Volcanic climate impacts can act as ultimate and proximate causes of Chinese dynastic collapse

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Abstract

State or societal collapses are mainly defined as rapid reductions in socioeconomic complexity, population loss or displacement, and/or political discontinuity, with climate thought to contribute mainly by disrupting a society's agroecological base. Here we use a state-of-the-art multi-ice core reconstruction of explosive volcanism, representing the dominant external driver of severe short-term climatic change, to reveal a systematic association between eruptions and collapse across two millennia of Chinese history. We next employ a 1,062-year reconstruction of Chinese warfare as a proxy for political and socioeconomic stress to reveal the dynamic role of volcanic climatic shocks in collapse. We find that smaller shocks may act as the ultimate cause of collapse at times of high pre-existing stress, whereas larger shocks may act with greater independence as proximate causes without substantial observed pre-existing stress. We further show that post-collapse warfare tends to diminish rapidly, such that collapse itself may act here as an evolved adaptation tied to the influential "mandate of heaven" concept in which successive dynasties received automatic legitimacy as divinely sanctioned mandate holders, facilitating a more rapid restoration of social order.

Introduction

Challenges persist in determining whether climate is systematically implicated in state and societal collapse, with efforts limited by the temporal accuracy and precision of available evidence *(1),* and with conclusions drawn from individual instances of coinciding climatic and societal change that may be non-generalizable. China's long history thus presents an unrivaled opportunity to examine whether abrupt climatic change plays a role in the recurrent and precisely-datable collapse of 68 dynasties throughout the first two millennia CE (Figure 1), including those that governed much of China's modern extent for long intervals, and many further important regional dynasties that at times governed parts of the territory or proximate areas (Supplementary Data 1).

The fall of these dynasties is often described in terms of "collapse" *(2-4)*. Some certainly occurred with apparent rapidity in the context of intense conflict and with the significant agroecological and socioeconomic disruption and population loss that are important components in many cases and definitions of "societal collapse" (*5-11)*, but still others occurred as (relatively) less disruptive transitions between ruling families and elites, with considerable political, bureaucratic and economic continuities. These events have also been historically set in the context of a "Dynastic Cycle" *(3, 12,13),* in which dynasties proceed through a period of virtue and vigor before decline and collapse, often traditionally credited to the immorality and corruption of the ruling family and elites. Socioeconomic and demographic pressures, mass migrations and population displacements, alongside mismanagement of natural resources and environmental degradation, are now more often stressed as causal factors *(*e.g., *14-18).* The contribution of climatic stresses has also begun to assume increased and often controversial prominence, for example with the collapse of the Tang Dynasty in 907 C.E., the Yuan Dynasty in 1368 C.E., and the Ming Dynasty in 1644 C.E. linked to episodes of drought and cold *(2, 4, 19-22).* Explosive volcanism has also been proposed as an underlying climatic forcing associated with specific individual collapses *(*e.g., *23-26),* but the extent to which such observations are generalizable to the broader multi-millennium history of collapse, with explosive volcanism (and abrupt climatic change by extension) playing a *systematic* role, has never been established.

Volcanic eruptions are one of the most important drivers of sudden and pronounced short-term climatic variability *(27-28).* In addition to pronounced summer cooling from aerosol scattering of incoming solar radiation *(29, 30)*, volcanic aerosols can reduce evaporation over water bodies (*27*) and affect the seasonal migration of the intertropical convergence zone *(27,* *31)*, promoting weakened summer monsoons *(32, 33, 34, 35)*. Major eruptions can thus introduce a double jeopardy of marked coldness and drought during the agricultural growing season. The resulting impacts may be compounded by livestock death, accelerated land degradation, and additional crop damage from the survival of agricultural pests during regionally mild winters that may be a further dynamical consequence of tropical volcanism in particular *(27, 36, 37)*. Because sophisticated agronomy was critical to sustain successive populous Chinese dynasties, abrupt climatic change and extreme weather thus held the potential to deeply perturb their political, economic and demographic functioning *(3, 38)*, providing multiple pathways by which volcanically induced climatic shocks might promote collapse. These pathways may have been amplified by the influential concept of the "Mandate of Heaven," in which contemporaries associated the perceived quality and moral authority of a dynasty's rule with the clemency of weather and related agricultural fortunes *(39-41)*.

To establish whether a systematic association exists between explosive volcanism and dynastic collapse during the first two millennia CE, comprising the great majority of China's Imperial Era, we compile a comprehensive dataset of collapse dates from 56 authorities (Supplementary Data 1; Methods). Consideration of variations in collapse dating has been effectively absent in examinations of environmental influences on collapse, yet our surveyed authorities frequently express disagreement. For example, 1644 is the most-cited date for the Ming Dynasty collapse, being the date in which the Ming capital, Beijing, fell to the rebel leader, Li Zicheng, and the Chongzhen Emperor committed suicide. However, 1662 is also credibly proposed, with the remnants of the Ming court having fled to southern China, offering variable resistance to the new Qing Dynasty until the capture and execution of the last serious Ming claimant to the throne by Qing military leader Wu Sangui in 1662. The dating of collapse thus clearly requires careful assessment to credibly identify any role for volcanic climate forcing, and in our analyses we thus use the consensus (i.e., most frequently cited) date for each collapse (Supplementary Data 1). We further employ a state-of-the-art ice-core-based volcanic forcing reconstruction *(42)* in which 156 explosive tropical and extratropical Northern Hemispheric eruptions are identifiable between 1 CE and 1915 CE through elevated sulfate in Greenland and Antarctic ice (Figure 1). This figure excludes eruptions with marginal sulfate mass deposition signals (<5 kg/km^{-2} in Greenland) and a likely negligible climatic influence. Importantly, this reconstruction corrects long-standing errors in major polar ice-core chronologies such as the Greenland Ice Core Chronology 2005 (GICC05) for the first millennium CE that have obscured linkages between volcanism, climate and society*(43-44)*.

FIGURE 1 AROUND HERE

Results

Association between dynastic collapse and explosive volcanism

We begin by establishing the frequency and timing of eruptions that closely precede our collapse dates (Figure 2A), taken as any eruption occurring within a -10 to +2 year window relative to each collapse (i.e., encompassing all years from the 10th preceding through to the 2nd following collapse, and denoted [-10, 2]). This conservative window allows for small remaining uncertainties (±2 years) in ice-core-based eruption dates (*42*), small uncertainties in collapse dates (Supplementary Data 1), and potentially variable lags between eruptions and the onset of notable climatic impacts. It also accommodates an understanding that societies are unlikely to respond mechanistically to climatic shocks (i.e., there is no reason to posit, *a priori*, that a complex societal phenomenon such as dynastic collapse will occur systematically in any specific post-eruption year). Historical evidence indeed suggests the opposite, with potentially variable lags in the onset of stresses such as famine, which can be prevented or delayed if coping mechanisms such as state famine relief measures are enacted *(16, 22)*. A windowed approach accounts for this potential variability, and we thus find within our [-10, 2] year window that one or more eruptions "preceded" the majority (62 of 68) of collapses. The high frequency of eruptions now identifiable in polar ice cores has contributed to a growing acknowledgement of explosive volcanism as the dominant external climate forcing throughout the most recent millennia (*45-48*), with the consequent ability to repeatedly impact society, but this frequency is now such that a substantial number of eruptions may be expected to precede collapses by chance.

To thus establish whether the nominally large observed association between eruptions and collapses is beyond what might be expected randomly, we conduct a "windowed" superposed epoch analysis (Figure 2A). In this, the average number of eruptions falling within our "central" 13-year window of [-10, 2] years relative to the dates of collapse is assessed for statistical significance against a randomized reference distribution generated by Monte Carlo resampling (10,000 iterations). In this, the 156 eruptions are redistributed in time, with a count made of those randomly falling within the central 13-year window relative to each collapse upon each iteration (Methods). For additional insight into whether the level of association observed between explosive volcanism and collapse within our central window can be deemed particularly noteworthy, we similarly calculate and assess the statistical significance of average eruption numbers falling within a set of 20 adjacent consecutive windows (10 preceding and

10 following the central window), each also necessarily of 13-years duration to maintain parity (and comparability) with the central window. We find that the average number of eruptions occurring in our central window is higher than expected randomly at 99.95% confidence (p = 0.0005), whereas the average number of eruptions falling in adjacent windows is uniformly smaller, and none breach the 99% significance threshold (Supplementary Table 1; Figure 2A).

FIGURE 2 AROUND HERE

To test the robustness of this result, we repeat our analysis using iteratively smaller lengths for our central and adjacent windows (i.e., using sets of central windows ranging in size from our initial 13-year [-10, 2] central window down to a 3-year [0, 2] window, with adjacent windows correspondingly varying in size for parity) to determine whether the observed statistical significance is highly dependent upon a specific choice of central window length. We find instead that the number of eruptions in every variant central window remains higher than expected randomly at 95% confidence or above (Figure 2B; Supplementary Data 2). This is not observed for the adjacent windows on either side of our central window. However, some statistical significance is increasingly observed in the set of first preceding adjacent windows as the corresponding variant central windows grow shorter (Figure 2B, Supplementary Data 2). This suggests that shorter central windows do not capture the full timescale upon which explosive volcanism may contribute to collapse, with eruptions falling just outside of these shorter central windows (i.e., occurring in the years immediately preceding) found in higher numbers than expected by chance, implying that these may also make a causal contribution to collapse. Thus, for example, the average number of eruptions occurring *within* a shorter 8-year central window of [-5, 2] years relative to the dates of collapse is higher than expected randomly at >95% confidence, but so too is the average number of eruptions occurring in the first preceding window (also of 8 years duration, spanning [-13, -8] years before collapse; Supplementary Data 2).

Effect window of explosive volcanism

This highlights a persistent uncertainty regarding the timescale over which climatic shocks can be societally effective. To thus localize the potential "window of effect" of explosive volcanism on collapse, we begin by re-testing for statistical significance as the number of years in our central window is progressively increased by adding one additional pre-collapse year (i.e., starting from window [0, 2] and progressing through [-1, 2], [-2, 2], [-3, 2] and beyond). This reveals a trend towards increasing statistical significance that peaks at 99.95% confidence (p = 0.0005) when counting eruptions out to the 10th pre-collapse year (i.e., window [-10, 2]; Figure 2C). This value is not exceeded by any larger window length tested (i.e., in testing all sizes out to and including 25 pre-collapse years (i.e., out to window [-25, 2]), though significance remains nominally high as an intrinsic property of this test (Methods; Supplementary Table 2).

To further localize the window of effect, we repeat the above test but now exclude the first ten years preceding collapse (i.e., beginning our window at pre-collapse year 11), and continue as before by enlarging the window in one year increments (Figure 2D). In this case we observe no statistical significance for any window length out to 25 pre-collapse years (i.e., from window lengths [-11, -11] to [-25, -11]; Supplementary Table 3), implicating the decade immediately preceding collapse as being the critical period during which explosive volcanism has been of systematic influence. Lastly, we complement the above analyses by maintaining a static central window size of 13-year length (corresponding to the [-10, 2] year window) but now shift this entire window away from our collapse dates as a single block in one year increments (e.g., [-13, -1], [-14, -2], [-15, -3]). In doing so we observe a broadly declining significance in which the association between volcanism and collapse falls permanently below 95% confidence when excluding the seven years immediately preceding collapse, and permanently below 90% when excluding the first nine years (Figure 2E; Supplementary Table 4).

These results for the first time confirm a repeated and systematic role for volcanic climatic shocks as causal agents in the collapse of successive dynasties in one of the world’s most populous and long-lasting civilizations, using the most complete and robust list of collapse dates yet compiled. Moreover, we localize the apparent “window of effect” of explosive volcanism to the first decade preceding collapse.

Explosive volcanism as ultimate and proximate causes of collapse

The precise nature of the human-environmental (socioecological) dynamics that lend an agency to volcanic climatic shocks in cases of collapse remain, however, an open and complex question. Certainly, such shocks are efficacious only to the extent that relevant (imperfectly mitigated) socioeconomic and political vulnerabilities exist (be they transient and particular only to certain historical moments or dynasties, or more persistent and intrinsic to the socioeconomics or political system of multiple dynasties). That collapse is absent (within a plausible timeframe) following some of the likely most “climatically effective” eruptions of the past two millennia, not least the great tropical eruptions of Tambora (1815), Huaynaputina

(1600) and Samalas (1257), is noteworthy here. Similarly in the first millennium, the immense 626 extratropical Northern Hemispheric eruption (precise location unknown) did not precede a dynastic collapse, despite being likely responsible for apparent dust-veil observations as widely separated as Ireland and the Near East, and elsewhere being implicated as a contributor to the fall of the Eastern Turkic Empire *(, 24, 30, 4249)*. Even in cases of collapse, that some dynasties persisted for up to a decade post-eruption, whilst others collapsed much more rapidly suggests the complexity of the underlying causal contributions and the inadequacy of monocausal or environmentally deterministic interpretations.

Nonetheless, given the existence of vulnerabilities to climatic shocks, it is plausible to posit that their efficacy as societal stressors will be at least partly determined by their magnitude, but also the magnitude of other pre-existing or coincident stressors (in cases where their impact also cannot be not mitigated, wholly or in part). Following from this, we thus hypothesize that volcanic climatic shocks will have acted along a spectrum from ultimate to proximate causality, driven by the severity of the associated climatic perturbation relative to the level of prevailing societal stress or instability. In this hypothesis, a comparatively modest climatic shock may act, via its impacts on agriculture, politics and other vulnerable or responsive societal processes, as the "ultimate" cause of a collapse when a high level of pre-existing or coincident instability has lessened societal resilience (thereby translating a modest volcanic climatic perturbation into a more effective shock). Conversely, we may posit that a sufficiently large volcanic climatic perturbation may act as the more fundamental "proximate" cause of collapse, even with minor pre-existing or coincident stress.

To test this, we employ warfare as a broad metric for socioeconomic and political stress, given that warfare can be both a response to and an amplifier of such stresses. Mechanisms include the high costs of financing and provisioning armies and military campaigns (offensive and defensive) against rival kingdoms, dynasties or rebellious subjects, with resulting infrastructure creation and damage, disruption to trade, industry and agriculture (e.g., especially from scorched earth tactics), impacts on labor supplies and a more active disease environment (triggered by large assemblies and movements of troops and ecological disturbance), as well as the empowerment of generals with the increased means and opportunity to rebel against weakened or distracted ruling dynasties. We thus draw upon a 1,061-year reconstruction of warfare frequency (Figure 1), quantified annually between 850 and 1911 CE using a multi-volume historical compendium that exhaustively registers warfare across the greater Chinese realm as known from the region's rich written record (Methods; *12)*. We begin by repeating our core test to confirm that volcanic eruptions remain statistically significantly associated with collapse dates when restricting our consideration to this post-849 CE period. We find this is the case at 99.3% confidence (central [-10, 2] year window) and note in passing that the association remains significant at 99.7% confidence for the earlier 1 to 849 CE period.

We next superpose annual warfare frequencies relative to the 25 collapse dates post-849 CE. This reveals an often marked elevation of warfare in the decades before collapse (spiking in years -18, -16, -11 and -3, which are statistically significantly elevated at >95% confidence, Figure 3A). Collapse years are the most dramatically elevated (at >99% confidence), with high warfare also seen in the second post-collapse years (at >96% confidence), beyond which warfare largely drops to lower values. These results confirm, to begin, an expected role for warfare as a stressor that can causally contribute to collapse and may to an extent also be a product of it.

FIGURE 3 AROUND HERE

To examine the dynamic between pre-collapse stress and the severity of volcanic climatic forcing, we next divide our collapses into those experiencing a below and above average number of eruptions within our [-10, 2] year central window (Supplementary Table 5) and superpose warfare relative to collapse dates for both groups (Methods). This reveals a marked distinction in which collapses associated with lesser volcanic forcing tend to occur in the context of already elevated average warfare (Figure 3B), whereas warfare tends to be notably less elevated before collapses associated with greater volcanic forcing (Figure 3C). During collapse years themselves, however, this pattern dramatically reverses. Here, notably greater relative warfare is seen for the higher volcanic forcing group (also exhibiting greater statistical significance at 99.99% versus at 96.75% confidence for the lower volcanic forcing group), such that these collapses are not ultimately non-violent, even if they are less associated with elevated longer-term preceding warfare. These results support our posited dynamic, in which more moderate volcanic climatic shocks may be more effective when acting in concert with pre-existing or coincident stress or instability, while larger shocks have greater capacity to act independently, with the immediate process and aftermath of collapse itself engendering severe short-term conflict. This hypothesis implies that a negative relationship (i.e., an inverse association) should pertain between the severity of volcanic climatic forcing and the level of pre-collapse warfare (and be statistically identifiable, given a sufficiently large sampling of collapses, if relevant unmitigated vulnerabilities persist or repeatedly evolve across multiple dynasties).

We thus calculate the Spearman Rank correlation coefficient (Methods) for the Northern Hemispheric climate forcing potential (as reflected by total Greenland volcanic SO_4 deposition *(42)* of all pre-collapse eruptions falling within our [-10, 2] year window, against warfare totals observed within iteratively larger window lengths ranging from the first to twentieth pre-collapse years, inclusive (Methods; Figure 4A). We test multiple window lengths in this way to again ensure that our results are not particular to, or dependent upon, any arbitrarily chosen number of pre-collapse years when calculating the level (and assessing the role) of pre-collapse stress. Our results confirm the prevalence of the hypothesized inverse association for all tested windows, peaking when including warfare totals in the first eleven pre-collapse years (Spearman $\rho = -0.407$, significant at 97.85%), and with significance of >95% for all windows incorporating the first eight to fifteen pre-collapse years (Figure 4B).

Inspection of the most significant window (i.e., considering warfare occurring up to 11 years pre-collapse, inclusive; Figure 4C) and the fitting of linear and non-linear trend lines (Methods) illustrates this inverse association in which collapses associated with lesser volcanic forcing tended to occur when more substantial pre-existing warfare prevailed and vice versa. The 1368 CE collapse of the long-lived Yuan Dynasty lies at one end of this spectrum, occurring without any apparent volcanic climatic forcing, but in the aftermath of the largest observed warfare levels preceding any of our 25 collapses (Supplementary Table 6). The collapses of the Western Liao (1211), Min and Later Jin (945 and 946, respectively, part of the famous Five Dynasties and Ten Kingdoms period) occur by contrast with considerably lesser preceding warfare, but a substantial volcanic forcing (Supplementary Table 6). Many collapses are also observed to follow moderate volcanic forcing and pre-existing warfare combined, such as the 1125 collapse of the Liao Dynasty (Supplementary Table 6), implying a strongly synergistic causal role in such cases. We note that these results are insensitive to other measures of volcanic forcing (and hence the likely magnitude of any subsequent climatic shock). Taking the number of pre-collapse eruptions rather than total volcanic SO_4 deposition (Methods) therefore returns consistent results with a persistent inverse association for all windows tested, and a peak Spearman ρ of -0.486 (significant at 99.3%) when including the first 13 pre-collapse years.

Considerable variability is expected and indeed observed within this broader pattern, attributable in part to a skewed forcing distribution with many more small and moderate eruptions than large eruptions *(42)*. Even where larger eruptions are potentially sufficient to independently promote collapse, they may also by chance occur during periods of high warfare and thereby appear as an outlier to the general inverse association in evidence. A notable example is the collapse of the Ming Dynasty in 1644 (Supplementary Table 6). This followed a major volcanic event in 1641 (likely Mt. Parker in the Philippines, which itself followed a more moderate extratropical Northern Hemispheric eruption in 1637 (*42*) at a time of already considerably elevated warfare (Figure 4C). This further highlights the need for a large sample size of collapse dates to identify underlying relationships, achievable only by surveying a large temporal span, as presented here. The complexity of human-environmental relations is a further likely contributor to the variability on display. Underlying political and socioeconomic structures that differ by region and period may, for example, render some dynasties more vulnerable to climatic shock than others, such that the impact of any given combination of pre-existing instability and climatic forcing may not scale linearly between dynasties.

FIGURE 4 AROUND HERE

Repeating our analysis for non-collapse years (Figure 4D; Methods) further emphasizes the reality of the hypothesized dynamic, with no convincing or strong association (positive or negative) observed between warfare and volcanic forcing preceding *non-collapse* years (Spearman ρ = -0.066 for non-collapse, versus -0.407 for collapse). Associations between climate and conflict are complex (e.g., potentially non-linear) and context-dependent. Climatic shocks may promote some forms of conflict (e.g., via scarcity induced resource competition (*4,50*), whilst suppressing others such as large-scale inter-state warfare that requires considerable resources to conduct and may be rendered more difficult in challenging meteorological circumstances (*51*). Although we do not discount a role for explosive volcanism in promoting warfare and hence contributing to collapse via this additional pathway, the above result (Figure 4D) suggests that this does not occur systematically. If such an effect was large and systematic, it would moreover tend to promote a positive association in Figure 4C (i.e., with larger volcanic climatic shocks promoting greater pre-collapse warfare). The inverse association that is instead observed suggests that volcanic climatic impacts and pre-collapse warfare occur largely independently. They may still, however, act in synergy and even through common pathways to promote collapse, e.g., where subsistence crises are amplified by combined climate-induced harvest failure and conflict-related agricultural impacts such as scorched earth tactics, and where state fiscal readiness to mitigate such impacts is impeded by reduced tax and grain intake from impoverished subjects (e.g., those experiencing harvest failure) and increased military expenditure (4).

Discussion

Our analyses reveal explosive volcanism as a systematic contributor to Chinese dynastic collapse throughout the first two millennia of the Common Era, playing a dynamic role along a spectrum from ultimate to proximate causality as influenced by the magnitude of the volcanic climatic perturbation relative to pre-existing stress, for which we employ warfare as a broad proxy. This highlights the inadequacy of monocausal or environmentally deterministic explanations of collapse, but also of traditional historical explanations that exclude environmental agency. Volcanically induced climatic shock must now take a prominent place among the constellation of factors frequently assigned a role in Chinese dynastic collapse.

This role will have been enabled by prevailing vulnerabilities, not least agricultural sensitivities to multi-year volcanically induced climate shocks that repeatedly impacted food security to an extent evidently difficult to fully or continuously mitigate by available measures (e.g., state grain reserves, price controls, tax relief) *(4, 32)*. Our results show that the efficacy of sudden climatic shocks must also, however, be seen as a part-function of their magnitude, relative to that of other existing stressors. It is logical to further posit that the impacts of multiple existing stressors will act synergistically, but the degree to which impacts from different stressors may compound (linearly or otherwise) will be mediated by prevailing vulnerabilities and remains an open question. Stressors may also be inter-dependent and synergistic in their incidence and magnitude. We thus employed warfare as a stressor, both intrinsically and as a potential proxy for related unmeasured stressors (e.g., warfare promoting food price stress through supply- and demand-side mechanisms, such as the deliberate destruction of crops and reduction of productivity (e.g., where farmers are drafted or used as corvée labour), and diversion of food to supply armies (4)). Additionally, while their impacts may still compound, the existence and magnitude of some stressors may operate antagonistically with, for example, severe cold directly reducing yields but also potentially depressing agricultural pest populations, indirectly benefitting yields. Further examination of the interactivity and net effects of multiple stressors will thus be essential, and may consider mass migrations, epidemic/epizootic diseases, pest outbreaks (bacterial, fungal, insect, rodent), the extractivity of taxation regimes, the intensity (e.g., casualty numbers, army sizes) of warfare, and other forms of conflict such as social unrest.

Other stressors are difficult to quantify (e.g., poor leadership, administrative corruption), and qualitative or mixed method case studies can clearly provide insight here, also particularly by identifying adaptative capacities and mitigative options available to individual dynasties (and hence their relative vulnerabilities) to determine those collapses most meaningfully impacted by which stressors. Such studies can also account for nuances through time and space. The warfare data employed here *(12)*, for example, comprises events summed across much of the study region, with variable relevance to different dynasties based upon their location, spatial extent, political and economic entanglements (e.g., intensity of market integration with afflicted areas). The complexities of the volcano-climate system can also make for societally meaningful regional variability in climate impacts that may be teased out by reference to the growing availability of palaeoclimatic reconstructions from written and natural archives *(32, 52)*. Volcanic climatic shocks also occurred in the context of longer-term societal and environmental changes that may have ameliorated, worsened, or introduced new vulnerabilities. Among these are demographic change, dynastic fiscal stability, institutional efficiency, succession disputes and discontinuities, encounters with external (e.g., Western) powers, technologies and ideas, novel disease environments, soil degradation, deforestation, and multi-decadal to centennial-scale climatic phases. These include the Late Antique Little Ice Age (or Dark Ages Cold Period), Medieval Climatic Anomaly (or Medieval Warm Period), and Little Ice Age *(53)*, of variable relevance across the greater study region. We might thus posit that volcanically induced drought or cold will be more efficacious in periods of greater demographic pressure, or when dynasties are already under pressure from longer-term trends toward aridity or cold, though this will again depend upon adaptive capacities and available mitigative measures.

Beyond material adaptations are those contingent upon prevailing belief systems, a striking example of which is the Chinese concept of the “mandate of heaven”, introduced during the Zhou Dynasty (1046-256 BCE). Although evolving in expression and varying in significance through time, this persistently held that rulers who abused their power or otherwise failed their people would have their divine sanction revoked *(39, 54-55)*. The concept may itself have plausibly promoted some instability by providing justification for rival claimants, rebellious populations, generals, governors, and expansionist neighbors, who could claim that incumbent dynasties had lost their mandate *(56)*, especially if supported by “ominous” natural phenomena such as comets, eclipses and rare planetary alignments deemed to express divine displeasure *(57)*. But such claims surely carried more weight (and greater likelihood of successfully overthrowing a dynasty) if coincident with genuine substantial material stress and grievance. In such cases, the concept offered a potentially efficient framework (and a widely known rationale) to replace poorly performing dynasties, perhaps particularly when explosive volcanism contributed to prevailing stress. Not only might eruptions promote material stress via extreme weather (itself potentially deemed "ominous" by virtue of its severity), but they might also simultaneously provide spectacular lunar and solar omens (e.g., "dark" total lunar eclipses, a dimmed or discolored solar disk, and/or coloured coronae or Bishop's Rings surrounding the lunar and solar disk) *(49, 58)*. By promoting a sense of continuity between dynasties, and a more ready (if not complete) acceptance of new dynasties that (by very virtue of successfully seizing power) demonstrated possession of the mandate, the concept may have ultimately promoted stability *(59)*. The observed rapidity with which warfare levels fall (on average) post-collapse certainly suggests this (Figure 3A-C). Indeed, rather than signifying a failure by society, "collapse" in this context might be more accurately seen as an adaptation to interwoven environmental, political and other stresses *(5)*, here facilitated by a deeply embedded cultural conception of the nature of rulership, dynastic legitimacy and change.

Our results emphasize the need to prepare for future eruptions, particularly in regions where populations are economically vulnerable (perhaps comparable to late Ming and Tang dynasty China) and/or have a history of resource mismanagement (as in Syria before the potentially part-drought-triggered 2011 uprising *(60,61*), compromising adaptive capacities and limiting available mitigative options. Eruptions during the twentieth and twenty-first centuries have been smaller than many experienced by China throughout the past two millennia. Even so, asymmetric stratospheric loading of volcanic aerosols from comparatively moderate eruptions may have contributed to the Sahelian drought of the 1970s-1990s, contributing in this economically marginalized region to ~250,000 deaths and the creation of 10 million refugees *(31)*. By perturbing the global monsoon against a background of inadvertent (or intentional, via geoengineering) human climate modification, future major eruptions are likely to profoundly impact agriculture in some of the Earth's most populous, and simultaneously most marginalized, regions.

Methods

Dynastic Collapse Dating

The collapse dates of Chinese, associated and proximate dynasties are sufficiently numerous, precise and accurate to allow for a detailed statistical determination of their association with sudden climatic changes inferred from high-resolution natural archives. This results from the great importance attached to these dates in Chinese historiography *(62)*, with most such histories accompanied by a tabulation of prevailing dynasties. There is, however, some disagreement among different authorities regarding these dates. Forty-four of 68 (64.7%) collapses have at least one cited alternative date, for example (Supplementary Data 1). Conflicts arise, for example, when preference is given to the date in which a dynasty loses power in practical terms (e.g., with the capture of most of its territory or capital), as against the sometimes later date of the final elimination of the royal family, which might seek sanctuary among allies or temporarily establish a rival capital in loyalist regions *(59, 62)*.

Divergence also exists between authorities on the dynasties included within their tabulations. During the past two millennia, there were periods of “disunion” when the characteristic territory of imperial Chinese dynasties fell under the rule of multiple kingdoms (e.g., the Sixteen Kingdoms period of the fourth to fifth centuries CE, or the Five Dynasties & Ten Kingdoms period of the tenth century CE *(62)*). Some authorities provide only singular end dates for these periods, rather than the collapse dates of the constituent kingdoms. Beyond these periods, the spatial extent of the dominant imperial dynasty also varies, sometimes markedly. Kingdoms with their own dynasties (sometimes ethnically and culturally distinct but becoming Sinicized to different degrees by adopting or adapting Han Chinese cultural elements) evolved or exercised control in proximate territories lost by or not yet incorporated into the territory of the reigning imperial power. These kingdoms feature intermittently in available tabulations, for example the Liao Dynasty of the (mainly) Khitan peoples, ruling regions now comprising contemporary Northern and Northeast China, Mongolia, areas of the Russian Far East and North Korea, and collapsing in 1125 (Supplementary Data 1). There are also notable instances in which the dynastic line of succession is “illegitimately” interrupted with the declaration of a new or rival dynasty by rebelling military commanders, powerful officials or other associates of the royal family. An example is the short-lived Xin dynasty declared by Wang Mang, a Han dynasty official who seized the throne from the ruling Han dynasty between 9 and 23 CE (Supplementary Data 1). Such “usurper” dynasties are, similarly, only variably included in available tabulations.

To compile the most credible and comprehensive list of relevant collapse dates, we thus surveyed 56 authorities (major historical works, encyclopedias and other reference works), and took a maximalist view on the inclusion of dynasties, resulting in a total of 68 collapses.

Supplementary Data 1 presents each dynasty and the range of cited collapse dates as a future research resource. For our testing, we employ the statistical mode (i.e., most commonly cited date per collapse), and describe this as the “consensus date.” For dates with equal numbers of citations, we use the earlier date as default.

Superposed Epoch Analyses, Variant Window Lengths and Positions

Superposed Epoch Analysis (SEA) is a robust and widely used “compositing” technique that can be used to determine the aggregate or average occurrence (or behaviour) of a given phenomenon (or of a continuous temporal process) relative in time to a set of dated “point events” that may exercise an influence on (or bear some hypothesized causal or correlative association with) the phenomenon or process of interest *(63)*. We employ this approach to determine whether any meaningful association can be observed between collapses (our dated point events) and explosive volcanism (our potential causal phenomenon), regarding the frequency of the association (number of eruptions preceding collapse), its temporal character (timing of these eruptions) and statistical significance (likely randomness of their frequency in any given pre-collapse period).

We start by calculating the average number of explosive eruptions that occurred in the years before, during and following all 68 dynastic collapses combined, hence also identifying the timing of these eruptions relative to collapse. We next assess statistical significance using a Monte Carlo approach that begins by selecting a set of point event dates at random (equivalent in number to the collapse dates) and re-calculating the average number of eruptions seen in periods (i.e., “windows” - see next paragraph) that fall before, encompass, and fall after these random “event” dates. This process is repeated 10,000 times to build a random reference distribution that informs us of how many eruptions we might expect to find occurring closely in time to our collapses purely by chance (i.e., if the posited association between explosive volcanism and collapse did not exist). In practice this involves determining where the average number of eruptions actually observed in any period relative to our true collapse dates falls within this random distribution. The further these actually observed numbers fall from the mean and toward the tails of this random distribution, the less likely they are (we may infer) to have occurred purely by chance. In Figure 2A, the “99% Monte Carlo significance threshold” thus marks the value below which 99% of average eruption numbers fell in our randomly generated reference distribution. We thus deem any actually observed value that breaches this threshold as having a less than 1% chance of occurring purely at random (thereby described as having a value that is greater than expected randomly at >99% confidence). We use this approach to generate all confidence thresholds in Figure 2A-D or reported in the main text (as well as corresponding *p* values, where >99% confidence equates to $p < 0.01$).

SEA approaches typically employ single-year time units. In this, the central "0" point (e.g., on the horizontal axis of Figure 2B) would represent all 68 collapse dates superposed, and the corresponding vertical axis value would represent the number of eruptions that occurred in these 68 years. Point 1 on the horizontal axis would then represent the number in the set of 68 years first following the collapse dates, while point -1 would represent the number in the set of 68 years first preceding, and so on. We adapt this approach to instead use broader multi-year "windows" as our individual time units. Our central window thus takes the position of point 0 on the horizontal axis and is 13 years long (Figure 2A). This encompasses each of the 10 years immediately preceding our 68 collapse years, each of the collapse years themselves, and each of the following two years (and is denoted window [-10, 2]). We then calculate the number of volcanic eruptions falling within this central window (averaged by window size), and do the same for further sets of adjacent windows of the same 13-year duration, adding a total of ten windows either side of our central window (Figure 2A). Window 1 thus spans the 3rd to 15th years following our 68 collapses (i.e., denoted [3, 15]), whereas window -1 covers the 23rd to 11th years preceding collapses (i.e., denoted [-23, -11]) (Figure 2A). This allows a comparison of the eruption frequency occurring closely in time to collapse (i.e., in the central or first preceding windows), with those more distant or that should not exhibit any systematic correspondence between collapse and volcanism (i.e., in post-collapse windows).

This windowed approach accounts for several concerns, beginning with the nature of our data, in allowing for small age uncertainties in the ice-core-based dates of explosive volcanism of approximately ±2 years *(42)* and some small uncertainty in our collapse dates (Supplementary Data 1). It also accounts for the character of our hypothesized association between volcanic forcing and dynastic collapse, in which we posit that there is no *a priori* reason to assume collapse will mechanistically (or deterministically) occur in any specific post-eruption year, and thus any "signal" (i.e., higher pre-collapse eruption frequencies) may be difficult to discern in a noisier annual SEA analysis. More specifically, it allows for variable lags between volcanic eruption dates and the meaningful onset of their climatic impacts, lags between their climatic impacts and the onset of major societal stresses such as food scarcity (e.g., which may be delayed by several years through use of stored grain reserves and other state relief mechanisms), and lags between the onset of major stress and the collapse of dynasties (which will occur via complex pathways and be mediated by many variables from the systemic down to the individual choices and abilities of leaders in facing crises).

To ensure our results and any observed statistical significance are not dependent upon the choice of a specific window length, we iteratively repeat our SEA analysis using sets of variant central window lengths ranging [0, 2], [-1, 2], [-2, 2] out to [-10, 2] years (i.e., lengths of 3, 4, 5 to 13 years). In each iteration, we also calculate the number and statistical significance of eruption frequencies falling within the ten adjacent windows preceding and following our central window, adjusting the size of these windows to maintain parity with the central window size. Results are presented in Supplementary Data 2 and summarized in Figure 2B, showing the mean average eruption frequency in all variant sets of central and adjacent windows, the mean 95% confidence threshold, plus the standard deviation around this mean.

To localize the potential "effect window" of explosive volcanism on collapse, we repeat our testing for all central window lengths from [0, 2], [-1, 2], [-2, 2] to [-25, 2] (i.e., Figure 2C; Supplementary Table 2). This reveals a broad trend toward higher significance as central window length increases, peaking at [-10, 2] with 99.95% significance, a value matched by window [-13, 2]. While significance is lower, it is still notably high for all wider lengths. This results from (1) the notably elevated eruption frequencies in the years immediately preceding collapse, (2) sustained by eruption numbers that vary above and below the average as expected by chance in each additional year added (i.e., sustained below average eruption numbers are required for significance to trend consistently down). We thus complement this test by instead beginning our window at year -11 and incrementally adding an extra year to each tested window out to [-25, -11] (i.e. systematically excluding the first 10 years preceding collapse in all cases). In this case no statistical significance is observed for any window (Figure 2D; Supplementary Table 3), implying the systematic window of effect of explosive volcanism occurs during the first decade before collapse. To confirm this, we employ a static window length (13 years, as per window [-10, 2]) and instead move this window in one year increments to increasingly encompass years further preceding collapse (i.e., starting at [-10, 2] and ending at [-25, -13]). This reveals a broadly decreasing significance that falls permanently below the 90% threshold when excluding the first nine pre-collapse years (Figure 2E, Supplementary Table 4).

Pre-Collapse Instability and Volcanism

To clarify the causal contribution of explosive volcanism to dynastic collapse, we posit that its role will vary along a spectrum from proximate to ultimate causality, dependent upon the magnitude of the volcanic climatic impact relative to levels of already ongoing pre-collapse stress. To determine the potential magnitude of volcanic climatic impacts, we use a multi-ice-core dataset of cumulative Greenland volcanic sulfate deposition (in kg/km^{-2}) and the number of eruptions inferred from this *(42)*. We employ warfare frequencies as a broad proxy for socioeconomic and political stress (including warfare with external groups and rival kingdoms, and that arising from internal rebellion, 850-1911 CE). These data derive from a multi-volume compendium of historical wars in (and involving) China, compiled by the Editorial Committee of China's Military History and quantified by Zhang *et al. (4)*. An SEA (in annual time-steps; Fig 3A) of warfare relative to all 25 collapse dates post-850 CE is used to confirm an association between ongoing elevated warfare in the decades preceding collapse. For an initial perspective on the role of volcanism, our 25 collapses are divided into those experiencing below vs. above average (median) eruption frequencies within the [-10, 2] year window (Supplementary Table 5). Repeating our SEA reveals greater preceding warfare for collapses with a below average preceding eruption frequency, and vice versa. Warfare frequencies are detrended by setting each annual value relative to a spline that captures multi-decadal trends in the data, and then normalized by setting each detrended annual value relative to the mean and standard deviation of the preceding 30 years of the detrended series. This facilitates comparability between relative warfare levels preceding collapses through time by removing longer term trends, e.g., toward greater or lesser frequencies, that may arise in part from variable record keeping or survival.

Correlation analyses are used to test for the hypothesized inverse association between the magnitude of potential volcanic climatic impact and level of pre-existing stress. Spearman rank correlation is used because the resulting distribution does not meet all assumptions of the Pearson correlation, and is in particular more robust to outliers. We correlate total volcanic SO_4 deposition within the [-10, 2] year window for each collapse, against total warfare frequencies in a range of windows preceding collapse from the 1st to 25th pre-collapse years (inclusive) to ensure our results are not dependent upon a specific or arbitrarily chosen number of pre-collapse years (Figure 4 A,B). Warfare frequencies in collapse years themselves are not included as they may be at least partly the product of the collapse itself (i.e., amplified by collapse) and hence obscure the role of preceding stress levels. We also employ eruption frequencies as an alternative metric to total volcanic SO_4 deposition for potential volcanic climatic forcing and observe consistent results. One-tailed p values are reported for this testing because we hypothesize a unidirectional association between the magnitude of volcanic forcing and pre-existing warfare.

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Data Availability: Datasets used in this study are available online in the supplementary data accompanying the original publication (the volcanic forcing dataset of Ref. 42 [https://static-content.springer.com/esm/art%3A10.1038%2Fnature14565/MediaObjects/41586_2015_BFnature14565_MOESM47_ESM.xlsx], representing ice-core-based dates (years) of explosive volcanism with SO_4 time-aggregated deposition measured in kg/km^{-2}) or upon direct request to the corresponding author (the Chinese warfare data of Ref. 12, representing counts of wars per year in integer format). The compilation of dynastic collapse dates (years) is available in

Supplementary Data 1 of the present paper and via the Trinity College Dublin Open Access repository, TARA: [*insert link here*].

Code Availability: Custom script used to conduct the Monte Carlo windowed superposed epoch analyses is available upon request from the corresponding authors.

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Figure 1. Chinese dynastic collapse, explosive volcanism, and warfare frequency, 1-1911 CE. Consensus dates for 68 dynastic collapses (blue dashed vertical columns; Supplementary Data 1), overlain by ice-core-based dates and climate forcing potential of inferred-tropical and extratropical Northern Hemispheric explosive volcanic eruptions (n=156) as inferred by multi-ice-core measurements of polar sulphate deposition (in kg/km^{-2}) (*42*) (graduated red circles), for 1-1911 CE. Also shown is annual warfare frequency from 850 to 1911 CE (*12*) (continuous tan line), with the thick brown line representing a 10-year smoothing using the Savitzky-Golay filter. Figure is split into two consecutive periods for visual clarity; **a** and **b** cover the first and second millennia CE, respectively.

Figure 2. Incidence of volcanic eruptions relative to Chinese dynastic collapse. Panel **a** Windowed superposed epoch analysis (SEA) showing the average number of eruptions occurring in 13-year windows relative to our 68 collapse dates (Supplementary Table 1; Methods). The position of the black line at Point 0 on the horizontal axis represents the average number of eruptions occurring within our central [-10, 2] year window, i.e., spanning 13 years from the 10th year preceding our collapse dates, out to the 2nd year following, inclusive. The black line at Point -1 thus represents the average number of eruptions falling within the 13-year window that first precedes this (i.e., encompassing the 23rd to 11th years preceding collapse), while the black line at Point 1 thus represents the average number of eruptions falling within the 13-year window that first follows this (i.e., encompassing the 3rd to 15th years following collapse), and so on. The 99% Monte Carlo significance threshold is indicated by the red line. **b** Summary of multiple SEAs using variant (increasingly smaller) window lengths (Supplementary Data 2; Methods). The thick black line shows the “composited” average (i.e., mean average) number of eruptions occurring relative to our 68 collapse dates, from all variant window lengths combined. The thin grey lines show the average number of eruptions for each tested window length, individually. These range from the 13-year window length shown in **a**,

at the largest, down to a 3-year length, at the smallest. The central window ([0, 2]) for this smallest variant window length thus falls at Point 0 on the horizontal axis, and encompasses the years of collapse (i.e., year 0) out to the 2nd years following, inclusive. Point -1 for this window variant thus encompasses the 3rd the 1st years [-3, -1] before collapse, and Point 1 the 3rd to 5th years following, and so on. The red dashed line shows the average of all individual 95% significance thresholds for each tested window length, while the dotted red lines show the ±1 standard deviation around this average. **c** The Monte Carlo statistical significance level reached when iteratively increasing the size of the central window by one year, from the smallest window of [0, 2] years (i.e., 3-year span) to [-25, 2] years (i.e., 28-year span) (Supplementary Table 2). **d** The same as **c** but *excluding* the first ten years preceding collapse (i.e., the first window tested comprises the 11th year alone before our collapses, while the final window tested comprises the 11th to 25th years before our collapses (i.e., window [-11, -11] with a 1-year span to window [-25, -11] with a 15-year span) (Supplementary Table 3). **e** Shows the Monte Carlo statistical significance level reached when maintaining the 13-year default central window length but now moving this window in one year increments away from the dates of collapse (i.e., beginning with the [-10, 2] year window relative to collapse, and progressing to the [-25, -13] year window) (Supplementary Table 4).

Figure 3. Annual warfare frequencies relative to Chinese dynastic collapse. Panel **a** Superposed epoch analysis of annual warfare frequencies (*29*) relative to all 25 collapses, 850-1911 CE (Supplementary Data 1). **b** Only those collapses with a lesser volcanic association (i.e., having less than the median number of eruptions within the [-10, 2] year window relative to the dates of collapse; n = 12 collapses). **c** Only those collapses with a higher volcanic association (i.e., having more than the median number of eruptions within the [-10, 2] year window; n = 13). See Supplementary Table 5. For all panels, warfare data are detrended to remove low-frequency variability and then normalized by setting each annual value relative to the mean and standard deviation of the preceding 30 years (i.e., vertical axis frequencies are expressed in z-scores). The horizontal axes cover each of the 20 years before collapse (Points -20 to -1), the years of collapse (Point 0), and the following 20 years (Points 1 to 20). Solid and dashed horizontal lines represent the upper and lower 95% and 99% confidence bounds, respectivey, produced by Monte Carlo resampling (10,000 iterations).

Figure 4. Association between pre-collapse warfare and pre-collapse volcanic forcing. Panel **a** Spearman Rank correlation coefficients (vertical axis) for the Northern Hemispheric

climate forcing potential (as reflected by total volcanic SO_4 deposition in Greenland in kg/km^{-2} (*42*)) of all pre-collapse eruptions (vertical axis) falling within our [-10, 2] year window relative to the dates of collapse, versus cumulative warfare totals for a selection of iteratively larger windows lengths that span the first to twentieth pre-collapse years (horizontal axis). **b** One-tailed p values corresponding to each window in **a**. **c** Linear (ordinary least squares) and non-linear (loess) trend-lines for the window that exhibits the largest inverse association (as per Spearman ρ) between volcanic forcing potential and level of pre-collapse warfare (i.e., including warfare during the first 11 pre-collapse years). Red dots represent the 25 individual collapses post-849 CE. Grey bands represent 95% confidence intervals. **d** Same as for **c**, but now showing the case for all non-collapse years (n = 1036).

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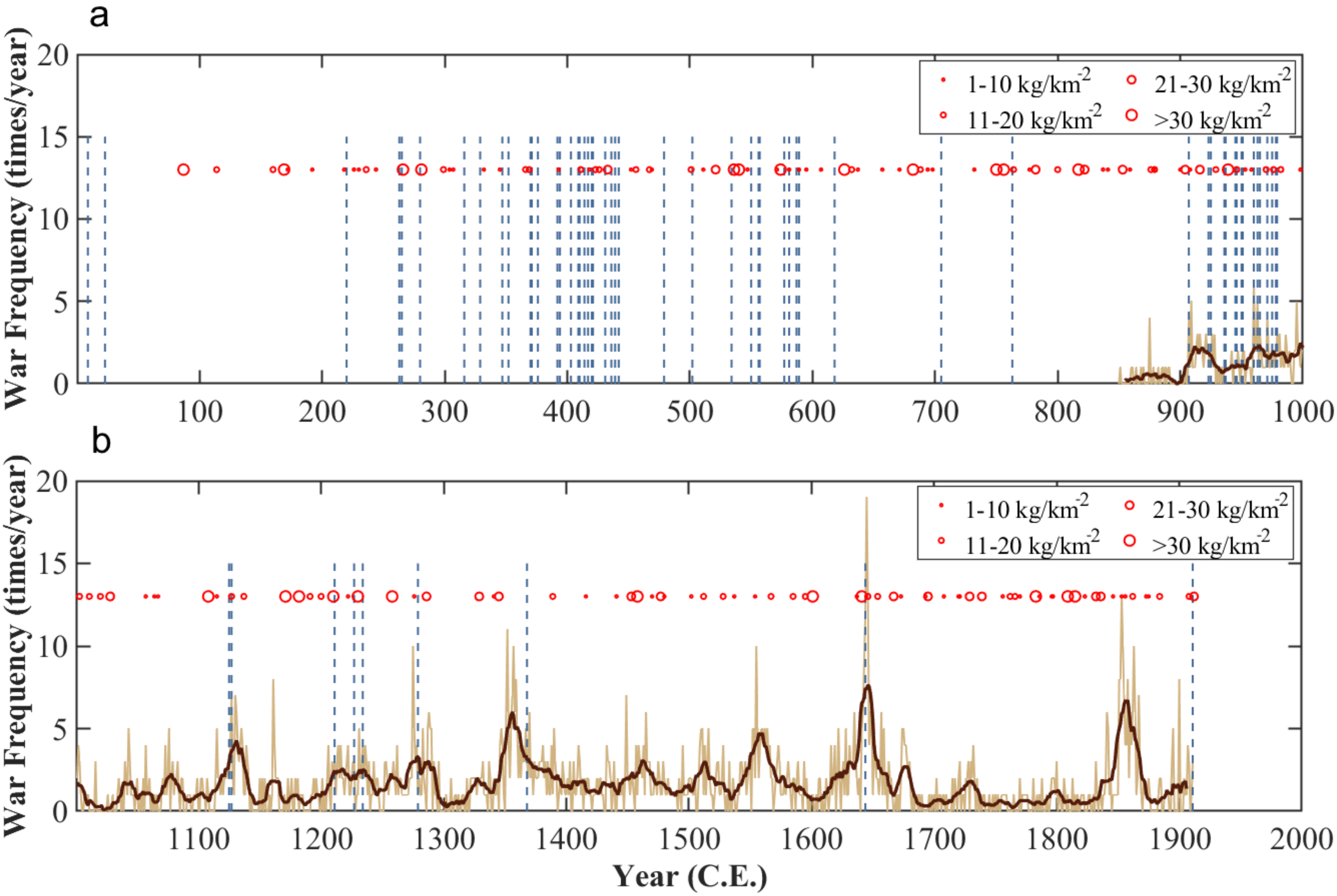
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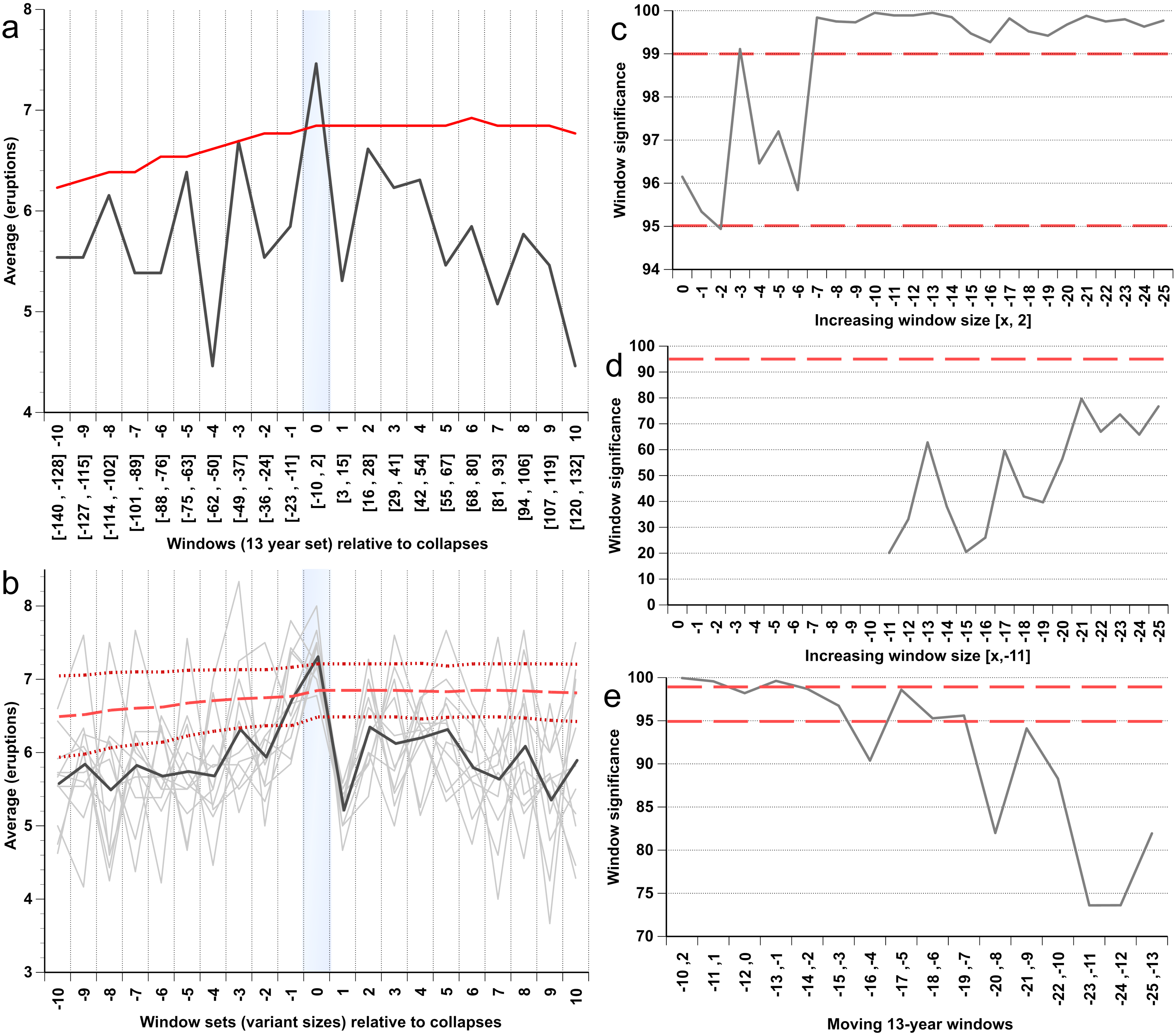
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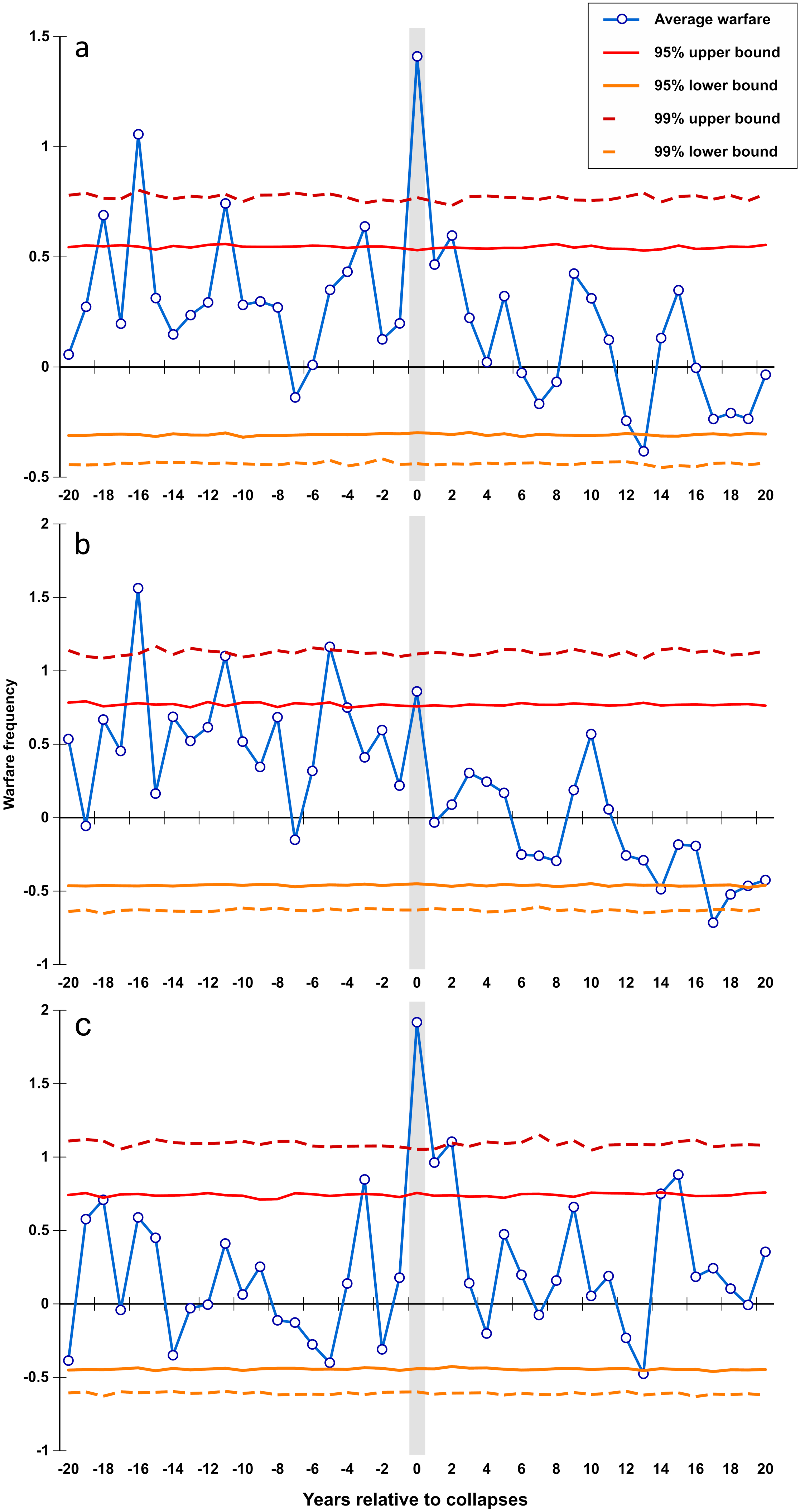
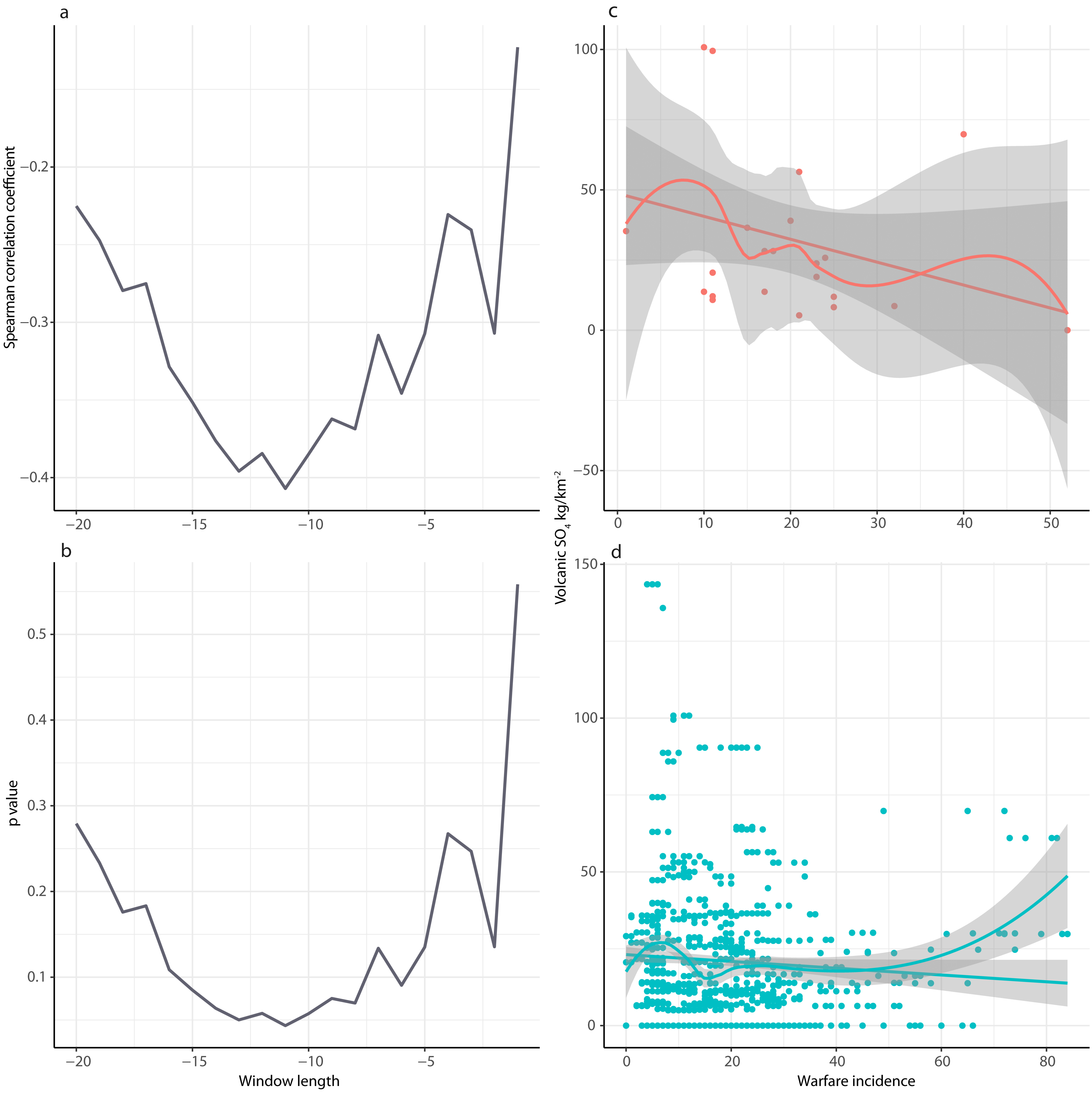
[-114 , -102]
[-101 , -89]
[-88 , -76]
[-75 , -63]
[-62 , -50]
[-49 , -37]
[-36 , -24]
[-23 , -11]
[-10 , 2]
[3 , 15]
[16 , 28]
[29 , 41]
[42 , 54]
[55 , 67]
[68 , 80]
[81 , 93]
[94 , 106]
[107 , 119]
[120 , 132]
Windows (13 year set) relative to collapses
b
Average (eruptions)
8
7
6
5
4
3
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
Window sets (variant sizes) relative to collapses
c
Window significance
100
99
98
97
96
95
94
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
Increasing window size [x, 2]
d
Window significance
100
90
80
70
60
50
40
30
20
10
0
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
Increasing window size [x,-11]
e
Window significance
100
95
90
85
80
75
70
-10 ,2
-11 ,1
-12 ,0
-13 ,-1
-14 ,-2
-15 ,-3
-16 ,-4
-17 ,-5
-18 ,-6
-19 ,-7
-20 ,-8
-21 ,-9
-22 ,-10
-23 ,-11
-24 ,-12
-25 ,-13
Moving 13-year windows


Average warfare
95% upper bound
95% lower bound
99% upper bound
99% lower bound
a
b
c
Warfare frequency
Years relative to collapses
1.5
1
0.5
0
-0.5
2
-1
-20
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10
12
14
16
18
20


a
b
c
d
Spearman correlation coefficient
−0.2
−0.3
−0.4
p value
0.5
0.4
0.3
0.2
0.1
−20
−15
−10
−5
Window length
Volcanic SO$_4$ kg/km^{-2}
100
50
0
−50
0
10
20
30
40
50
150
100
50
0
0
20
40
60
80
Warfare incidence