good news bad? *Phil. Trans. R. Soc. A* **373**, 20150092. (doi:10.1098/rsta.2015.0092)
38. Lewandowsky S, Risbey JS, Smithson M, Newell BR, Hunter J. 2014 Scientific uncertainty and climate change: part I. Uncertainty and unabated emissions. *Clim. Change* **124**, 21–37. (doi:10.1007/s10584-014-1082-7)
39. Lewandowsky S, Risbey JS, Smithson M, Newell BR, Hunter J. 2014 Scientific uncertainty and climate change: part II. Uncertainty and mitigation. *Clim. Change* **124**, 39–52. (doi:10.1007/s10584-014-1083-6)

40. Parker WS, Risbey JS. 2015 False precision, surprise and improved uncertainty assessment. *Phil. Trans. R. Soc. A* **373**, 20140453. (doi:10.1098/rsta.2014.0453)
41. Feinman GM. 1998 Scale and social organization: perspectives on the archaic state. In *Archaic states* (eds GM Feinman, J Marcus), pp. 95–133. Santa Fe, NM: School of American Research.
42. Marcus J. 1993 Ancient Maya political organization. In *Lowland Maya civilization in the eighth century A.D.* (eds JA Sabloff, JS Henderson), pp. 111–183. Washington, DC: Dumbarton Oaks.
43. Marcus J. 1998 The peaks and valleys of ancient states: an extension of the dynamic model. In *Archaic states* (eds GM Feinman, J Marcus), pp. 59–94. Santa Fe, NM: School of American Research.
44. Cowgill GL. 2012 Concepts of collapse and regeneration in human history. In *The Oxford handbook of Mesoamerican archaeology* (eds DL Nichols, CA Pool), pp. 301–308. Oxford, UK: Oxford University Press.
45. Adams RM. 1978 Strategies of maximization, stability and resilience in mesopotamian society, settlement, and agriculture. *Proc. Am. Phil. Soc.* **122**, 329–335.
46. Yoffee N. 1988 The collapse of ancient Mesopotamian states and civilizations. In *The collapse of ancient states and civilizations* (eds N Yoffee, GL Cowgill), pp. 44–68. Tucson, AZ: University of Arizona Press.
47. Kowalewski SA, Blanton RE, Feinman GM, Finsten L. 1983 Boundaries, scale and internal organization. *J. Anthropol. Archaeol.* **2**, 32–56. (doi:10.1016/0278-4165(83)90007-7)
48. McCormick M. 2001 *Origins of the European economy: communications and commerce, AD 300–900*. Cambridge, UK: Cambridge University Press.
49. Smith ME. 1992 Rhythms of change in postclassical Central Mexico: archaeology, ethnohistory, and the Braudellian model. In *Annales, archaeology and ethnohistory* (ed. AB Knapp), pp. 51–74. Cambridge, UK: Cambridge University Press.
50. Steward JH. 1955 *Theory of culture change: the methodology of multilinear evolution*. Urbana, IL: University of Illinois Press.
51. Service ER. 1975 *Origins of the state and civilization*. New York, NY: Norton.
52. Diamond J. 2005 *Collapse: how societies choose to fail or succeed*. New York, NY: Viking.
53. McAnany PA, Yoffee N. 2010 *Questioning collapse: human resilience, ecological vulnerability, and the aftermath of empire*. Cambridge, UK: Cambridge University Press.
54. Kohler T, van der Leeuw S. 2007 *Model-based archaeology of socionatural systems*. Santa Fe, NM: SAR Press.
55. Rosen AM, Rivera-Collazo I. 2012 Climate change adaptive cycles, and persistent foraging economies during the late Pleistocene Holocene transition in the Levant. *Proc. Natl Acad. Sci. USA* **109**, 3640–3645. (doi:10.1073/pnas.1113931109)
56. Puleston C, Tuljapurkar S, Winterhalder B. 2014 The invisible cliff: abrupt imposition of Malthusian equilibrium in a natural-fertility, agrarian society. *PLoS ONE* **9**, 1–13. (doi:10.1371/journal.pone.0087541)
57. Kirch PV, Zimmerer KS. 2010 Dynamically coupled human and natural systems: Hawai'i as a model system. In *Roots of conflict: soils, agriculture, and sociopolitical complexity in ancient Hawai'i* (ed. PV Kirch). Santa Fe, NM: School for Advanced Research Press.
58. Willey GR. 1991 Horizontal integration and regional diversity: an alternating process in the rise of civilization. *Am. Anthropol.* **56**, 197–215. (doi:10.2307/281415)
59. Renfrew C, Cherry J. 1986 *Peer polity interaction and socio-political change*. Cambridge, UK: Cambridge University Press.
60. Martin S, Grube N. 2001 *Chronicle of the Maya kings and queens: deciphering the dynasties of the ancient Maya*. London, UK: Thames and Hudson.
61. Munson JL, Macri MJ. 2009 Sociopolitical network interactions: a case study of the classic Maya. *J. Anthropol. Archaeol.* **28**, 424–438. (doi:10.1016/j.jaa.2009.08.002)
62. Marcus J. 2012 Maya political cycling and the story of the Kaan polity. In *The ancient Maya of Mexico: reinterpreting the past of the northern Maya lowlands* (ed. GE Braswell), pp. 88–116. London, UK: Equinox Press.
63. Brown PRL. 1971 *The world of late antiquity*. London, UK: Thames and Hudson.
64. Potter TW. 1980 Rome and its empire in the West. In *The Cambridge encyclopedia of archaeology* (ed. A Sherratt), 232–238. New York, NY: Crown.
65. Swain S, Edwards M. 2004 *Approaching late antiquity: the transformation from early to late empire*. Oxford, UK: Oxford University Press.

66. Cowgill GL. 1997 State and society at Teotihuacan, Mexico. *Annu. Rev. Anthropol.* **26**, 129–161. (doi:10.1146/annurev.anthro.26.1.129)
67. Cowgill GL. 2015 *Ancient Teotihuacan: early urbanism in Central Mexico*. Cambridge, UK: Cambridge University Press.
68. Büntgen U *et al.* 2011 2500 years of European climate variability and human susceptibility. *Science* **331**, 578–582. (doi:10.1126/science.1197175)
69. Zhang DD, Brecke P, Lee HF, He YQ, Zhang J. 2007 Global climate change, war, and population decline in recent human history. *Proc. Natl Acad. Sci. USA* **104**, 19 214–19 219. (doi:10.1073/pnas.0703073104)
70. Zhang DD, Lee HF, Wang C, Li B, Pei Q, Zhang J, An Y. 2011 The causality analysis of climate change and large scale human crisis. *Proc. Natl Acad. Sci. USA* **108**, 17 296–17 301. (doi:10.1073/pnas.1104268108)
71. Sanders WT. 1956 The Central American symbiotic region. In *Prehistoric settlement in the new world* (ed. WR Willey), pp. 115–127. New York, NY: Wenner Gren Foundation.
72. Kolata AL. 1986 The agricultural foundations of the Tiwanaku state: a view from the heartland. *Am. Ant.* **51**, 748–762. (doi:10.2307/280863)
73. Higham C. 2001 *The civilization of Angkor*. London, UK: Weidenfeld and Nicolson.
74. Evans D, Pottier C, Fletcher R, Hensley S, Tapley I, Milne A. 2007 A comprehensive archaeological map of the world's largest preindustrial settlement complex at Angkor, Cambodia. *Proc. Natl Acad. Sci. USA* **104**, 14 277–14 282. (doi:10.1073/pnas.0702525104)
75. Lachniet MS, Bernal JP, Asmerom Y, Polyak V, Piperno D. 2012 A 2400 yr Mesoamerican rainfall reconstruction links climate and cultural change. *Geology* **40**, 259–262. (doi:10.1130/G32471.1)
76. Thompson LG, Mosley-Thompson E, Davis ME, Zagorodnov VS, Howat IM, Mikhalenko VN, Lin P-N. 2013 Annually resolved ice core records of tropical climate variability over the past 1800 years. *Science* **340**, 945–950. (doi:10.1126/science.1234210)
77. Smith ME, Montiel L. 2001 The archaeological study of empires and imperialism in prehispanic Central Mexico. *J. Anthropol. Archaeol.* **20**, 245–284. (doi:10.1006/jaar.2000.0372)
78. Millon R. 1957 Irrigation systems in the valley of Teotihuacan. *Am. Ant.* **23**, 160–166. (doi:10.2307/276439)
79. Sanders WT, Parsons JR, Santley RS. 1979 *The basin of Mexico: ecological processes in the evolution of a civilization*. New York, NY: Academic Press.
80. Marcus J. 2006 The roles of ritual and technology in Mesoamerican water management. In *Agricultural strategies* (eds J Marcus, C Stanish), pp. 221–254. Los Angeles, CA: University of California, Cotsen Institute of Archaeology.
81. Nichols DL. 1988 Infrared aerial photography and prehispanic irrigation at Teotihuacan: the Tlajinga canals. *J. Field Archaeol.* **15**, 17–27.
82. Nichols DL, Spence MW, Borland MD. 1991 Watering the fields of Teotihuacan: early irrigation at the ancient city. *Anc. Mesoam.* **2**, 119–129. (doi:10.1017/S0956536100000432)
83. Millon R. 1973 *Urbanization of Teotihuacan, Mexico*, vol. 1, *the Teotihuacan map*. Austin, TX: University of Texas Press.
84. Mastache AG, Cobean RH, Healan DM. 2002 *Ancient Tollan: Tula and the Toltec Heartland*. Boulder, CO: University Press of Colorado.
85. Sugiyama S. 2003 Governance and polity at classic Teotihuacan. In *Mesoamerican archaeology: theory and practice* (eds JA Hendon, RA Joyce), pp. 97–123. Malden, MA: Blackwell Publishing.
86. Sugiyama S. 2005 *Human sacrifice, militarism, and rulership: materialization of state ideology at the Feathered Serpent Pyramid, Teotihuacan*. Cambridge, UK: Cambridge University Press.
87. Cordova CA, del Pozzo ALM, Camacho JL. 1994 Palaeolandforms and volcanic impact on the environment of prehistoric Cuicuilco, Southern Mexico City. *J. Archaeol. Sci.* **21**, 585–596. (doi:10.1006/jasc.1994.1058)
88. Plunket P, Urunuela G. 2011 Where east meets west: the formative in Mexico's Central highlands. *J. Archaeol. Res.* **20**, 1–51. (doi:10.1007/s108-011-9051)
89. Sugiyama S, Castro RC. 2007 The moon pyramid project and the Teotihuacan state polity: a brief summary of the 1998–2004 excavations. *Anc. Mesoam.* **18**, 109–125. (doi:10.1017/S0956536107000053)
90. Sanders WT, Michels J. 1977 *Teotihuacan and Kaminaljuyú: a study of prehistoric culture contact*. University Park, PA: Pennsylvania State University Press.

91. Carballo DM. 2013 The social organization of craft production and interregional exchange at Teotihuacan. In *Merchants, markets, and exchange in the pre-Columbian world* (eds KG Hirth, J Pillsbury), pp. 113–140. Washington, DC: Dumbarton Oaks and Trustees for Harvard University.
92. Nichols DL. In press. Teotihuacan. *J. Archaeol. Res.* (doi:10.1007/s10814-015-9085-0)
93. Braswell GE. 2003 *The Maya and Teotihuacan: reinterpreting early classic interaction*. Austin, TX: University of Texas Press.
94. Manzanilla LR. 2015 Cooperation and tensions in Multiethnic corporate societies using Teotihuacan, Central Mexico, as a case study. *Proc. Natl Acad. Sci. USA* **112**, 9210–9215. (doi:10.1073/pnas.1419881112)
95. Cowgill GL. 2013 Possible migrations and shifting identities in the central Mexican epiclassic. *Anc. Mesoam.* **24**, 131–149. (doi:10.1017/S0956536113000060)
96. Mastache AG, Cobean R. 1989 The Coyotlatelco culture and the origins of the Toltec state. In *Mesoamerica after the decline of Teotihuacan, AD 700–900* (eds R Diehl, J Berlo), pp. 49–68. Washington, DC: Dumbarton Oaks.
97. Hirth KG. 1989 Militarism and social organization at Xochicalco. In *Mesoamerica after the decline of Teotihuacan, AD 700–900* (eds R Diehl, J Berlo), pp. 78–90. Washington, DC: Dumbarton Oaks.
98. Hirth KG. 2000 *Archaeological research at Xochicalco*. Salt Lake City, UT: University of Utah Press.
99. Smith ME. 2011 Tula and Chichén Itzá: are we asking the right questions? In *Twin Tollans: Chichén Itzá, Tula, and the epiclassic to early postclassic Mesoamerican world* (eds JK Kowalski, C Kristan-Graham), pp. 469–499. Washington, DC: Dumbarton Oaks.
100. Kowalski JK, Kristan-Graham C. 2011 *Twin Tollans: Chichén Itzá, Tula, and the epiclassic to early postclassic Mesoamerican world*. Washington, DC: Dumbarton Oaks.
101. Cobean RH. 1990 *La ceramic de Tula, Hidalgo*. *Estudios sobre Tula 2*, México City, México: INAH.
102. Healan DM. 1989 *Tula of the Toltecs*. Iowa City, IA: University of Iowa Press.
103. Cowgill GL. 1996 Discussion, special section: recent chronological research in Central Mexico. *Anc. Mesoam.* **7**, 325–332. (doi:10.1017/S0956536100001498)
104. Hassig R. 1985 *Trade, tribute, and transportation: the sixteenth century political economy of the valley of Mexico*. Norman, OK: University of Oklahoma.
105. Morehart C. 2012 Mapping ancient Chinampa landscapes in the Basin of Mexico: a remote sending and GIS approach. *J. Archaeol. Sci.* **39**, 2541–2551. (doi:10.1016/j.jas.2012.03.001)
106. Stanish C. 1994 The hydraulic hypothesis revisited: Lake Titicaca basin raised fields in theoretical perspective. *Latin Am. Ant.* **5**, 312–332. (doi:10.2307/971820)
107. Ortloff CR, Kolata AL. 1993 Climate and collapse: agro-ecological perspectives on the decline of the Tiwanaku state. *J. Archaeol. Sci.* **20**, 195–221. (doi:10.1006/jasc.1993.1014)
108. Thompson LG, Mosley-Thompson E., Bolzan JF., Koci BR. 1985 A 1500-year record of climate variability recorded in ice cores from the Tropical Quelccaya Ice Cap. *Science* **229**, 971–973. (doi:10.1126/science.229.4717.971)
109. Rowe JH. 1946 Inca culture at the time of the Spanish conquest. In *Handbook of South American Indians*, vol. 2 (ed. JH Steward), pp. 183–330. Washington, DC: Bureau of American Ethnology, Bulleton 143.
110. McEwan GF. 2005 *Pikillacta: the Wari empire in Cuzco*. Iowa City, IA: The University of Iowa Press.
111. Jennings J, Alvarez WY. 2015 *Tenahaha and the Wari state: a view of the middle Horizon from the Cotahuasi valley*. Tuscaloosa, AL: University of Alabama Press.
112. Kolata AL. 1993 *The Tiwanaku: portrait of an Andean civilization*. Cambridge, UK: Blackwell Publishers.
113. Kolata AL. 2003 Tiwanaku ceremonial architecture and urban organization. In *Tiwanaku and its hinterland: archaeology of an Andean civilization*, vol. II (ed. AL Kolata) 175–201. Washington, DC: Smithsonian Institution Press.
114. Janusek JW. 2004 Tiwanaku and its precursors: recent research and emerging perspectives. *J. Archaeol. Res.* **12**, 121–183. (doi:10.1023/B:JARE.0000023711.96664.1b)
115. Kolata AL, Ortloff C. 1989 Thermal analysis of Tiwanaku raised field systems in the Lake Titicaca Basin of Bolivia. *J. Archaeol. Sci.* **16**, 233–263. (doi:10.1016/0305-4403(89)90004-6)
116. Schreiber KJ. 1992 *Wari imperialism in middle horizon Peru*. Ann Arbor, MI: University of Michigan.

117. McEwan GF. 1996 Archaeological investigations at Pikillacta, a Wari Site in Peru. *J. Field Archaeol.* **23**, 169–186. (doi:10.1179/009346996791973945)
118. Covey RA, Bauer BS, Bélisle V, Tsesmeli L. 2013 Regional perspectives on Wari state influence in Cusco, Peru (c. AD 600–1000). *J. Anthropol. Archaeol.* **32**, 538–552. (doi:10.1016/j.jaa.2013.09.001)
119. Williams PR. 2001 Cerro Baúl: a Wari center on the Tiwanaku frontier. *Latin Am. Ant.* **12**, 67–83. (doi:10.2307/971758)
120. Abbott M, Binford M, Brenner M. 1997 A 3,500^{14}C yr high-resolution sediment record of lake level changes in Lake Titicaca, Bolivia/Peru. *Quat. Res.* **47**, 169–180. (doi:10.1006/qres.197.1881)
121. Binford MW, Kolata AL, Brenner M, Janusek JW, Seddon MT, Abbot M, Curtis JH. 1997 Climate variation and the rise and fall of an Andean civilization. *Quat. Res.* **47**, 235–248. (doi:10.1006/qres.1997.1882)
122. Flores JC, Bologna M, Urzagasti D. 2011 A mathematical model for the Andean Tiwanaku civilization collapse: climate variations. *J. Theor. Biol.* **291**, 29–32. (doi:10.1016/j.jtbi.2011.09.018)
123. Courture NC, Sampeck K. 2003 Putuni: a history of palace architecture in Tiwanaku. In *Tiwanaku and its hinterland: archaeology of an Andean civilization*, vol. II (ed. AL Kolata), pp. 226–263. Washington, DC: Smithsonian Institution Press.
124. Janusek JW, Kolata AL. 2004 Top-down or bottom-up: rural settlement and raised field agriculture in the Lake Titicaca Basin, Bolivia. *J. Anthropol. Archaeol.* **23**, 404–430. (doi:10.1016/j.jaa.2004.08.001)
125. Arkush E. 2008 War, chronology, and causality in the Titicaca Basin. *Latin Am. Ant.* **19**, 339–373.
126. Arkush E. 2011 *Hillforts of the ancient Andes: Colla warfare, society and landscape*. Gainesville, FL: University Press of Florida.
127. Arkush E, Tung T. 2013 Patterns of war in the Andes from the Archaic to the Late Horizon: insights from settlement patterns and cranial trauma. *J. Archaeol. Res.* **21**, 307–369. (doi:10.1007/s10814-013-9065-1)
128. Tung TA. 2012 *Violence, ritual, and wari empire: a social bioarchaeology of imperialism in the ancient Andes*. Gainseville, FL: University of Florida Press.
129. Kurin DS, Lofaro EM, Gómez Choque DE, Krigbaum J. In press. A bioarchaeological and biogeochemical study of warfare and mobility in Andahuaylas, Peru (*ca*. AD 1160–1260). *Int. J. Osteoarchaeol.* (doi:10.1002/oa.2398)
130. Bauer BS. 1992 *The development of the Inca State*. Austin, TX: University of Texas Press.
131. D'Altroy TN. 1992 *Provincial power in the Inka Empire*. Washington, DC: Smithsonian Institution Press.
132. D'Altroy TN. 2015 *The Incas*, 2nd edn. West Sussex, UK: Blackwell Publishing Ltd.
133. Winterhalder B, Puleston C, Ross C. In press. Production risk, inter-annual food storage by households and population-level consequences in seasonal prehistoric agrarian societies. *Environ. Archaeol*. (doi:10.1179/1749631415Y.0000000025)