Sam White
Christian Pfister • Franz Mauelshagen
Editors

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Editors
Sam White
Ohio State University
Columbus, OH, USA

Christian Pfister
Institute of History
Oeschger Centre for Climate Change
Bern, Switzerland

Franz Mauelshagen
Institute for Advanced Sustainability
Studies, University of Potsdam
Potsdam, Germany

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CHAPTER 32

The Climate Downturn of 536–50

Timothy P. Newfield

32.1 Introduction

The 536–50 CE climatic downturn has a contentious and imperfect history. Its most basic characteristics long eluded consensus and disparate explanations exist for its cause, chronology, geography, and impact. Was this anomaly interregional, hemispheric, or global in scale? Was it a singular vast phenomenon or a complex of near-simultaneous events? Was it terrestrial or extraterrestrial in origin? Was it a cultural and demographic watershed or a minor incident inconsequential for all and unnoticed by most?

Histories of the downturn vary in part because reconstructions of its origin, scope, and severity have evolved steadily since the anomaly was discovered in the early 1980s.[1] Its meaning for scholars of classical Maya Central America, north–south dynastic China, migration-period Scandinavia, the late antique Mediterranean, and other parts of the sixth-century world remains in flux. The written evidence is finite, but interpretations of key passages have differed. Some of the natural evidence, namely from ice, lakebeds, and trees, has proven mutable, and perhaps some of it is still ambiguous. Not only do new ice-core and dendroclimatological studies continue to appear at a good clip, but many

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T. P. Newfield (✉)
Departments of History and Biology, Georgetown University, Washington, DC, USA

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earlier studies have since been reinterpreted. Some relevant paleoclimate data, including results pivotal to the event's discovery, have been refined, reworked, and retracted.

This is not to say that nothing about the anomaly is known for certain. Far from it. Dozens of natural indices for pre-instrumental temperature and precipitation from around the globe, but the Northern Hemisphere in particular, illuminate the downturn and its causes. It is clear that it was a major episode of cooling, as dendroclimatology has long signaled, and it was possibly, but not necessarily, global in scale. Indeed, dramatic cooling is seen clearly in many proxies north of the equator, but a drop in Southern Hemisphere temperature, severe or not, is less certain. Multimillennial temperature proxies there are few, and uncertainties exist in some of the proxy records assembled.[2] Still, downturn volcanism is archived in both Greenlandic and Antarctic ice, lending the event a global history.

Several recent paleoclimate studies have underscored the downturn's magnitude and extraordinariness. For example, a new bipolar ice-core chronology of volcanism paired with a composite of multimillennial-long Northern Hemispheric tree ring chronologies identified the downturn eruptions as some of the largest of the last 2500 years, and 536–45 as the second most extreme decade of post-volcanic cooling over the same period. Of the sixteen coldest summers north of the equator since 500 BCE (compared to the paper's modern reference period of 1901–2000), six occurred between 536 and 550.[3] A study using Alpine and Altai trees found that the 540s was the coldest decade of the Common Era in the European series and the second coldest since 100 CE in the Central Asian series (with respect to 1961–90). Moreover, the authors of this article established that the downturn's abrupt temperature plunge ushered in an unprecedented period of cooling—a Late Antique Little Ice Age—over large swathes of Eurasia.[4] Another new composite tree ring-based study, but of European summer temperatures stretching back to antiquity, positioned the 536–50 dip as one of the coldest and most dramatic in the series. Over the European peninsula, the decade-and-a-half came in at about 1°C colder than the study's modern reference period (1961–90). Seven years of the departure were well below that mark.[5] Most recently, modeling of the climate forcing of the two largest downturn eruptions implied that they were each comparable to the strongest eruptions of the last 1200 years and that together, over the decade of 536–44, they exercised an impact on extratropical Northern Hemispheric climate upwards of 50% larger than any decade-long cluster of eruptions since 800 CE. North of 30° they were 1.5 times stronger than the combined effects of the large 1809 unknown eruption and 1815 Tambora event (see Chap. 35).[6]

The exceptionality and severity of the downturn are well established. Yet, despite the prominence assigned to the event in "old" and recent paleoclimate studies, it is important to stress that our understanding of it will continue to evolve as more paleoclimate data emerges, existing data is perfected, and the techniques of climate reconstruction continue to develop.[7]

The 536–50 anomaly has attracted a diverse set of scholars. Some are predisposed to assign the downturn considerable historical agency, others not. Often, these differences reflect more the intellectual background from which they have arisen than the current state of knowledge about the downturn itself.[8] Paleoclimatologists, anthropologists, archaeologists, geographers, and popular historians who prioritize paleoclimate data and presume that premoderns were weak and rigid in the face of abrupt environmental change have adopted maximalist interpretations, leaning toward or embracing catastrophism and determinism. Minimalist interpretations, less numerous, are mostly limited to humanists who are shy of natural proxies and tend to write nature out of history.[9] So, at one extreme, the downturn has been privileged as an "epoch-making disaster" and "the real beginning of the modern world," and at the other, it has been disparaged as the "latest Great Disaster theory" and a demographically "marginal event."[10] Moderatist stances acknowledge the anomaly's extent and severity but emphasize its limited duration and the resilience of contemporaries.[11]

This chapter surveys the evolution of research on the 536–50 downturn from the early 1980s to 2016. It presents the written evidence for climatic anomalies over the Mediterranean alongside the ever-growing wealth of relevant ice core and tree ring scholarship, and it highlights changes in reconstruction and interpretation as scholars reworked old data and injected new data. Judgments about its long-term historical significance are mentioned but not assessed: there is space here neither to support nor to refute the numerous roles that this downturn has been assigned.

In line with current evidence, the chapter concludes that the anomaly was a discontinuous complex of phenomena whose effects were extreme but varied across space and time. A cluster of very large volcanic eruptions triggered exceptional cooling and possibly drought across several parts of the globe. This was not simply a "536 event." It was a decade and a half of marked cold, with summer lows around 536, 540–1, and 545–6. It is a testament to advances in paleoclimatology that we must speak now of a fifteen-year anomaly as opposed to an episode of twelve or eighteen months' duration. This volcanic climate forcing led, via its effects on food production, to a pronounced but short-term demographic contraction in several regions of the world. Although most assessments of the downturn privilege written sources for dust veiling around the Mediterranean—the so-called 536 "mystery cloud"—that clouding was but one component of the event. In fact, its centrality to an explanation of the multiple temperature plunges registered in the world's trees or the violent volcanism catalogued in ice between 535 and 550 is debatable.

32.2 Texts

Five contemporary and independent accounts of the dimming of the sun around 536 survive from the Mediterranean region. Four were fundamental to the original formulation of the 536–50 downturn in the early 1980s; all five have underpinned reconstructions and histories of the event since 1988.[12] The scholar Procopius—who spent 536 in Italy, Tunisia, and possibly Turkey, and 537 in Italy alone[13]—observes in his lengthy history of Justinian's wars that in 536/7 "the sun gave forth its light without brightness, like the moon, during this whole year." He continues, "it seemed exceedingly like the sun in eclipse, for the beams it shed were not clear nor such as it is accustomed to shed."[14] Similarly, but from Rome, the senator and consul Cassiodorus, in a letter to his deputy variously dated to late 536, 537, or mid-538, speaks of the dimming of the moon and of the sun having lost its "wonted light" and appearing "bluish" as if in "transitory eclipse throughout the whole year" without the might to produce shadows at noon. He writes of "strange" weather with, as he puts it, "a winter without storms, a spring without mildness and a summer without heat." In short, it was unusually cold and dry with a "prolonged frost and unseasonable drought."[15] The Constantinopolitan administrator John the Lydian in his work on signs and portents written in the early 540s reports the sun dimming "for nearly a whole year" in 535/6, although it has been suggested this date is a simple mistake for 536/7.[16]

The churchman John of Ephesus, who lived in southeastern Turkey (Amida) and traveled much before settling in Constantinople in the early 540s, also describes the event in the second section of his ecclesiastical history which survives in the third part of the late eighth-century compilation of the so-called Pseudo-Dionysius, a chronicler of the Zuqnin Monastery near Amida. In this work, the sun is documented as "covered with darkness" for eighteen months in 530/1, and the sun's rays visible for only two or three hours a day "as if diseased."[17] The twelfth-century chronicle of Syriac Patriarch Michael the Great, which made use of this text, includes a nearly identical passage, although the daily sunlight is stretched to four hours and the date is corrected to 536/7, presumably to John's original.[18] Lastly, the so-called Pseudo-Zachariah Rhetor, a Syrian monk who likely compiled his history in the third quarter of the sixth century somewhere in southeastern Turkey (probably also Amida), observes the darkening of the sun and moon from March 24, 536 to June 24, 537: "the sun began to become dark at daytime and the moon by night."[19] He also refers then to the Mediterranean in an "awkward phrase" usually translated as "stormy with spray"[20] but which could be read instead as "clouded by moisture" or "confused by wet clouds."[21] Pseudo-Zachariah as well notes that the 536–7 winter in Syria was severely cold and unusually snowy, causing birds to die.[22] Other texts document difficult weather at the time but not veiling. Notably, Marcellinus Comes' Constantinopolitan continuator remarks that 536 saw "excessive drought" that destroyed western Asian pastureland and forced the migration of 15,000 people from modern-day Iran to Syria.[23]

These accounts, truncated as such, have been taken "as is" with few qualms. The exception is John the Lydian's passage, which Arjava demonstrated was often read too selectively.[24] Unlike the other sources, this John offered an explanation and range of the sun's dimming.[25] The sun became dim, he writes, "because the air is dense from rising moisture." This moisture "evaporated and gathered into clouds dimming the light of the sun so that it did not come into our sight or pierce this dense substance." John also tells us the aqueous phenomenon was European in scope; Persia and India, he specifies, were not affected.[26] As discussed below (see Sect. 32.7 "Collapse and Resilience"), Arjava employs John's remarks, alongside Pseudo-Zachariah's vague comments about a stormy or cloud-covered Mediterranean, to argue that mystery clouding was circumscribed, tropospheric (that is, in the lower atmosphere), and not volcanic in origin.

But just how much should we make of John's interpretation? The Byzantine may have been well informed about current events in Persia but likely not in India,[27] and he was present in neither to witness clear skies firsthand. He may also spare Persia and India sun dimming since he conceived of them as being dry, or at least drier than Mediterranean Eurasia: "India and the Persian realm and whatever dry land lies toward the rising sun were not troubled at all." In any case, his understanding of the cause of the sun's dimming, whether his own or another's,[28] need not be accurate.

There is then the East Asian evidence, which requires closer attention than it has been given or can be given here. In the eastern region between the Yangtze and Yellow Rivers, for example, there are reports of drought, early frost, and snow in 536, and then very unusual summertime cold, frost, and snow in 537. Particularly adverse conditions are reported in 536 for Ching state, south of Shandong peninsula. The eighteenth-century encyclopedic compilation, *Gujin Tushu Jicheng*, contains references to a dire drought in 537 in Gansu, Henan, Shanxi, and Xi'an provinces. There is also a hint of atmospheric clouding, since sources from southern China report that Canopus, the second brightest star, could not be seen at either the spring or fall 536 equinoxes. Additionally, the early seventh-century *Nanshi* chronicle refers to "yellow dust" that "fell like snow" in 536 and 537. In the latter year, it "filled scoops when picked up." The dust was almost certainly Gobi sand (not volcanic ash), but this signals that 536 and 537 were unusually dry.[29] Further droughts are cited in 542, 543, 547, and 550.[30]

In the Japanese *Nihon Shoki*, likely compiled between 681 and 720 from earlier sources, there is a brief mention of people "starving of cold" and hunger in summer 536. It also includes references to the necessity of public granaries in "preparation for evil years," grain distribution to regions underserved by granaries, and the construction of new granaries to deal with "extraordinary occasions."[31] The thin *Silla Annals* of Korea's Samguk Sagi, from the southeast of the peninsula, record the winter blossoming of peach and plum trees in 540, and (presumably extraordinary) snowfall in spring 541, but nothing else potentially relevant for the years 535–50.[32] The *Koguryo Annals* of the Samguk Sagi, which concern a large region on either side of the Yula and Tumen Rivers, report this unusual blooming but not the snowfall. Importantly, this text observes in 536 that "due to a severe drought during the spring and summer officials were dispatched to relieve the suffering of the people." Following this drought, and a plague of locusts, there was famine in 537.[33]

Read separately or together, these passages suggest something atmospherically and climatologically unusual during and after 536. It is hardly clear, however, whether the Mediterranean clouding was linked to events reported in China, Korea, or Japan, or to European accounts of food shortage addressed below. From the written sources alone, it remains altogether unknown whether sun veiling extended far beyond Byzantine territories. Yet support for vast volcanic dust veils and climatic impacts emerges when the written evidence is combined with high-resolution tree ring-based indices for sixth-century temperature and precipitation.

32.3 Tree Rings

Multiple dendroclimatological studies identify an unusually cold-dry anomaly between 536 and 550. Some studies consider several indicators of temperature and precipitation, including tree ring width (TRW), maximum latewood density (MXD), cell wall thickness, and the variability of stable carbon and oxygen isotopes ($\delta^{13}C$ and $\delta^{18}O$). Tree ring-based climate reconstructions have commonly isolated 536–50 as one of the coldest periods of the last several millennia. Many of these studies find temperature declines of 1.5–4 °C below their referenced instrumental series for one or more years of the downturn. Thin growth rings as well as one or more rare frost rings, which indicate growing-season freezing, are not uncommon across the roughly fifteen-year period. Such poor growth is often related to impacts of major volcanic eruptions on climate and associated sudden drops in temperature.[34] Mature trees at high altitudes or high latitudes archive these drops best. Low elevations specimens, in contrast, speak to precipitation. Relevant dendroclimatology has emerged at a rapid rate and has revealed a severity and abruptness lost in lower-resolution climate proxies. High-resolution tree ring studies illustrate that the downturn exceeds the magnitude and the temporal and spatial scope of the anomaly suggested in the written evidence.

Too many relevant tree-based studies have appeared to discuss them individually here. Table 32.1 summarizes twenty-eight of these publications. The vast majority survey thousands of years of climate and simply mention (or depict) the 536–50 downturn as a truly extraordinary but brief climate departure. Baillie authored the first studies to integrate tree ring data into the discussion of a 536 event (5). In his 1991 and 1994 papers, he drew on published tree ring material concerning northern Sweden and California (1, 3). He also introduced an unpublished TRW series of bristlecone pines from Nevada that showed exceptionally poor growth in the late 530s and 540s—with nadirs at 536–7, 540–1, 546–7, and 552–3—and compiled a composite of fifteen oak TRW series from England, Ireland, Germany, and Scotland that revealed 536–50 as an extreme trough, with lows at 536 and 540–1 and recovery in 537–8 and 546–7. In Irish oaks, 540 was identified as the worst growing year of the last several millennia.

Baillie's work has been confirmed repeatedly in reassessments of European and US data and in new series from these and other regions. The 536–50 cooling stands out in 1500- and even 7500-year-long chronologies. Multiple and varied analyses of all but two of the more than ten tree ring series encompassing the downturn show it as an exceptionally pronounced period of temperature and/or precipitation anomaly.

Naturally, there is some variation among chronologies and analyses. Most series (about 85% of those in Table 32.1) are chiefly temperature sensitive. A few (e.g., 12, 14, 20, and 24–25—three of which come from Qinghai Province, China) specifically concern precipitation, and neither the degree of deviation nor the years identified as most extreme are always the same. Most studies consider TRW alone. One recent study (24), however, demonstrates the array of measurable parameters. Ring width, cell-wall thickness, and cellulose $\delta^{13}C$ and $\delta^{18}O$ were assessed with specific attention to the 530s and 540s in three multi-millennial larch series from Russia's northern Krasnoyarsk Krai, northeastern Sakha Republic, and Altai Republic. TRW minima were established in the northerly Krasnoyarsk and Sakha chronologies at 536 and 541, and in the high-altitude Altai chronology at 536 and 539. Exceptionally thin cell walls were visible in the Sakha series at 536 and 541 and in the Altai series at 536 and 537. Cell-damaged frost rings could be seen in the latter at 536, 537, and 538. Pronounced $\delta^{13}C$ declines, telling of a cold but moist growing season, were visible at 536 in the Krasnoyarsk and Sakha series. Krasnoyarsk $\delta^{13}C$ values remained low until the 550s, with a 538 minimum, while Sakha values showed respite at 537 and another plunge at 541. Altai $\delta^{13}C$ values hardly varied. Exceptionally diminished $\delta^{18}O$ values were uncovered at 536 in the Altai series, indicating a very cold growing season, but $\delta^{18}O$ remained steady at Krasnoyarsk and Sakha. Taken together, this data indicates multiple unusually short growing seasons during the downturn and June–July temperatures dipping well below the referenced instrumental series (by up to 4 °C in the Altai series).[35]

One explanation for the variation in the years of extreme temperature departures is that TRW is less sensitive than MXD to sudden cooling and TRW may give an extended response to cold events.[36] Furthermore, not all tree species respond equally to climatic phenomena, and high-latitude chronologies—as opposed to high-altitude ones—seem to give a sharper and lagged response to sudden cooling.[37] Still, in all but two studies surveyed (3, 24), 536 marks the downturn's onset.[38] One study of pines from Finland (8) illustrates in particular how abrupt the event could be. The series identifies the July of 535 as the warmest of the last 7500 years and the 535–6 interannual transition as the second most extreme since at least 5520–5519 BCE. There is also some discrepancy regarding moisture. While the northern Siberian Krasnoyarsk and Sakha chronologies (24) register cold-wet conditions, Central European and central Chinese series (12, 14, 20, 25) tell of a cold-dry downturn.

Two other growth minima center around 540–1 and 545–6 CE. In multiple series, many of the intervening and subsequent years show growth minima as well: notably 537, 539, 541, 542, 543, 544, 547, and 549. Some studies

Table 32.1 Twenty-eight dendroclimatological studies (1990–2015) relevant to the 536–50 downturn

	Location	*Span*	*Parameter*	*Observations*
1	Sweden, Norrbotten County	500 CE–1980 CE	TRW, MXD	April–August 536 5th coldest in series, 1.5 °C below SIM; summer cold trough late 530s & early 540s.
2	Sweden, Norrbotten County	500 CE–1980 CE	MXD	July–August 536 2nd coldest in series at 2 °C below SIM; multiyear cold period around 540.
3	USA, California State	1 CE–1980 CE	TRW	June–January 536, 535, 541 2nd, 3rd & 4th coldest, 3.13 °C, 3.07 °C & 2.93 °C below SIM; 542–61 coldest 20-year stretch, 1.95 °C below SIM.
4	Chile, Los Lagos Region	1634 BCE–1987 CE	TRW	Extreme poor-growth period (December–March temperatures) *c*. 540.
5	Composite European Series & USA, Nevada	See text	TRW	See text.
6	Mongolia, Zavkhan Province	262 CE–1999 CE	TRW, MXD	Frost rings, MXD evidence exceptional cold at 536; TRW evidence, August–July temperatures, 536–45 cold trough, nadirs at 536 & 543; TRW minimum at 543; respite 538.
7	Russia, northern Krasnoyarsk Krai	212 BCE–1996 CE	TRW	June–July 536 4th coldest in series (estimated at 3.5 °C compared to average instrumental observation period (1933–89) temperature of 9.6 °C); 533–52 3rd coldest 20-year period in series.
8	Finland, Lapland Regions	5520 BCE–1999 CE	TRW	July 536 1.78 °C below SIM; 541–50 4th coldest non-overlapping 10-year period, 1.17 below SIM; 542–51 coldest decade of last 4000 years, 1.33 below SIM; July 535 warmest, 6.17 °C above SIM; 535–6 2nd most extreme interannual fluctuation.
9	Sweden, Norrbotten County	5407 BCE–1997 CE	TRW	Severely cold June–Augusts around 540; multiple frost rings & TRW minima; 1 of 6 coldest short periods in series.
10	Russia, north Krasnoyarsk Krai	431 BCE–1996 CE	TRW	June–July 536 5th coldest in series (estimated at 3.7 °C compared to average instrumental observation period (1933–89) temperature of 9.6 °C, or 2.8 °C below SIM); cold trough spanning late 530s & 540s.
11	Sweden, Norrbotten County	5407 BCE–1997 CE	TRW	Exceptionally cold June–Augusts between 536 and 553; lows at 536, 542, 544–5, & 550.
12	China, Qinghai Province	326 BCE–2000 CE	TRW	536 first year of decade plus of low May–June precipitation.

(*continued*)

Table 32.1 (continued)

	Location	*Span*	*Parameter*	*Observations*
13	Sweden, Jämtland County	2893 BCE–1998 CE	TRW	Several very low summer temperatures between 536 & 550; minima at 536, 539, 542, & 544.
14	China, Qinghai Province	515 BCE–2000 CE	TRW	Several years (July–Junes) of very low precipitation in 530s & 540s.
15	USA, Arizona State	266 BCE–1997 CE	TRW	534–43 6th coldest ‘short period’ in series at 1.34 °C below SIM.
16	Norway, Troms County	320 CE–1994 CE	TRW	Exceptionally low July temperatures in mid 530s–540s, some of the deepest plunges in series.
17	Austria, Tyrol State	5125 BCE–2000 CE	TRW	Trough of cold May–Septembers 536–52; lows at 545 & 549.
18	USA, Arizona, California, Nevada	3000 BCE–2002 CE	TRW	Remarkably cold ‘warm seasons’ in 536, 537, 541, 542, 543, 545, & 547; cold trough 536–47; frost rings 536 & 541; 2/5 sixth-century frost rings & 6/7 sixth-century ring-width minima took place between 536 and 550.
19	Sweden, Norrbotten County	500 CE–2004 CE	TRW, MXD	Sharply cold April–Augusts in mid 530s & 540s; multiple lows in range of 2 °C below SIM.
20	Central European Composite Series	500 BCE–2000 CE	TRW	Dry April–Junes in northeast France, northeast & southeast Germany & cold June–Augusts in Austrian Alps; cold-dry lows *c.* 537, 542, 545, & 550.
21	Finland, Lapland Region	5500 BCE–2000 CE	TRW	536 one of the five coldest Julys in series at more than 3 °C below SIM; summer 542 nearly as cold.
22	Sweden, Norrbotten County	500 CE–2008 CE	TRW, MXD	Several sharply cold May–Augusts mid 530s & 540s; lows 536, 542, & 545. 1 of coldest short periods in TRD and MXD series.
23	Sweden, Norrbotten County & Finland, Lapland Region	5510 BCE–1999 CE TRW, 1 CE–1997 CE MXD	TRW, MXD	Summer 542 2nd coldest over last 2000 years in TRW & MXD series, 5th coldest in TRW series; summer 536 less frigid, 36th in TRW series; yet 536 1 of 10 coldest years 1–1000 CE in MXD series.
24	Russia, north Krasnoyarsk Krai, northeastern Sakha Republic, Altai Republic	See text	TRW, MXD, CWT, $\delta^{13}C$, $\delta^{18}O$	See text.
25	China, Qinghai Province	2637 BCE–2011 CE	TRW	Extremely dry July–Junes mid 530s & 540s; follows drier short periods in late 300s & late 400s; last short dry period for 600 years.
26	USA, California, Nevada	2575 BCE–2006 CE	TRW	Exceptionally cold July–Septembers mid 530s & 540s.
27	Austria, Upper Austria State	88 CE–2008 CE	MXD	Sharply cold July–Septembers around 540; especially light ring at 536.

(*continued*)

Table 32.1 (continued)

	Location	*Span*	*Parameter*	*Observations*
28	Composite European Series (ES), Composite Northern Hemispheric Series (NS)	1 CE–2000 CE (ES), 500 BCE–2000 CE (NS)	TRW, MXD	1.6 < 2.5 °C drop June–August 536, 1.4 < 2.7 °C drop June–August 541, against preceding 30 years in ES with lows at 536, 541, 543, 544, 545, 546, 549; in ES 536–40 2nd coldest run of June–Augusts; in NS 535–50 has 6 of 13 strongest tree-growth reductions 500 BCE–1250 CE & 536–45 strongest decade-long tree-growth reduction (coldest decade) 500 BCE–2000 CE; 536–45 & 546–55 2 of 10 coldest decades in NS.

TRW = Tree-Ring Width; MXD = Maximum Latewood Density; CWT = Cell Wall Thickness; $\delta^{13}C$ = Stable Carbon Isotope; $\delta^{18}O$ = Stable Oxygen Isotope; SIM = Series Instrumental Mean. **1** K. Briffa et al., “A 1400-Year Tree-Ring Record of Summer Temperatures in Fennoscandia,” Nature 346 (1990), pp. 437 (Fig. 2), 439. **2** K. Briffa et al., “Fennoscandian Summers from AD 500: Temperature Changes on Short and Long Time Scales,” Climate Dynamics 7 (1992), pp. 116 (Fig. 8), 117. **3** L. Scuderi, “A 2000-Year Tree Ring Record of Annual Temperatures in the Sierra Nevada Mountains,” Science 259 (1993), p. 1435. **4** A. Lara and R. Villalba, “A 3620-Year Temperature Record from *Fitzroya cupressoides* Tree Rings in Southern South America,” Science 260 (1993), p. 1106 (Fig. 3); Cf. R. Villalba, “Interdecadal Climatic Variations in Millennial Temperature Reconstructions from Southern South America,” in P. Jones et al., eds., Climatic Variations and Forcing Mechanisms of the Last 2000 Years (Springer, Berlin, 1996), pp. 164 (Fig. 1), 170 (Fig. 5). **5** M. Baillie, “Marking in Marker Dates: Toward an Archaeology with Historical Precision,” World Archaeology 23 (1991), pp. 233–238; idem, “Dendrochronology Raises Questions about the Nature of the AD 536 Dust-Veil Event,” The Holocene 4 (1994), pp. 213–15. **6** R. D’Arrigo et al., “Spatial Response to Major Volcanic Events In or About 536, 934 and 1258: Frost Rings and other Dendrochronological Evidence from Mongolia and Northern Siberia,” Climatic Change 49 (2001), pp. 241–42; R. D’Arrigo et al., “1738 Years of Mongolian Temperature Variability Inferred from a Tree-Ring Width Chronology of Siberian Pine,” Geophysical Research Letters 28 (2001), pp. 544–45. **7** M. Naurzbaev and E. Vaganov, “Variation of Early Summer and Annual Temperature in East Taymir and Putoran (Siberia) over the Last Two Millennia Inferred from Tree Rings,” Journal of Geophysical Research 105 (2000), p. 7324. **8** S. Helama et al., “The Supra-Long Scots Pine Tree-Ring Record for Finnish Lapland: Part 2, Interannual to Centennial Variability in Summer Temperatures in 7500 Years,” The Holocene 12 (2002), pp. 683 (Table 3), 685 (Table 4), 686. **9** H. Grudd et al., “A 7400-Year Tree-Ring Chronology in Northern Swedish Lapland: Natural Climatic Variability Expressed on Annual to Millennial Timescales,” The Holocene 12 (2002), p. 663. **10** M. Naurzbeav et al., “Summer Temperatures in Eastern Taimyr Inferred from a 2427-year Late-Holocene Tree Ring Chronology and Earlier Floating Series,” The Holocene 12 (2002), pp. 732, 734 (Table 4). **11** H. Grudd, “A 7400-Year Tree-Ring Chronology in Northern Swedish Lapland: Natural Climatic Variability Expressed on Annual to Millennial Timescales,” The Holocene 12 (2002), p. 663; Larsen et al., “New Ice Core Evidence,” L04708 (Fig. 1). **12** Q. Zhang et al., “A 2326-Year Tree-Ring Record of Climate Variability of the Northeastern Qinghai-Tibetan Plateau,” Geophysical Research Letters 30 (2003), p. 1739 (Fig. 3); C. Zhang and Q. Zhang, “Is There a Link between the Rise and Fall of the Tuyuhun Tribe (Northwestern China) and Climatic Variations in the fourth–seventh centuries AD?” Journal of Arid Environments (2016), p. 148. **13** B. Gunnarson et al., “Holocene Humidity Fluctuations in Sweden Inferred from Dendrochronology and Peat Stratigraphy,” Boreas 32 (2003), pp. 348–49, 351–52, 355–56; Larsen et al., “New Ice Core Evidence,” L04708 (Fig. 1). **14** P. Sheppard et al., “Annual Precipitation Since 515 BC Reconstructed from Living and Fossil Juniper Growth of Northeastern Qinghai Province, China,” Climate Dynamics 23 (2004), p. 876. **15** M. Salzer and K. Kipfmueller, “Reconstructed. Temperature and Precipitation on a Millennial Timescale from Tree-Rings in the Southern Colorado Plateau, USA,” Climatic Change 70 (2005), pp. 473 (Fig. 4), 476 (Table IV). **16** A. Kirchhefer, “A Discontinuous Tree-Ring Record AD 320–1994 from Dividalen, Norway: Inferences Climate and Tree-Line History,” in Mountain Ecosystems:

(*continued*)

Table 32.1 (continued)

Studies on Tree Line Ecology, eds. G. Brill and B. Keplin (Berlin, 2005), p. 225. Though this chronology stretches back to 320, detailed analysis is presented only for 587–980 and 1507–1993 and the severity of the downturn has to be inferred from Fig. 3. **17** K. Nicolussi et al., "Holocene Tree-Line Variability in the Kauner Valley, Central Eastern Alps, Indicated by Dendrochronological Analysis of Living Trees and Subfossil Logs," Vegetation History and Archaeobotany 14 (2005), pp. 221–34; Larsen et al., "New Ice Core Evidence," L04708 (Fig. 1). **18** M. Salzer and M. Hughes, "Bristlecone Pine Tree Rings and Volcanic Eruptions Over the Last 5000 yr," Quaternary Research 67 (2007), pp. 62 (Table 2), 63 (Table 4), 65 (Table 6), 66. **19** H. Grudd, "Torneträsk Tree-Ring Width and Density AD 500–2004: A Test of Climatic Sensitivity and a New 1500-Year Reconstruction of North Fennoscandian Summers," Climate Dynamics 31 (2008), p. 853. **20** U. Büntgen et al., "2500 Years of European Climate Variability and Human Susceptibility," Science 331 (2011), pp. 580, 581 (Fig. 4); Kostick and Ludlow, "Dating of Volcanic Events," p. 16 (Fig. 1). **21** S. Helama et al., "A Chronology of Climatic Downturns through the Mid- and Late-Holocene: Tracing the Distant Effects of Explosive Eruptions from Palaeoclimatic and Historical Evidence in Northern Europe," Polar Research 32 (2013), p. 15866 (Fig. 2). **22** T. Melvin et al., "Potential Bias in 'Updating' Tree-Ring Chronologies Using Regional Curve Standardisation: Re-Processing 1500 Years of Torneträsk Density and Ring-Width Data," The Holocene (2013), p. 371 (Fig. 5). **23** P. Jones, "Cool North European Summers and Possible Links to Explosive Volcanic Eruptions," Journal of Geophysical Research: Atmospheres 118 (2013), p. 6263. **24** O. Churakova et al., "A Cluster of Stratospheric Volcanic Eruptions in the AD 530s Recorded in Siberian Tree Rings," Global and Planetary Change 122 (2014), pp. 145–49; O. Churakova et al., "Siberian Trees: Eyewitnesses to the Volcanic Event of AD 536," Pages Magazine 23 (2015), pp. 64–65. **25** B. Yang, "A 3500-Year Tree-Ring Record of Annual Precipitation on the Northeastern Tibetan Plateau," PNAS 111 (2014), p. 2906. **26** M. Salzer et al., "Five Millennia of Palaeotemperature from Tree-Rings in the Great Basin, USA," Climate Dynamics 42 (2014), p. 1524 (Fig. 6). **27** M. Klusek et al., "Multi-Century Long Density Chronology of Living and Sub-Fossil Trees from Lake Schwarzensee, Austria," Dendrochronologia 33 (2015), pp. 46 (Fig. 4), 47. **28** M. Sigl et al., "Timing and Climate Forcing of Volcanic Eruptions for the Past 2500 Years," Nature 523 (2015), pp. 547–48, Extended Data Table 5 (e.g., 28) identify another low in the early 550s. The year 538 is a "respite" or good growth year in most (but not all) studies; and some chronologies identify respites in 537, 542–3, and 547–8. The cold trough of 536–50, then, represents a general and significant departure from normal temperature and—at least in western China, southern Russia, and Central Europe— from normal precipitation. It was not a period of consistent poor-growth conditions, but in the vast majority of dendroclimatological studies, it remains *one of* or *the* coldest short periods on record (see, for example, 3, 5, 6, 8, 9, 11, 13, 15, 17, 18, 20, 22, 24, 28). The tree ring-based Old World Drought Atlas, not included in Table 32.1, also demonstrates that climate forcing was not steady. Yet it does suggest that the downturn was by and large dry north of the Alps. The summers of 549 and 550 emerge as rather wet in the atlas, but those of 536, 538–41, 546, and 551 seem to have been very dry.[39] A 2015 study (28), using a composite northern hemispheric tree ring chronology spanning 500 BCE–2000 CE, established the consecutive decades of 536–45 and 546–55 as the first and tenth coldest decades in the series, respectively. The same trees also put six of the thirteen most significant tree-growth anomalies (coldest years) between 500 BCE and 1250 CE within the limits of the downturn. A forthcoming study reconfirms these findings.[40]

Of course, this dendroclimatology presents challenges. Most tree rings that provide a temperature signal come from high-altitude or high-latitude sites—that is, thinly populated regions far removed from written descriptions of dust veils and famines. Temperature signals obtained from trees are more homogenous than precipitation signals and can be regionally representative,[41] but there is a dearth of crop-level climate data. The climate signals obtained from trees reveal neither winter temperature nor winter precipitation but only growing-season conditions; yet winter precipitation is fundamental for food production in many parts of the world. Moreover, even though sulfates logged in Antarctic ice cores reveal that the downturn was at times global in scope, at least from 540 (see Sect. 32.5 "Ice Cores"), most of the proxy data comes from north of the Tropic of Cancer and is Eurasian in focus. The available South American dendroclimatology (4), which seems to register a temperature plunge about 540, does little to fill out the downturn's impacts in the Southern Hemisphere. Multimillennial Tasmanian and New Zealand TRW series indicative of November–April temperatures do not register significant or unusual downturn cold, though it has been suggested that they reflect volcanic climate forcing poorly.[42]

Finally, tree ring evidence cannot yet confirm the climate impacts of the Mediterranean mystery cloud described in Byzantine sources. There is still only one truly Mediterranean chronology spatially and temporally consistent with the documented veiling: a floating Constantinopolitan series thought to span 398–610 CE.[43] TRW analysis of that series, however, returned neither a severe 536–50 cold trough nor extreme lows at 536 or 540. Narrow but "non-anomalous" rings are apparent at 537 and 541. These results are not as surprising as they may seem. Low elevation, mid-latitude trees typically tell us about precipitation, not temperature. Rather than failing to indicate major post-eruption cooling, these rings may instead evidence some anomalous post-eruption dryness.[44] In any case, work remains to be done on this series. The authors observe that the date range of the series is not absolute; Aegean trees may experience better-than-average growing conditions in cold anomalies or, as is more likely, fail to register cold anomalies altogether; and this particular chronology may provide a microclimate signal rather than a "broader regional or hemispheric" one.[45] The tree ring series closest to the documented clouding that register the downturn temperature plunge come from the Alps (17, 20, 27–8).[46]

A vast array of tree ring graphs could be presented that demonstrate the abruptness and severity of 536–50 summer cooling. Figure 32.1 presents Christiansen and Ljungqvist's 2000-year-long multiproxy temperature reconstruction for the extratropical Northern Hemisphere (north of 30°) alongside the PAGES 2k Consortium's tree-based temperature reconstruction for Europe. Figure 32.2 presents sixth-century sections of these series as well as composite tree ring temperature reconstructions for Scandinavia and the Alps. The downturn registers clearly in all four series, but there are differences. The PAGES and Scandinavian reconstructions are rather choppy. The hemisphere-wide and Alpine series suggest more sustained low temperatures. In addition, they indicate that the downturn persisted well into the 550s.

32.4 Other Proxies

The fact that tree rings demonstrate a cold trough at the same time that written sources describe clouding and food shortages suggests but does not prove a link. Other archives—including cave formations (speleothems) and ice cores—can offer further information about global and local climate histories.

Studies of stable isotope variability in speleothems offer data on regional climates. Like trees, these cave formations can provide annually resolved proxies of past temperature and precipitation.[47] For example, studies of layer thickness in a speleothem outside Beijing, China, indicative of May–August temperature, and analysis of oxygen isotope variability in a Wanxiang Cave (Gansu, China) speleothem reflective of May–September precipitation, have turned up evidence of rapid climate change during the 530s and 540s. The latter shows a major $\delta^{18}O$ spike around 536, indicating the most sudden and severe drought conditions in the 1810-year chronology.[48] This speleothem may reveal the climate triggers of famine in eastern China in the 530s, as dendroclimatology may the triggers of famine in temperate Europe.

Many less-resolved climate proxies also reveal 536–50 cooling and drying. For instance, an analysis of ice accumulation and oxygen isotope variability in ice cored from Peru's Quelccaya glacier reveals a pronounced cold-dry period lasting about two decades around 540; dendrochronologically dated fossil wood demonstrates that Switzerland's Lower Grindelwald glacier advanced from 527 to 578; a study of alkenone in varved lake sediments in northeastern China shows a marked decline in spring-summer temperatures about 540; and an assessment

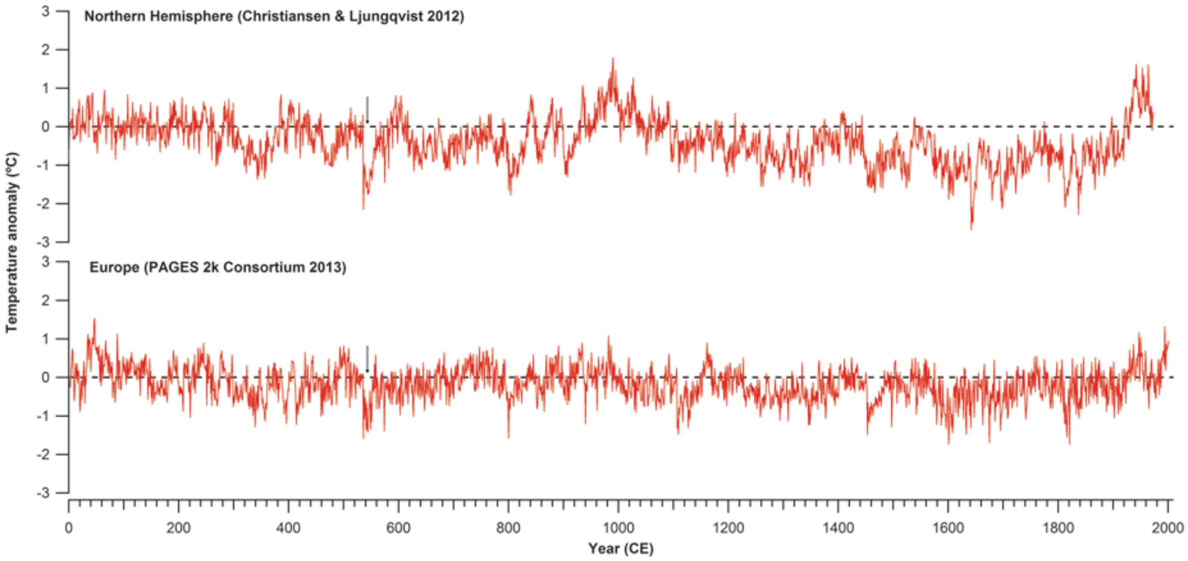

Fig. 32.1 Summer temperature anomalies for the past two millennia. Summer temperature anomalies noted by Christiansen and Ljungqvist (2012) are with respect to 1880–1960. The PAGES June–August temperature anomalies are relative to 1961–90. Five tree-based temperature reconstructions are rolled into the Scandinavian series and four into the Alpine series [the data comes from Büntgen and Tegel (2011)]. These European series reflect June–August temperature anomalies with respect to 1860–2004. The author thanks Ulf Büntgen for sharing this data and Inga Labuhn for drawing these graphs

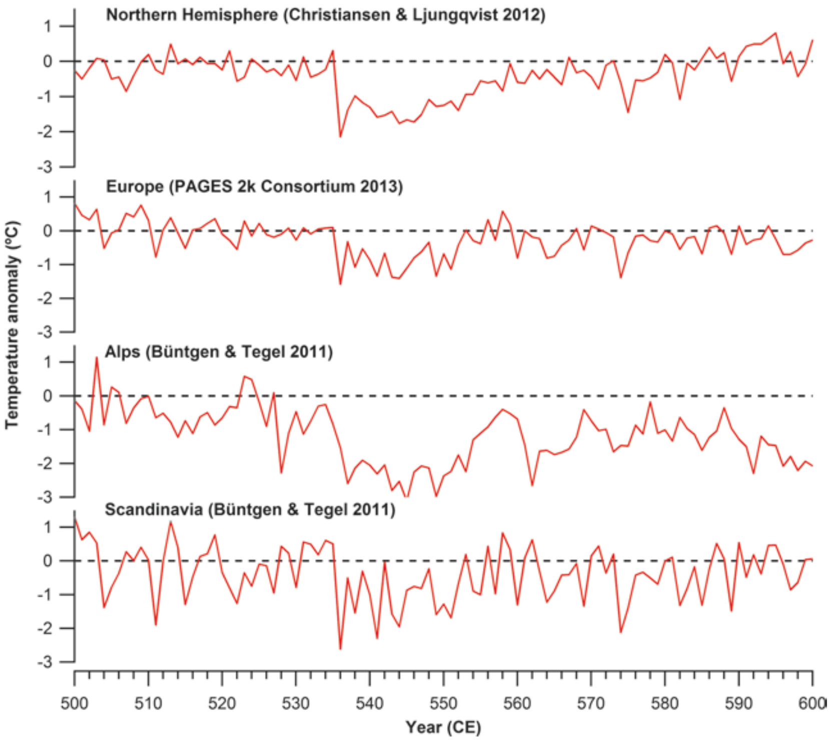

Fig. 32.2 Summer temperature anomalies 500–600 CE. Summer temperature anomalies noted by Christiansen and Ljungqvist (2012) are with respect to 1880–1960. The PAGES June–August temperature anomalies are relative to 1961–1990. Five tree-based temperature reconstructions are rolled into the Scandinavian series and four into the Alpine series [the data comes from Büntgen and Tegel (2011)]. These European series reflect June–August temperature anomalies with respect to 1860–2004. The author thanks Ulf Büntgen for sharing this data and Inga Labuhn for drawing these graphs

of water-table depths in Tierra del Fuego peat bogs roughly indicates a shift from drier to wetter conditions around 550.[49] There are also isotopic assessments of gases trapped in polar ice. For example, analysis of argon and nitrogen isotopes from the Central Greenland GISP2 core (resolved to about twenty years) established a sharp multiyear temperature drop around 540.[50] Although there are uncertainties, work on oxygen isotopes in Antarctic ice suggests that temperature did not fall much over the frozen continent in the mid-sixth century. In fact, it may have risen.[51]

Naturally, poorly resolved proxies are less valuable where high-resolution indices are already available. Nevertheless, in regions such as Central America—where many think the downturn hit hard—low-resolution proxies are all we have.[52] Paleoclimatology in this region has focused on climate trends underlying the so-called Maya classical collapse (750–1000). However, the Maya "hiatus"—a sharp break between the Early and Late Classical periods, spanning about 535–95—has not gone unnoticed. Archaeologically, the period saw a leveling off or decline in stelae and monumental building, and potentially population contraction and settlement desertion. Increasing $\delta^{18}O$ values in a sediment core taken from the Yucatán Peninsula's Punta Laguna in the mid-1990s indicate an "exceptionally arid event" at 585 ± 50 and a study of gypsum horizons in the sediment of neighboring Chichancanab Lake also seemed to reveal a hiatus-era drought about a decade long. Later studies, however, suggested that this drought was not dire.[53]

More recently, an annually resolved study of oxygen isotope variability in a Yucatán stalagmite turned up evidence of severe multiyear droughts (increased $\delta^{18}O$) in the early sixth century comparable to later "collapse"-era droughts. Yet the study fixed these droughts at 501–18 and 527–39, so predating the 536–50 downturn.[54] Analysis of a Belizean speleothem has also identified a drought around 517 (±0.5–3 years).[55] Considering the chronological uncertainties in these records, however, it remains possible that one or more of these arid intervals were linked to the eruption of 539/40. Less firmly dated evidence of sixth-century drought in Central America comes from $\delta^{18}O$ analysis of a roughly resolved sediment core from Guatemala's Salpetén Lake,[56] titanium in a marine core taken off the coast of Venezuela in the Cariaco Basin,[57] and analysis of plant δD in lacustrine cores from the Dominican Republic's Laguna Castilla.[58] Not all of these proxies necessarily reflect the 536–50 downturn. Higher-resolution indices that span the mid-sixth century are very much needed for this region.

32.5 Ice Cores

Assessment of sulfate in polar ice provided the first indications of a mid-sixth-century climate anomaly. While tree rings archive annual changes in growing-season climate, ice layers archive sulfate and tephra from large or local volcanic eruptions. Different dating methods have produced slightly different results for eruptions. Sulfuric acid aerosols are deposited as sulfates months and possibly years after eruptions. Evidence of massive tropical eruptions can appear at both poles.[59]

A study published in 1980 first identified an acid horizon from a major mid-sixth-century eruption in a south Greenlandic ice core, dated to 540 ± 10.[60] A similar horizon was identified at about 535 in the Greenlandic Dye-3 ice core two years later.[61] A few years after that, both of these signals were redated to around 516.[62] Volcanic acid layers subsequently emerged in the GISP2 core at 530 ± 2, in the GRIP core at around 527, and the Dye-3 core at around 530—all too early for the reported 536 clouding.[63] The GISP2 ice core section pertaining to the mid-500s (likely "from A.D. 620 to 545") was lost during retrieval and no relevant signal was detected for several years in other Greenlandic or Antarctic archives.[64]

Then studies in 2004 and 2007 found a major volcanic signal in the Antarctic Dronning Maud Land and Dome-C cores dated to 542 ± 1; and in 2008 Larsen and his team uncovered two significant signals in Dye-3, GRIP, and NGRIP Greenlandic cores at 529 ± 2 and 533/4 ± 2.[65] The latter, it was argued, related directly to the 536–50 climatic downturn. Following a comparison of sixth-and seventh-century volcanic horizons, this team proposed that Antarctic ice core dates be shifted back six years and Greenlandic dates up two to three years, meaning that an eruption possibly accountable for the 536 event would be evident in multiple cores at both poles. Only months later, however, dendrochronologist Baillie proposed that the dates of these newly detected acidities be bumped up six or seven years, which would put major eruptions at around 535 and 539. These eruptions could explain the Mediterranean clouding and the poor growth registered in trees around 536 and 540.[66]

This redating was not immediately accepted. A 2011 study of a new South Pole core dated an "unusually large" eruption to 531 ± 15; and a 2012 study found a major volcanic signal in an East Antarctic core and finely dated it, via the counting of annual ice layers, to late 531.[67] The authors of the first study proposed that a single large eruption was behind their strong 531 ± 15 signal and the 542 ± 17 Antarctic signal identified in 2004, but they wagered that the source event occurred about 535 rather than 539 (the pull of Mediterranean clouding was stronger it seems than narrow tree rings at 540–1). The authors of the latter study agreed that the Greenlandic and Antarctic signals at 533 and 542 referred to a signal episode, as Larsen proposed, but they fixed it a date of 531–3—which meant it could no longer explain either the clouding of 536–7 or the thin tree rings of 540–1.

Then in 2013–15, several studies came out refining both the dating and scale of eruptions identified in ice cores. The first of these found both of Larsen's large eruptions, at around 529 and 534, in new ice cores from Greenland and Antarctica.[68] The second, using additional Antarctic cores, found signals at 543 ± 17 and 515 ± 18 and tied them to Larsen's Greenlandic horizon of 533/4 ± 2 and the 536 event.[69] Another 2014 paper, combining a reappraisal/redating of multiple existing Antarctic cores with several new and existing ones, identified an eruption at 531 as a bipolar "global-scale" event, and the fifth-largest eruption of the last 2000 years—big, but a not insignificant demotion.[70] A 2015 analysis of several Greenlandic cores, which employed Baillie's six- to seven-year bump, then found large sulfate horizons at 535/6 and 539/40. It located the second, but not the first, of these eruptions in Antarctic cores.[71] Most recently, glacier ice from the Western Belukha Plateau in Siberia's Altai Mountains was shown to contain high sulfate levels rather roughly dated at 520 ± 100, 540 ± 100 and 550 ± 10, one of which was assigned to the 536 event. Study of the oxygen isotope variability in this core, indicative of seasonal air temperature, also suggested that the most prominent of these signals was associated with some of the coldest temperatures (lowest δ^{18}O) of the first millennium CE in the region.[72]

32.6 Origins

Soon after a major mid-sixth century eruption was detected in Greenland ice, scholars turned to Byzantine writers to fill out the details of an important climatic event.[73] Once they had connected the acid horizons in ice cores and the narrow and frosty tree rings to historical descriptions of mystery clouding, natural scientists essentially concluded that the phenomenon was volcanic in origin, extended far beyond the Mediterranean Sea, and had an extra-Mediterranean source.

Large, violent volcanic eruptions can inject tens of millions of tons of ash, hydrochloric acid, and sulfur dioxide into the atmosphere. The first and second fall to earth within weeks. The sulfur dioxide, however, mixes with water in the atmosphere to produce fine sulfuric acid aerosols. If these reach the stratosphere, they can dim incoming sunlight on a hemispheric or even global scale for multiple years. In the stratosphere, sulfuric acid aerosols absorb and backscatter solar radiation, warming the stratosphere's temperature but lowering that of the earth's surface. Recent eruptions, far less explosive than those during the downturn, are known to have lowered global temperatures by 0.1–0.4 °C for upwards of three years, with more dramatic cooling in the first three months where veiling was densest. At the height of the 1991 Pinatubo event, a downturn of 1.3 °C was observed instrumentally.[74] The 1815 Tambora eruption—still smaller in most proxies than the sixth-century volcanism—is thought now to have lowered temperatures by upwards of 4 °C (see Chap. 35).[75]

Various volcanoes have been blamed for mid-sixth-century cooling. The first proposed, in 1980, was Mount Churchill, Alaska, whose eruption had been radiocarbon dated to around 700 ± 100.[76] This possibility was dismissed shortly thereafter for an eruption at Rabaul, Papua New Guinea, then radiocarbon dated to 1430–1390 BP and dated, by Stothers, to 540 ± 90.[77] Rabaul was soon rejected, too, in favor of a Northern Hemisphere eruption: in 1986, an Antarctic ice core had emerged showing a horizon only at around 505 and it was surmised that the clouding around 536 originated north of the equator, though by then the ice core signals for a big event in the mid-530s had been redated.[78] Following the 2004 detection of a large volcanic episode in Antarctic ice, Rabaul was reproposed as the source of the downturn; however, subsequent studies of the eruption site reassigned Rabaul's eruption to the seventh century (first to around 633–70, then around 667–99), taking it once more out of contention.[79] In his popular history, *Catastrophe*, Keys assigned the cooling to a super-eruption at Indonesia's Krakatau, which he thought severed Sumatra and Java.[80] This proposal gained little currency.

In any case, a single massive eruption could not account for more than a decade of cooling, as paleoclimatologists have now long acknowledged. Moreover, as the trees tell us, the cold was not constant. Recent assessments of polar ice affirm that multiple unique sources underlay the downturn, including a cluster of large eruptions; the first two, and the largest, occurred at 535/6 and 539/40.[81] The record of sulfates in Arctic and Antarctic ice firmly places the first eruption in the Northern Hemisphere, quite possibly at high latitudes, and the second in the tropics.[82] Additional downturn volcanism, smaller but still large, around 545/6 and 550/1, has attracted less attention.[83] The ice core records strongly suggest that the downturn only became global with the eruption at about 540. Indeed, while the eruption of around 536 left a big mark on Greenlandic ice, it is, so far, only faintly visible in Antarctica in the West Antarctic Ice Sheet core. The follow-up 540 eruption is very visible in both Antarctic and Greenlandic ice. Recent work on sulfur isotopes, using samples from the Greenlandic Tunu13 core, confirms that eruptions both around 536 and around 540 were stratospheric, that the former was high-latitude Northern Hemispheric, and that the latter was near equatorial.[84]

Tephra and palynological studies led, in 2009, to the dating of a major explosive event at Mexico's El Chichón to the early sixth century. This event, fixed at 550–650 in 1984 and 553–614 in 2000,[85] was proposed to have occurred precisely in 539, following the dendroclimatological data for severe cooling about 540—rather than reports of mystery clouding, which the authors suggest was sourced by a local tropospheric Mediterranean eruption.[86] A year later, it was argued, Ilopango, El Salvador, was the source of dark Mediterranean skies in 536. A reappraisal of physical evidence for Ilopango's Tierra Blanca Joven (TBJ) eruption, considered the largest Central American volcanic event of the last 84,000 years, moved the episode's date up from 260 ± 114 to 495 ± 55, and a fragment of a tree carbonized in the TBJ event was given a date consistent with 535, making Ilopango a very good fit.[87] However, the more recent finding that the second major eruption of the downturn (*c.* 540) was near the equator, unlike the first atmospheric-clouding event, has led one team of scholars to bump Ilopango to 539/40.[88] A separate study concluded that an eruption site at about 15°N best matched the distribution of the remnants of volcanism found in polar ice at 540.[89] Ilopango sits at 13.67°N and El Chichón at 17.21°N. Another possibility raised for the northern high-latitude eruption that initiated the downturn is Haruna, Japan.[90] The major Plinian eruption of this mountain, northwest of Tokyo, has been dated archaeologically to the mid-500s.[91] If Haruna erupted in about 536, detailed analysis of tephra lodged at the 535–6 mark of Greenland's NEEM core, still in part being worked on, suggests that it was not alone. This work finds that there were multiple eruptions around 535. Although it is uncertain how many of these events were stratospheric, the tephra implies several North American sources, casting doubt on Haruna's role.[92] North American or not, the ice core data concurs that a large eruption of 535/36 was Northern Hemispheric and mid-latitude.[93]

The veiling observed over the Mediterranean in 536 and the global cooling registered in tree rings could have different origins. Silence in other European texts,[94] and the absence of severe cold at 536 in the Constantinopolitan tree ring chronology (assuming those trees register cold events, which they very well may not), both suggest that the observed veiling may have been temporally and spatially limited.[95] In his 2005 analysis of the literary sources, Arjava argued that Mediterranean observations of veiling only testify to an affected zone north of 35° or 40°.[96] Earlier, however, it was argued that since observers north of 40° report twelve months of veiling and John of Ephesus (thought then to be have been somewhere between 30° and 37°N) reported eighteen months of veiling, the eruption should be located south of 30/37°N.[97] These estimates are a touch rough, but they could still agree with the tephra-based reasoning that the eruption at around 535 was North American and with the conclusion, pulled from ice cores, that the event was extratropical. They also fit with the abovementioned modeling, which finds the densest aerosol loading for the 535/6 eruption north of 30°.[98]

Nevertheless, it is possible that a smaller Mediterranean eruption caused the mystery cloud at the same time that some larger event initiated the downturn. Mediterranean volcanic activity is restricted largely to central and southern Italy (Etna, Stromboli, Vesuvius, and Vulcano) and the southern Aegean (Kos, Methana, Milos, Nisyros, Santorini, and Yali). Much ancient and medieval volcanism in the region remains obscure. Scholars have harnessed various written and archaeological sources as well as archaeomagnetic dating of lava flows and radiocarbon dating of tephra layers to construct eruption series for individual sites.[99] Many Mediterranean events, such as the 1631 CE Vesuvian eruption, the most lethal in that mountain's history with perhaps 8000 dead, were explosive, but did not affect climate.[100] Some, such as the 472 CE "pollena" eruption from that same "extinguisher of all green things," left traces in the archaeological, ice core, and tree ring record but still did not greatly shift climate.[101] Marcellinus Comes wrote that this eruption "showered the whole surface of Europe with fine particles of dust" and was celebrated annually on November 6 in Constantinople some 1200 km away. Another Byzantine tells us that the ash in the imperial city was four fingers deep.[102]

There is no witness of a large Mediterranean eruption or ash fallout in 535–50. In 536, Procopius reported rumbling at Vesuvius alongside a description of a typical volcanic event.[103] Between 472 and 536, that mountain had already vomited ash and lava in a regional event in July 512.[104] Procopius' account has led some volcanologists (seemingly unaware of the dendroclimatological and ice evidence for the downturn) to assign the mystery clouding to the Campanian site.[105] Yet there is also archaeomagnetic evidence for "a large explosive eruption" at Stromboli in 550 ± 50.[106] A local eruption at either site might account for the reported dimming of the sun and a greater, distant event detectable in the form of the first dip in global temperatures discerned in tree rings, speleothems, and polar ice. A new Alpine ice core extracted in 2013 along the Swiss–Italian border may soon shed light on this matter.[107]

Not all researchers, however, have thought a volcano responsible. Before the recent redating of many major eruptions—when it still appeared that there were no volcanic horizons in polar ice plausibly related to the 536–50 climatic downturn—some scholars proposed that a "medium-sized asteroid" struck "one of the world's oceans" or a comet disintegrated in the upper atmosphere ("an airburst") and ignited "one or more large-scale forest fires." Both asteroids and comets were thought capable of filling the atmosphere with debris, which could reflect enough sunlight to cause a decade-long "climatic recession" beginning in 536.[108]

Several authorities judged an extraterrestrial vector a "much less likely" explanation than a volcanic event even without evidence for an eruption,[109] and Baillie, the principal advocate of the impact theory, retracted his proposition in

2008.[110] Nevertheless, in 2004, it was mathematically determined that a comet of less than one kilometer in diameter could generate multiple, successive years of dust veiling, and it was suggested that the earth may have been struck by such a rock as it passed through the Taurid meteor complex, as it does every November–June, and which is thought to have broken up around 500 CE.[111] In 2008, iron oxide and silicate spherules, alongside other plausible ejecta indicators, were recovered in meltwater at the "lost" 536 mark of the GISP2 core, again suggesting an impact event. Further analyses found nickel and tin particles and a high concentration of calcium. The latter was interpreted as calcium carbonate (a primary component in seashells) following the discovery at the same horizon of an assemblage of tropical and subtropical marine-life microfossils—a first for Greenlandic ice cores. Based on the radiocarbon dating of the formation of the Gulf of Carpentaria crater (Australia), the crater's chemical similarities with this GISP2 horizon, and the size of extraterrestrial rock considered necessary to generate both the crater and the observed dust veil, a team of scholars proposed that an impactor 640 m in diameter landed in Australia, causing the 536 event.[112]

To account for these findings, these scholars argued that the downturn's first low had multiple origins: a major volcanic eruption coincided with a comet impact and/or a low-latitude oceanic "explosion."[113] The possibility of multiple origins of the first low around 536 cannot be discounted.[114] Other phenomena were also raised as potential causes when ice core evidence for volcanism was still lacking: an "interstellar cloud" of unknown origin and, for Mediterranean dimming specifically, a tropospheric "damp fog."[115] It is certainly clear that multiple events forced the downturn as a whole: at least several large explosive volcanic eruptions, the first (one but possibly two or more[116]) 535/6 in the Northern Hemisphere, possibly at Haruna but more certainly in northern North America, and the second a near equatorial "global" event about 539/40, perhaps Ilopango or El Chichón.

32.7 Collapse and Resilience

Much has been written on whether the 536–50 climatic downturn—however understood—caused cultural, demographic, or socioeconomic change. As with many pre-modern short-term climate events, its human impacts are difficult to discern where the written sources are "thick," enigmatic where they are thin, and nearly imperceptible where they are non-existent. Archaeology, the sole source of relevant data for most affected regions, is incapable of revealing the downturn's toll with precision. No matter how vast and severe, the human implications of climate anomalies are often hard to tease out of the material record.

There has been a tendency among historians to ignore or downplay the paleoclimatic evidence, to demote the anomaly to a minor atmospheric incident, and thereby understate its cultural, demographic, and economic significance. These scholars miss an opportunity to see the downturn for what it was and to highlight the resilience of contemporary societies to abrupt and severe climatic anomalies. Indeed, many prefer to write history as though sixth-century peoples (and pre-modern organic agrarian economies in general) were undisturbed by dramatic temperature fluctuations.[117] At the other end of the spectrum, many natural scientists, and some historians and archaeologists who prioritize climate proxies, have described the event as a watershed, an almost unparalleled phenomenon that shook sixth-century societies. These scholars tend to view sixth-century peoples as highly vulnerable to environmental change, socioeconomically weak and rigid, and consequently incapable of adapting to an anomaly of this scale.[118]

The 536–50 downturn was a significant and rare event. Yet claims that it spawned a new era—whether in the Americas, Asia, or Europe—are as groundless as suggestions that it did not affect contemporary peoples are short-sighted. Although no account directly connects the Mediterranean mystery clouding of 536 to famine, qualitative evidence for harvest quality in the 530s and 540s suggests that the downturn did drive some demographic and economic change. A comparative approach that considers the effects of lesser volcanic episodes on better-documented populations also suggests that the sixth-century eruption cluster would have negatively affected harvests in many regions. It is the cultural and socioeconomic effects imputed to these food shortages that remain questionable.

It has long been recognized that sudden drops in summer temperature of 0.5–1 °C or more can have disastrous consequences for food production in temperate regions by shortening the growing season, limiting arable land, and augmenting the risk of harvest failures.[119] But proxies must be employed carefully to understand the downturn's effects on crops, and gaps in the paleoclimate data must be acknowledged also. The impact of a spectacularly cold and/or dry year would have varied from region to region, harvest to harvest, and plant to plant. Regions already cold and dry perhaps suffered more than warm and wet ones. As noted, trees reveal only growing-season conditions, and their temperature signals do not offer the timing and precision needed to fully understand the impact of a year's weather on crops. Not only the severity but also the timing of a downturn's climatic shifts within the growing year are important (see Chap. 27).

Here, analogies with more recent eruptions are instructive. Multiproxy paleoclimatology indicates that large tropical eruptions of the last 500 years have caused cold-dry summers but wet-warm winters in the Northern Hemisphere for two or three years, unlike large high-latitude eruptions which forced cold-dry winters and summers.[120] The first and second lows of the downturn, therefore, may have affected crops differently. In the Mediterranean, where winter precipitation is fundamental, the tropical event of 539/40 may have been beneficial in some ways. Its climate forcing may also explain the aforementioned blossoming of Korean fruit trees in the winter of 540. That said, warm-wet winters would not have been a boon for food production in all regions, and a shorter growing season is detrimental for crops everywhere.

Moreover, if most sixth-century societies were able to absorb one bad year, very few were able to absorb successive harvest failures. Back-to-back years of extremely poor growing conditions were certain to take a toll. Sharp cooling of 1.5 to 4 °C in consecutive years should be expected to have generated significant subsistence crises—true famines, in other words.[121] It has been shown that at least eight volcanic events between 750 and 950 registered in polar ice correspond to harvest failures recorded in European sources.[122] Not one of these eruptions or food shortages created catastrophe, although each undoubtedly eroded human numbers through hunger and associated epidemic disease. The eruptions and cooling of 535–50 were significantly more severe, suggesting that they would have generated more widespread and ruinous harvest failures. Yet, such events are not easily detected in sixth-century sources. We surely cannot generalize about an intercontinental famine spanning 536–50.[123]

At least one region, Thrace, was already suffering dearth on the eve of the mystery cloud. Justinian referenced a grain shortage there in a *novella* (decree) directed to a local consular, dated June 15, 535.[124] The initial low of the downturn presumably worsened that dearth. In addition to the description of the mystery cloud, the letters of Cassiodorus give several indications of crop failures. In 537, he wrote of a general food shortage throughout the provinces, failed harvests in Liguria, and "starving people" in Lombardy, but a rich Istrian harvest (of grapes, olives, and grains). In 538, he reports growing-season frost and drought injuring grain, fruit, and grape crops, as well as general food scarcity, although his letters also mention "an exceptionally abundant" previous harvest that should be able to stave off present penury. In 538, he also observed another good grape crop in Istria but Friulians and Venetians suffering a dearth of millet, wheat, and wine crops.[125]

John the Lydian stated bluntly that the dimming of the sun destroyed crops, and John of Ephesus observed that it harmed the harvest and prevented fruits from ripening ("all the wine had the taste of reject grapes"), but neither speaks of widespread hunger.[126] Pseudo-Zachariah wrote simply of the 536–7 winter causing "distress" in Syria.[127] The provisioning, disruptions to agriculture, and destruction of arable associated with the initial phase of Justinian's Italian reconquest (535–40) caused multiple local Italian shortages and possibly worsened a general agricultural crisis.[128] John the Lydian and Pseudo-Zachariah may indicate that a food shortage existed beyond the theater of war. Other sources shine some light here. The *Liber Pontificalis* documents a hard shortage within besieged Rome in 537 but also a great subsistence crisis "throughout the entire world"—one so dear that, according to a report from a Milanese bishop, Ligurian mothers were driven to consume their own children.[129]

To the north, Irish annals document a "failure of bread" in 536 and 539 (the latter is possibly a doublet), and the Welsh *Annales Cambriae* speak of a "mortality in Britain and Ireland" in 537.[130] Severe food shortages are reported in China as well. In the eastern region between the Yangtze and Yellow Rivers, the cold summer of 537 is written to have caused widespread harvest failure and triggered a famine the following autumn. Unusual weather is associated with famine and human mortality for multiple years in China, in 536, 537, and 538. The population of a kingdom north of the Yellow River is reported to have declined 70–80%.[131] There are indications, as noted, that harvests were poor in Korea (then south and north of the Yalu River) and Japan too.

These texts convey short-term demographic shocks in several regions of Eurasia, but not a vast long-term crisis across continents. Europe and the Mediterranean certainly did not then "decline into the Dark Ages."[132] The dearth of evidence for a vast population crisis in 536–7, and the lack of any mention of poor harvests or mortality in the sources for some regions, may reflect the success of some peoples and the failure of others to cope with the poor harvests that the downturn caused. Alternatively, the lack of evidence for a pan-Eurasian crisis may reflect the unequal effects of volcanic dust clouding as well as geographical and seasonal variation in the downturn's climatic effects. The aforementioned simulations of downturn volcanism suggest that the densest aerosol loading from the two largest eruptions was by and large confined to the Northern Hemisphere. Clouding in 536 was severe north of 30°N and 540 clouding north of about 5°N. But the clouding of both events was markedly worse north of 50°N. The same study identified the Baltic region in particular as hard hit.[133] A multiproxy study that covers China's sixth-century climate also suggests, albeit with some uncertainty, that the downturn did not everywhere cool temperatures and that its effects varied regionally. Indeed, at least one area of East Asia (far northeastern China) seems to have experienced warming.[134]

Absence of evidence is not always evidence of absence. Yet, the downturn has been posited as the cause of massive population contraction in some regions altogether lacking written records. Some scholars have considered this anomaly a plausible explanation for the considerable demographic and socioeconomic change revealed by archaeology in late migration period Scandinavia and late classical Maya Central America. In Scandinavia, successive widespread harvest failures and famine are thought to account for declining sixth-century settlement numbers, abandonment of arable and pasture, and a noticeable increase in gold hoards. The chronology of these phenomena and the dating of the archaeology, however, require that such bold claims be softened. Most of the gold hoards are only roughly dated to the first half of the century, others to mid-century. One deposit can be affixed a narrower 525–50 date.[135] Neither the decline (or shifting) of settlement nor the contraction of cultivation can be assigned precisely to the mid-530s either. In fact, both phenomena clearly predate 500. For example, Göthberg's data on the number of (excavated) settlements in Uppland province (Sweden) spans millennia. It shows an unprecedented sixth-century "collapse" in the range of 75% of sites, but a gradual decline had set in from about 300 CE.[136] Likewise, the abandonment of tens of well-worn gravesites in Västmanland province (Sweden) can be assigned a rough sixth-century date, but such burial ground desertion was nothing new there.[137]

These uncertainties have not stopped some scholars from assigning vast consequences to the downturn in Scandinavian and Baltic countries.[138] These include the reorganization of power structures, property rights, trade networks, and burial customs, as well as a contraction in metallurgy and craft production: all phenomena only loosely discernable in the material record and vaguely dated to the sixth century.[139] More tenuous are associations between the downturn and mythical bouts of severe weather, for instance the dimming of the sun, moon, and stars, and the Fimbulwinter—a three-year-long, snowy, frost-laden winter that precedes Ragnarök, the destruction of the known world.[140] Yet, the paleoclimatology and climate modeling does indicate that the downturn greatly affected climate in this region.

An ocean away, Gill has argued that the downturn accounts for the Maya "hiatus" described above. He accordingly assigned a firm start date of 536 for this Mesoamerican interval, drawing on high-resolution dendroclimatology from elsewhere. Gill implicated El Chichón, then with a large eruption roughly dated to the fifth or sixth century, and tied 536 aridity and cold to unrest, conflict, and population collapse: "a genuine demographic disaster" of 70–73% in "large areas" of the Maya Lowlands.[141] How dramatic the effects of downturn volcanism were in this world region, however, remains to be seen. In the modeling mentioned already, Central America, unlike Scandinavia and the Baltic, is largely spared both the brunt force of the 536 event and also the worst of the larger 540 event.[142]

The downturn is commonly thought to have affected populations in and beyond these regions through harvest failures and famine. In Europe and Western Asia, mass poisoning and pandemic disease are also implicated.[143] One theory connects population contraction in late migration period Scandinavia to the widespread poisoning of common grains (cold-tolerant rye but also barley and wheat). It is hypothesized that the anomalous weather encouraged the growth and spread of the parasitic plant fungus *Claviceps purpurea*, causing ergotism.[144] This theory hinges partially on the extensive cultivation and consumption of rye, the grain most vulnerable to ergot, in pre-downturn Scandinavia. Another theory holds that the downturn drove neighboring Estonians to start cultivating rye.[145]

The downturn's connection to the well-known Justinianic Plague is more complex.[146] Many scholars have rightly grouped the demographic effects of the climate anomaly with those of the first wave of this pandemic.[147] Procopius reports the arrival of the fast-spreading lethal disease in the Nile Delta region in mid-July 541. Through him and other witnesses, we can piece together the pathogen's subsequent dissemination through Western Asia and Southern Europe between 541 and 543. Other regions of Asia, Africa, and Europe were certainly affected, too, before and after this 541–3 window. Ireland was likely hit in 544.[148] The sudden and dramatic mortality in the plague may have precluded famine during the 540s and partially explain the absence of evidence for dearth following the second eruption of 539/40.[149]

Some scholars have proposed that the climate anomaly actually caused or triggered the pandemic.[150] The proposed connections between the two events depend on the *Yersinia pestis* diagnosis of the pandemic and the path envisioned for the pathogen's dissemination. Keys has argued that a drought followed by extreme rainfall fostered a population explosion of sylvatic rodents in East Africa (where there is no high-resolution data for climate in 536–41 or the sixth century generally).[151] The rodents expanded their natural range and spread the pathogen eventually to commensal rats in the Mediterranean.[152] Other scholars have found the basic tenets of this theory plausible.[153]

Historians long favored a Central or East African origin for the Justinianic Plague (*Y. pestis* now possesses enzootic foci in rodents there).[154] Genetic studies have recently concluded, however, that the *Y. pestis* found in Justinianic Plague-era graves from Bavaria ultimately came from northwestern China.[155] An alternative theory, by historian Stathakopoulos, that the drought-triggered migration of 15,000 people from Iran to Syria introduced the pathogen to the Mediterranean region, better suits this recent finding.[156] So too does McCormick's proposal that the pathogen reached Pelusium at the eastern edge of the Nile Delta via the Red Sea and points further east.[157] It should be noted that although the *Y. pestis* strain isolated from late antique skeletons best matches plague strains found in northwestern China, it is not impossible that the Justinianic *Y. pestis* emerged from a region closer to the Mediterranean than East-Central Asia. Extinct reservoirs could have existed for this northwestern Chinese-like strain in, for example, Africa or West Asia. It has also been proposed, though *Y. pestis* is not an opportunistic infection, that the downturn heightened plague mortality through harvest failure, famine, and malnutrition,[158] and that the unusual weather encouraged the dissemination of pneumonic plague, bubonic plague's more mortal variant, which does well in colder climates, as it spreads most effectively in closed indoor environments.[159]

Of course, if the climate anomaly did lend itself to this pandemic, it can account only for the initial occurrence, not the subsequent thirteen to seventeen outbreaks which took place over the next two centuries.[160] Although climate anomalies are thought to underlay many European recurrences of the Black Death (via their effects on bubonic plague-carrying Asian rodent populations),[161] and are generally considered vital in the history of disease,[162] similar environmental triggers have not been established yet for reappearances in the Mediterranean world of the Justinianic Plague.[163] It is worth noting, however, that recent genetic research indicates that the *Y. pestis* introduced to Europe with the Black Death seems to have become endemic or enzootic in some European regions.[164] Were this also shown for the Justinianic Plague, the downturn could be firmly implicated in the erosion of West Asian and European populations through plague from the mid-sixth to mid-eighth centuries. In other words, if the downturn was instrumental in spreading the plague to the wider Mediterranean region after 541 and if, once there, the plague focalized in one or more reserviors, then the downturn undoubtedly had a major demographic impact.

Downturn-driven dearth and malnutrition may explain why the initial outbreak of 541–4 seems to have spread farther and persisted longer in Europe and Western Asia than later outbreaks. Malnutrition may have raised mortality slightly, and poor harvests possibly fostered wider and longer lines of trade, facilitating disease transmission. On the other hand, the downturn may have inhibited the dissemination of a pathogen hosted in part by commensal rodents which favor warm climates and depend partially on stored grains. Similarly, the exceptional summer cold may have lessened the burden of malaria, a temperature-sensitive parasitic disease transmitted by anopheles mosquitoes.[165]

In whatever way it was related to the Justinianic Plague, it is reasonable to think that the 536–50 climate anomaly caused some demographic contraction in many parts of the world. Not all scholars have affixed significant cultural and economic change to this depopulation. A number of historians see the 536–50 event not as a significant driver of change but as a short cold trough in a larger multicentury climate reorganization (or "deterioration"[166]) of late antiquity (that for some predates 536 but for others starts in 536), which fostered a large but gradual agricultural and demographic transformation of late antique Western Europe and the Mediterranean.[167] Some emphasize the downturn's unfortunate timing. From a Byzantine perspective, the cooling and aridity drove a "reduction of revenues and available resources in a time of high expenditure and rising insecurity."[168] This moderatism takes the position that socioeconomic and environmental explanations of change are not mutually exclusive. Such scholars find direct, mono-causal links between the downturn and long-term agrarian or population trends "quite unconvincing." Yet, they do not dismiss the anomaly outright. Rather than a watershed, it was an accelerator of change already underway.[169]

Similar approaches have emerged for other world regions.[170] Scholars of the northern and southern dynasties in China have argued that the anomaly contributed to—but did not cause—political instability, since poor harvests affected the collection of grain taxes and shrank state resources.[171] One recent study of the downturn in Central America held that it brought severe drought but argued that Maya cities were unevenly affected: some were prepared to absorb and respond to sudden climate "deterioration," others not. Calakmul, for instance, experienced profound growth, even "florescence," during the hiatus.[172] Differences in aridity and elevation also meant some settlements were more vulnerable than others. Already dry cities suffered more from arid episodes. Of course, water access and management mattered greatly as well in Maya cities, if they relied on tribute for access to reservoirs that could dry up in droughts.[173] A focus on hydrology has led to the suggestion that low-lying coastal sites were most resilient during the "hiatus" and "collapse."[174]

In short, the downturn's effects were complex and varied, more indicative of the dynamism of human–environment relationships than of system collapse.[175] The ability of contemporary populations to be resilient in the face of poor harvests should not be underestimated. Poor yields were not new anywhere in the 530s and contemporaries can be expected to have possessed a number of coping strategies to ward off dearth.[176] Scholars who propose that the downturn generated widespread famine in Europe and Western Asia may overestimate reliance on grains. Although the sudden onset of successive years of severe cooling would have affected adversely plant life of all sorts, not just sown crops, including grasslands, silvopasture, and possibly aquatic flora essential for animal and fish populations, traditional ecological knowledge and collective memory, however difficult to discern now, would have ensured some adaptive capacity across the globe.[177] Of course, neither harvest failures nor the ability to cope were everywhere equal, and some populations would have been more resilient than others, as crop varieties, cropping strategies, and systems of agrarian production and management varied tremendously. There may have been, as such, big variations in mortality over relatively small spaces.

32.8 Conclusion

The 536–50 downturn has no definitive history yet. Paleoclimatology now makes clear that a cluster of very large volcanic eruptions underlay the anomaly, including explosive events around 535/6 and 539/40, and lesser but still large eruptions in about 545/6 and 550/1. Each of these events shows up in tree rings in the Americas, Asia, and Europe. The first eruption was one of the largest of the last several millennia in the Northern Hemisphere. The second, a tropical eruption, was bigger. From 540, the downturn appears to have gone global. That said, more high-resolution paleoclimatology is needed, particularly data from the Southern Hemisphere. Proxies that reveal winter conditions and multiple climate parameters are also badly needed. Data on the impact of downturn volcanism on precipitation is sparse. Yet, while our understanding of the downturn's spatial and temporal contours will improve, its exceptionality and severity have been well established. The uniqueness of the event is locked in trees and other natural archives. Written descriptions of the Mediterranean mystery clouding are no longer the most telling evidence.

Historians must keep apace as more natural proxies of sixth-century temperature and precipitation come into play and existing proxies are perfected. Local, regional, and global histories continue to assign the event different degrees of importance, depending on the inter- or multidisciplinarity brought to bear, the priority given to different categories of evidence, as well as the resiliency envisioned of contemporary societies. To understand the origins, extent, severity, impact, and human responses we must bridge disciplines and weave together paleoclimatic, written, and archaeological data.

That temperatures fell dramatically in the mid-sixth century, and that multiple regions experienced especially dry conditions, does not mean catastrophe ensued. Resiliency and vulnerability to sudden and severe climate anomalies will have differed between and within contemporary cultures. Even in the worst-affected regions (perhaps Central America and Japan if the eruptions took place there), people would have been affected unequally according to the uneven distribution of, or entitlement to, resources. It has been proposed that the effects of the dearth in Sweden varied between classes, that elites with larger reserves of foodstuffs and ability to participate in long-distance trade had a better chance of survival as well as a "window of opportunity" to seize deserted lands and better themselves.[178] Of course, not all regions were equally affected to begin with: veiling density and distribution varied, so too the effect of cooling and drying on agro-ecosystems. By carefully interweaving the information afforded by natural archives with understandings of the ability of cultures to respond, we will begin to tease out how the 536–50 downturn registered with people on the ground. Neither unnoticed nor a demographic watershed, this anomaly was remarkably severe and unusual in recent millennia. It remains a major episode in environmental history warranting further investigation.

NOTES

1. A handful of antiquarians and Byzantinists drew attention to accounts of a *c.* 536 Mediterranean mystery clouding before the 1980s (Stathakopoulos, 2003, 247–49), but none envisioned this atmospheric phenomenon was part of a European, Eurasian, hemispheric, or global climatic event before NASA scientists Stothers and Rampino: Stothers and Rampino, 1983a, 412, 1983b, 6357, 6362–63, 6367, 6369; Stothers, 1984; Rampino, 1988, 87–88. Early Byzantinist scholarship notably includes Koder, 1996, and Farquharson, 1996, 266–68, 76–77.
2. Masson-Delmotte et al., 2014; Steig et al., 2013, 373; PAGES 2K Consortium, 2013, Tab. 1, Fig. 2; Jones et al., 2009, 6, 7. Although there remain many large gaps in our knowledge, limited evidence indicates temperature was not unusual in the mid-sixth century near the South Pole. Recent simulations of the climate forcing of downturn volcanism also suggest that the Southern Hemisphere was relatively unaffected: Toohey et al., 2016, 406. It is notable that Tambora too appears not to have much disturbed extratropical climates south of the equator: Raible et al., 2016, 569, 572, 582. The climate forcing of that 1815 eruption was slightly less than that of the *c.* 540 event: Sigl et al., 2015, 547–48, Extended Data Tab. 4. Yet, as Raible et al., 2016, remark (576), a dearth of climate records in the Southern Hemisphere may account for Tambora's poor showing in the south. Of course, there are even fewer records for the sixth century.
3. Sigl et al., 2015, 547–48, Figs. 2 and 3, Extended Data Tabs. 4 and 5.
4. Büntgen et al., 2016. This LALIA falls within a longer period of less extreme cooling (known by many names, including Vandal Minimum, Late Roman Cold Period, Migration Period Pessimum, and Early Medieval Cold Anomaly) that commenced, depending on the proxy employed, in the fourth or fifth century and petered out in the seventh or eighth century. For example, Büntgen et al., 2011, 581; McCormick et al., 2012, 191–99.
5. Luterbacher et al., 2016, Fig. 1.
6. Toohey et al., 2016, 401, 405, 406, 410, Fig. 2.
7. Some historians have over-generalized the fragility of paleoclimate dating: try Moorhead, 2001, 143. The dendroclimatological data has proven robust. The ice core data is trickier. Yet the former cannot be problematized on account of the challenges the latter can present.

8. Bondesson and Bondesson, 2014, 63, for instance, claimed the cause of the downturn, which they consider both vast and severe, “remains unclear,” and they seem to suggest the event was restricted to the mid-530s, even though its volcanic origin was reconfirmed in 2008 (and only since reinforced) and its decadal duration was made evident no later than 1994.
9. The notable exception is Arjava, 2005, 73–94. Many in the humanities continue to read the paleoscience through Arjava’s paper, though much has changed since 2005. See Power, 2012, 190; Lee, 2013, 290.
10. Keys, 2000; Wickham, 2005, 549.
11. McCormick writes of a “tremendous volcanic winter” in 536 with widespread atmospheric effects that “must have had serious economic and human consequences” but which only “weakened and did not destroy” the Roman Empire revived under Justinian: McCormick, 2013, 72, 88.
12. Cassiodorus’ first appearance: Rampino, 1988, 87.
13. Cameron, 1985, 14.
14. Procopius, 1916, IV.14, 328–29.
15. Cassiodorus, Variae 12.25, 518–20.
16. Lydian, 1897, 25. On the misdating: Arjava, 2005, 80.
17. Pseudo-Dionysius of Tel-Mahre, Chronicle, 65.
18. Michael the Syrian, 1901, 220–21.
19. Pseudo-Zachariah Rhetor, Chronicle 9.19, 370.
20. Pseudo-Zachariah Rhetor, Chronicle, 370 n. 305.
21. Arjava, 2005, 79.
22. Pseudo-Zachariah Rhetor, Chronicle 10.1, 399.
23. Marcellinus Comes, Chronicle, 39.
24. Arjava, 2005, 80–83; Stothers and Rampino, 1983b, 6362.
25. Notably: Stothers, 1984, 344–45; Rampino, 1988, 87: “the densest and most persistent dry fog in recorded history was observed during AD 536–537.”
26. Lydian, 1897, 25; Arjava, 2005, 80.
27. By which John may have meant Ethiopia or southern Arabia. Sixth-century Byzantines sometimes confused the two: Sarris, 2002, 171; Schneider, 2015, 184–202.
28. It was suggested John borrowed his explanation from Campestris who lived centuries earlier. Arjava thinks this dubious: Arjava, 2005, 81.
29. Keys, 2000, 253; Abbott et al., 2014b, 413.
30. Weisburd, 1985, 91–94; Houston, 2000, 71, 73, 77. Whether there is textual evidence for exceptional cold and drought in West Asia and Europe in the 540s remains to be determined. Previous searches have centered on 536.
31. Aston, 1896, 34–35.
32. Shultz, 2012, 122–24. There appears to be nothing potentially related to the downturn in Paekche Annals of the Samguk Sagi.
33. Koguryo Annals of the Samguk Sagi, 168–69. There appears to be nothing potentially related to the downturn in the Paekche Annals of the Samguk Sagi.
34. LaMarche and Hirschboeck, 1984, 121–26 (cf. Parker, 1985); Briffa, 2000, 87–105; Gao et al., 2008; Cole-Dai, 2010, 824–39.
35. Churakova et al., 2014, 145–49.
36. Esper et al., 2013, 2, 2015.
37. On these issues: Esper et al., 2015, 62–70; García-Suárez et al., 2009, 183–98.

38. 535 registered as the second coldest June–January in an early TRW study of a Sierra Nevadan pine chronology spanning 1–1980 CE (536 placed first), TRW and cell wall thickness analysis also drew attention to a 532 cold plunge in the aforementioned Altai series, and TRW analysis of the associated Sakha series revealed a pre-downturn 533 low. These Russian lows may be connected to local volcanism and suggest that the downturn had an early start in Siberia.
39. Cook et al., 2015.
40. Büntgen et al., 2011.
41. For instance: Esper et al., 2013, 736, Fig. 3.
42. Cook et al., 2006, 689–99; Larsen et al., 2008.
43. Pearson et al., 2012.
44. Major low-latitude eruptions, like the *c.* 540 event, are known to reduce global mean precipitation: Iles et al., 2013. Fischer et al., 2007, finds drier conditions in Central and Eastern Europe after more recent large (tropical) eruptions. Also Luterbacher and Pfister, 2015.
45. Pearson et al., 2012, 3405, 3411–12. Vesuvius' 472 eruption also does not register in this series. Narrow rings are apparent, however, at the 475 mark (see below), perhaps indicating a post-472 eruption dry spell.
46. Esper et al., 2013, 736, Fig. 3.
47. See Fig. 2.6 and references there cited in Luterbacher et al., 2012, 103.
48. Tan et al., 2003, 1617; Zhang et al., 2008, 940, 941 (Fig. 1).
49. Holzhauser et al., 2005; Thompson et al., 1985, 973, 1994, 85, 87, 92. The second study indicates dryness recommencing *c.* 570, following a decade-long hiatus, and continuing until 610. Chu et al., 2011, 789–90; Van Bellen et al., 2015, 1, 9. The Patagonian dry period, which seems to predate but span the downturn, is visible as well in another southern South American proxy too: Moreno et al., 2014.
50. Kobashi et al., 2011.
51. See note 2 above.
52. Sixth-century sections of long high-resolution Central American proxies are wanting. The region is held to suffer heightened aridity following large eruptions—see Gill and Keating, 2002, 125–33.
53. Hodell et al., 1995, 393 (Fig. 3); Curtis et al., 1996, 41, 44–46; Hodell et al., 2001, 1368 (Fig. 2), 2005, 1421, 1424 (Figs. 10, 15). These studies focus on the more severe and prolonged droughts corresponding to the classical "collapse," not the hiatus, though the latter is visible in them. The very existence of severe and prolonged classical-era droughts, however, has been questioned. The Chichancanab data has been reassessed and it has been argued that the arid cycles identified in the aforementioned 2001 and 2005 papers are "methodological artifacts": Carleton et al., 2014, 151–61. Dry conditions evident in the Chichancanab data, though, appear in other independent proxies from the region: Wahl et al., 2014, 23.
54. Medina-Elizalde et al., 2010, 260 (Fig. 7).
55. Webster et al., 2007, 1, 12, 13–14.
56. Rosenmeier et al., 2002, 183, 185, 188–89.
57. Haug et al., 2003, 1733 (Fig. 2).
58. Lane et al., 2014, 93, 95.
59. Gao et al., 2008; Cole-Dai, 2010, 824–39.
60. Hammer et al., 1980, 235.

61. Herron, 1982.
62. Hammer, 1984, 51–65; Clausen et al., 1997, 26,707–23.
63. Zielinski, 1995, 20,939, 20,944; Clausen et al., 1997, 26,707–23.
64. For instance: Cole-Dai et al., 2000, 24,435, 24,438–39; Kurbatov et al., 2006. On the missing GISP2 section, Zielinski, 1995, 20,940, 20,949, 20,953.
65. Traufetter et al., 2004, 141; Severi et al., 2007, 367–74; Larsen et al., 2008.
66. Baillie, 2008. Recently supported by Sigl et al., 2015, 543.
67. Ferris et al., 2011; Plummer et al., 2012, 1931, 1933–36.
68. Sigl et al., 2013, 1159.
69. Motizuki et al., 2014, 785, 798.
70. Sigl et al., 2014, 693, 694, 695.
71. Sigl et al., 2015, 544, 545, 547–48; also Büntgen et al., 2016.
72. Aizen et al., 2016, Fig. 5a.
73. Stothers and Rampino, 1983b, 6357, 6362–63, 6369; Stothers, 1984, 344–45.
74. Simarski, 1992, 3–5; Kelly and Sear, 1984, 740–43; Bradley, 1988, 221–43; Schmincke, 2004, 259–72.
75. Luterbacher and Pfister, 2015, 246.
76. Hammer et al., 1980, 233, 235. This 'White River Ash' eruption was redated recently to 833–50/847 ± 1: Jensen et al., 2014, 875–78.
77. Stothers and Rampino, 1983a, 412, 1983b, 6362; Rampino, 1988, 88. Cf. Heming, 1974, 1259.
78. Stothers, 1999, 717.
79. Traufetter et al., 2004, 141, 145; McKee et al., 2011, 27–37, 2015, 1–7. Stother's 540 ± 90 date was shown as well to be a mistake.
80. Keys, 2000, 277–78, 86–91.
81. Sigl et al., 2014, 695, 2015, 547–48. The second eruption had been earlier put in the tropics: Ferris et al., 2011 (who dated it to *c.* 535) proposed a "low latitudes" site and Larsen et al., 2008 (who dated it to 533/4 ± 2) were confident the eruption took place near the equator. Larsen et al., 2008, assigned the first event (with a 529 ± 2 date) a "more northerly source."
82. Sigl et al., 2013, 2015.
83. Both seem to register only in Greenlandic ice: Sigl et al., 2015, 547 (Fig. 5).
84. Andrea Burke, personal correspondence, June 20, 2016.
85. Tilling et al., 1984, 747–49; Espíndola et al., 2000, 90, 93, 102.
86. Nooren et al., 2009, 97, 101, 106–07. It is not specified why the dendroclimatological data for widespread cooling *c.* 536 was overlooked. Recently, Nooren et al., 2017 has again assigned the eruption to El Chichón.
87. Dull et al., 2010. Dull had previously dated the eruption to 410–535 and, more precisely, *c.* 430, Dull et al., 2001, 25, 27; Dull, 2004, 238, 243. A wide mid-fourth- to mid-sixth-century window is advanced independently in Mehringer et al., 2005, 199, 203–04, and Kitamura, 2010, 28.
88. Sigl et al., 2015, Extended Data Tab. 4 puts the Ilopango event at 540.
89. Toohey et al., 2016, 410.
90. Suggested by Larsen et al., 2008, but assigned to 529 ± 2 before being bumped by Baillie to *c.* 535.
91. Suzuki and Nakada, 2007, 1545, 1565; Soda, 1996, 40.
92. Sigl et al., 2015, 547; Gill Plunkett personal communication June 20 and 22, 2016.
93. Toohey et al., 2016, 406.

94. Gregory of Tours, Marius of Avenches, John of Biclaro, Victor of Tunnuna, and Isidore of Seville mention nothing plausibly related to Mediterranean sun dimming 536–7.
95. Pearson et al., 2012, 3402–14. One might also question why Cassiodorus had to inform his deputy about the dust veil (see above). If it were a major event, would he not have known? See also Grattan and Pyatt, 1999, 173–74, 77–78; Arjava, 2005, 73–94. Not long before the important study of Larsen et al., 2008, which established evidence for a volcanic origin of 536 clouding at both poles, Larsen advised Arjava (p. 77 n. 24) “nothing of interest” was found in Greenlandic ice layers between 531 and 550.
96. Arjava, 2005, 81–83.
97. Rampino, 1988, 87–88.
98. The modeling employed written accounts of clouding duration to help constrain the height of the eruption column. However, ice core data was used to establish the eruption’s latitude, which is the important factor for understanding the latitudinal spread of volcanic aerosols. Matt Toohey, personal correspondence, November 1 and 2, 2016.
99. For instance: cf. Tabs. 1 and 7 in Principe et al., 2004, 705, 716–17, 719.
100. Oppenheimer and Pyle, 2009, 444; Mrgić, 2004, 238. Others, notably Rosi and Santacroce, 1983, 250, consider the most mortal Vesuvius eruption that of 472.
101. Rosi and Santacroce, 1983, 250–51, 253–55; Pearson et al., 2012, 3406 (Fig. 4). On 472: Kostick and Ludlow, 2015, 8–13.
102. Marcellinus Comes, Chronicle, 25; John Malalas, Chronicle, 14.42, 205–06; Chronicle Paschale, 90–91. For discussion, Stothers and Rampino, 1983b, 6361–62; Kostick and Ludlow, 2015, 8–13. These scientists also link Hydatius’ account (35) of poor weather in northern Portugal to this event (Chronicon, ed. T. Mommsen MGH AA XI p. 35), though Hydatius’ text stops in 469 and this passage should be fixed a late 460s date.
103. Procopius, 1919, VI.4, 324–27.
104. Cassiodorus, 1886, 261–62. Discussion: Macfarlane, 2009, 109–11; Cioni et al., 2011, 789–810.
105. See Principe et al., 2004, 705–07, 710 who attribute a ^{14}C dated tephra layer to 450 ± 50 to 536 (not 472 or 512) and speak of “an explosive eruption” that “must have occurred” considering evidence for Mediterranean clouding. Stothers and Rampino note 536 was “probably not” Mediterranean in origin, but Vesuvius may have erupted after Procopius left Campania: 1983b, 6362, 6367.
106. Arrighi et al., 2004.
107. http://climatechange.umaine.edu/colle_gnifetti_2013_.
108. Clube and Napier, 1991, 49; Baillie, 1994, 216, 1999; Rigby et al., 2004, 123–26. Further discussion of the impact of extraterrestrial impactors: Napier, 2014, 391–92.
109. For instance: Stothers, 2002, 4; D’Arrigo et al., 2003, 257.
110. Baillie, 2008.
111. Rigby et al., 2004, 123–26.
112. Abbott et al., 2008.
113. Abbott et al., 2014a, 2014b.
114. Kostick and Ludlow, 2015, 15.

115. Baillie, 1994, 216; Arjava, 2005, 79, 80, 93.
116. See note 92 above.
117. Moorhead, 2001, 147–48, concentrates on Mediterranean mystery clouding, misdates Cassiodorus' letter to 533, ignores other accounts of sun veiling, and emphasizes the "remarkable ability" of human societies to "bounce back from disasters, including widespread failures of crops."
118. Tvauri, 2014, 35, is well versed in the paleoclimology of the downturn (30–32) and suggests "primitive" agrarian technology then in Baltic countries made contemporaries especially vulnerable to famines far worse than those of the historical period. He proposes that a "single incident of famine" could erode centuries of population growth.
119. Parry and Carter, 1985.
120. Fischer et al., 2007.
121. The food shortage spectrum: Garnsey, 1988, x, 6, 20–37, 271.
122. McCormick, 2007b, 878–89; cf. Newfield, 2013, 125–48. Later examples: Atwell, 2001, 32, 42–62.
123. The 1257–8 eruption, recently assigned to Samalas, Indonesia, and long known as the largest of the Common Era, did not generate widespread famine. Unlike downturn events, however, dendroclimatology indicates this event did not much affect climate. Stothers, 2000, 361–74; Timmreck et al., 2009; Mann et al., 2012, 202–05; Anchukaitis et al., 2012, 836–37; Esper et al., 2013, 736.
124. For discussion: Stathakopoulos, 2004, 265.
125. Cassiodorus, 1886, 519–20; 12.22 (513–14); 12.27 (521); 12.28 (523–24); 12.26 (520–21).
126. John the Lydian, 1897, 25; Pseudo-Dionysius of Tel-Mahre, Chronicle, 65; Michael the Syrian, Chronique, 220–21.
127. Pseudo-Zachariah Rhetor, Chronicle, 10.1 (399).
128. Procopius documents several tactical siege shortages then: Stathakopoulos, 2004, 270–77.
129. Davis, 2000, 56. Note the reconquest reached Liguria in 538 and this episcopal report was delivered in person in Rome over the winter of 537–38 meaning the dire situation in Liguria is to be assigned to 537. Milan suffered a multi-month-long siege during the war, but in 538–39, also after this report.
130. Charles-Edwards, 2006, 94–95; Williams, 1965, 4. Note the CELT (Corpus of Electronic Texts) transcription of the Annals of Ulster dates the bread failure to 538: www.ucc.ie/celt/published/T100001A/index.html.
131. Weisburd, 1985, 93. Weisburd implies Chang State's summer snow and autumnal famine occurred in 536 in the text, but the map caption (also p. 93) seems to date these events to 537.
132. Grove and Rackham, 2001, 143–44; Diaz and Trouet, 2014, 168.
133. Toohey et al., 2016, 401, 406, 408–09, 410, Fig. 2.
134. Ge et al., 2010, Figs. 2 and 3.
135. Axboe, 1999, 186–88, 2001, 119–35. Bondesson and Bondesson, 2012, 167–70, discuss a twenty-item deposit dating to the second quarter of the sixth century.
136. Discussed in Gräslund and Price, 2012, 433–34; also Price, 2015, 258–59. Continuity is seen at many settlements.
137. Löwenborg, 2012, 10–13.

138. Gräslund and Price, 2012, 431–36; Löwenborg, 2012, 5–7; Tvauri, 2014, 32–34, 35–39, and references therein. Detailed discussion of a sixth-century site where bread was found as a burial offering: Arrhenius, 2013, 1–14.
139. Löwenborg, 2012, 5, 8–10, 15–17, 19–23; Tvauri, 2014, 39–40, 42–43, 44–47, 48.
140. The Fimbulwinter was recorded first in the late Viking period and long thought by modern scholars to be rooted in the climatic transition away from a warm Scandinavia Bronze Age about 600–450 BCE: Pettersson, 1914, 24. More recently it was assigned to the downturn: Axboe, 1999, 187; Gräslund and Price, 2012, 436–40.
141. Gill, 2000, 228–33, 245, 287, 313, 318.
142. Toohey et al., 2016, 401, 406, 408–09, 410, Fig. 2.
143. For example: Koder, 1996, 277; Farquharson, 1996, 266; Houston, 2000, 73, 74; Gräslund and Price, 2012, 433, 438; Löwenborg, 2012, 7, 17–18, 22; Tvauri, 2014, 32, 35, 36, 46, 48.
144. Bondesson and Bondesson, 2014, 61–67.
145. Palynology indicates a sixth- or seventh-century date for the wide sowing of rye in Estonia: Tvauri, 2014, 30, 47–48, 49.
146. Justinianic Plague: Stathakopoulos, 2004, 110–54; Horden, 2005, 134–60; Little, 2007.
147. Cheyette, 2008, 155–56; Gräslund and Price, 2012, 434; Löwenborg, 2012, 7, 17, 19, 24; Tvauri, 2014, 35; Headrick, 2012, 39–40; Kostick and Ludlow, 2015, 16. Long ago, Farquharson emphasized that the downturn was part of "an extraordinary clustering of events," which included pandemic and epizootic disease: 1996, 267.
148. Maddicott, 1997, 10–11, 17.
149. Campbell has observed that the Black Death's arrival in England forestalled a sequence of exceptionally poor harvests from creating famine: Campbell, 2010, 301–04; Campbell, 2012, 140, 144–47, 159.
150. Stathakopoulos, 2003, 254 observes that Seibel lumped this Justinianic Plague and mystery clouding together as though they were causally associated in his 1857 work. Recent linkages include: Brown, 2001, 92–94; Stathakopoulos, 2003, 253–54, 2007, 100; McCormick, 2003, 20–21, n.33; Horden, 2005, 152–53; Sallares, 2007, 284–85; McCormick et al., 2012, 198–99; Gräslund and Price, 2012, 433–34; Lee, 2013, 290; Sigl et al., 2015, 548; Haldon et al., 2014, 123; Izdebski et al., 2015.
151. Though low-resolution paleoclimatology now illuminates a pronounced humid period setting in about 550 in Central Africa: Oslisly et al., 2013. In Western and Northern Africa, there is evidence for dry conditions. Low-resolution hydroclimate proxies in Chad and Algeria identify the sixth century as fitting into a two- or three-century dry period. In some proxies from Ghana and Senegal, this dryness is part of much longer-term aridity. In others, from Nigeria and Cameroon, dry conditions appear to set in abruptly in the sixth century. Reconstructions from Eastern Africa are more variable. The sixth century is the last of a long humid period in parts of Kenya. But proxies from other areas, like Tanzania, indicate dry conditions setting in abruptly in the mid-sixth century. Conversely, wetness sets in suddenly in Rwanda, Namibia, and north-east South Africa in the mid-sixth century: Nash et al., 2016, 6–8.
152. Keys, 2000, 16–23.

153. For example: Sallares, 2007, 284–85; Stathakopoulos, 2007, 100; also Lee, 2013, 290. Horden expressed skepticism, Brown thought the temperature sensitivity of plague-bearing rodent fleas problematic to Key's theory, and McCormick suggested that the connection was more complex than Keys allowed, though he too thought that the two events connected via the effect of climate change on rodent populations: Horden, 2005, 152–53; Brown, 2001, 92–94; M. McCormick, 2003, 20–21, n.33.
154. Biraben and Le Goff, 1975, 50, 58, 64; Sarris, 2002, 169, 170–72; Sallares, 2007, 251, 285–86 thought the plague popped up closer to home, possibly in Egypt.
155. Morelli et al., 2010, 1140–3; Harbeck et al., 2013; Wagner et al., 2014, 323; Feldman et al., 2016.
156. Stathakopoulos, 2003, 254.
157. McCormick, 2003, n.33; McCormick, 2007a, 303–04.
158. McCormick et al., 2012, 198–99.
159. It is not limited to cold climates or seasons, but pneumonic plague does generally require close contact for transmission. Sallares, 2007, 241–42, 286.
160. Unless the disease became endemic or enzootic following the initial introduction. Justinianic recurrences: Biraben and Le Goff, 1975, 58–60; Stathakopoulos, 2004, 113–24; Horden, 2005, 138–39, n.6.
161. Schmid et al., 2015, 3020–25; Kausrud et al., 2010, 112; Ben-Ari et al., 2011. Campbell has demonstrated the Black Death occurred, in Europe, within a distinct climatic anomaly: Campbell, 2010, 287, 300–05; Campbell, 2012, 144–47.
162. McMichael, 2015.
163. Though see Kausrud et al., 2010.
164. Bos et al., 2016; Seifert et al., 2016.
165. The same would apply to other mosquito-borne diseases. In Europe, both *vivax* and *malariae* varieties of malaria were well established south and north of the Alps by 550. Gowland and Western, 2012; Newfield, 2017.
166. See note 5 above.
167. For example: Stathakopoulos, 2004, 166–67, 268; Cheyette, 2008, 155–56; Devroey and Jaubert, 2011, 10; Izdebski et al., 2015.
168. Farquharson, 1996, 267.
169. Arrhenius, 2013, 13.
170. Widgren, 2012, 126, 131–33; Nunn, 2007, 9. In Satingpra, Thailand, a downturn drought is seen as spurring major irrigation works: Stargardt, 2014, 129–30.
171. Houston, 2000, 71, 74.
172. Dahlin and Chase, 2014, 127–55.
173. Lucero, 1999, 814–22.
174. Dunning et al., 2012, 3652–57.
175. Turner and Sabloff emphasize spatial and temporal variability in the effects of Maya droughts: Turner and Sabloff, 2012, 13,908–14.
176. A survey of late antique Mediterranean famines: Stathakopoulos, 2004, 23–30, 35–56.
177. Smit and Wandel, 2006, 282–92; Berkes, 1993, 1–10.
178. Löwenborg, 2012, 22–23.

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