Volcanoes and the Climate Forcing of Carolingian Europe, A.D. 750–950

By Michael McCormick, Paul Edward Dutton, *and* Paul A. Mayewski

Revolutionary advances of the natural sciences will transform our understanding of the human past. This case study supports that thesis by connecting new data arising from the last decade's scientific work in palaeoclimatology with the history of the Carolingian empire. For medievalists, it may open the door to a potent new set of insights into the total past of European civilization. For climate scientists, this study clarifies an opportunity to observe the impact on human society of scientifically established proxy measures of climatic anomalies and shows that the human evidence for the first millennium of our era is much richer than scientists generally assume.

Food production was the foundation of the medieval economy, the generation and distribution of wealth. In the early-medieval world of limited storage and interregional transport, severe climatic anomalies, among other factors, could disrupt food production and supply. Particularly if they caused famines, such disruptions have long attracted historians concerned with demography (mortality), politics (rebellions), and, most recently, culture or mentality.[1] Direct correlation between severe climatic anomalies and historical events is often obvious, even if the details prove to be complex. For instance, in the reign of Pippin III, the severe winter of 763–64 provoked famine, and that surely explains the suspension of the major effort by the king to conquer Aquitaine the following summer.[2] This paper explores palaeoclimate data recovered from the Greenland Ice

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[1] Wolfgang Behringer, Hartmut Lehmann, and Christian Pfister, "Kulturelle Konsequenzen der 'Kleinen Eiszeit'?" in *Kulturelle Konsequenzen der "Kleinen Eiszeit,"* Veröffentlichungen des Max-Planck-Instituts für Geschichte 212 (Göttingen, 2005), pp. 7–27, give an overview of the examples of the potential cultural impact of the harsh winters that attended one of the peaks of the "Little Ice Age" discussed in that volume. On the medieval fear of harsh winters, see Radivoj Radic, *Strah u poznoj Vizantiji, 1180–1453* [Fear in late Byzantium, 1180–1453], 2 vols. (Belgrade, 2000), 2:54–62. For an analysis of the early-medieval cultural implications of the subjective, human perception of the climate, see Paul Edward Dutton, "Observations on Early Medieval Weather in General, Bloody Rain in Particular," in *The Long Morning of Medieval Europe: New Directions in Early Medieval Studies,* ed. Jennifer R. Davis and Michael McCormick (Aldershot, Eng., in press).

[2] Michael McCormick, "Pippin III, the Embassy of Caliph al Mansur, and the Mediterranean World," in *Der Dynastiewechsel von 751: Vorgeschichte, Legitimationsstrategien und Erinnerung,* ed.

Sheet Project Two (GISP2) in relation to written evidence for exceptionally severe climate anomalies in Europe from the eighth to the tenth centuries.

Climate scientists and historians have explored intensively the second millennium of our era. Important observations that have emerged include the late-medieval episode of Rapid Climate Change (hereafter RCC) commonly known as the "Little Ice Age" and, of course, accumulating insights into the present period of apparently accelerating climate change.[3] By contrast, the first millennium has attracted scant attention, despite the fact that the scientific evidence is basically the same as for the later period. Moreover, from a climatological point of view, in many ways the climate then may have been more closely comparable to the twentieth century than the intervening period. In the view of some scientists, the first millennium was relatively quiet, lacking anomalies even close to the Little Ice Age; both with respect to average hemispheric temperatures and atmospheric circulation data, it seems to offer an excellent, if slightly cooler, potential analogue for current conditions.[4] If this is correct, the first millennium urgently deserves more intensive scientific scrutiny. The written record is less rich than for the second millennium, but it is by no means negligible. Indeed, in Europe and the Mediterranean, the first and last several centuries of the first millennium are fairly richly recorded; moreover, archaeology is supplying a swiftly growing quantity of new data across the entire first millennium, some of which have implications for climate studies.

We asked whether one of the most unambiguous signals in the scientific record of climate forcing—that is, of severe climate anomalies, in this case, unusual cooling resulting from shifts in the balance of energy between the Sun and Earth—can be detected in the written records of western Europe between about 750 and 950. Written sources begin to become more abundant around 750 and grow more dense thereafter, although there may have been some ups and downs in that process.[5] Because most of the indirect, or "proxy," indicators of palaeoclimate relate

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Matthias Becher and Jörg Jarnut (Münster, 2004), pp. 221–41, at pp. 237–38, with n. 74. For more on this winter, see below, p. 878.

[3] Specialists now do not favor the terms "Little Ice Age" and "Medieval Warming Period" since the climatic manifestations of the underlying phenomenon of these RCC events can differ greatly from one region of the world to another and the connotations of climate homogeneity within those periods can be misleading. See, e.g., A. E. J. Ogilvie and T. Jónsson, "'Little Ice Age' Research: A Perspective from Iceland," *Climatic Change* 48 (2001), 9–52. Medieval historians' current concern with climate history began with Emmanuel Le Roy Ladurie, "Histoire et climat," *Annales: Économies, sociétés, civilisations* 14 (1959), 3–34, whose contributions extend down to his *Histoire humaine et comparée du climat,* 2 vols. (Paris, 2004); other notable contributions came from Pierre Alexandre, *Le climat au moyen âge en Belgique et dans les régions voisines (Rhénanie, Nord de la France): Recherches critiques d'après les sources narratives et essai d'interprétation,* Centre belge d'histoire rurale, Publication 50 (Louvain, 1976), and his *Le climat en Europe au moyen âge: Contribution à l'histoire des variations climatiques de 1000 à 1425, d'après les sources narratives de l'Europe occidentale* (Paris, 1987). Among the key early contributions from climate scientists was the remarkably perspicacious synthesis of H. H. Lamb, *Climate, History and the Modern World* (London, 1982), now updated in a 2nd ed. (London, 1995), pp. 156–210. In addition to the bibliography cited in this paper, see n. 2 of Dutton's forthcoming "Observations on Early Medieval Weather."

[4] For more details, see below, n. 20.

[5] At present it is impossible directly to document in any precise way the quantitative changes of

to climate in ways that are complicated and nonlinear, it is difficult to array most proxy indicators and extrapolate from them a direct comparison of the written and archaeological records of the climate. Most detailed work on this period has concentrated on deducing patterns from multiple mentions in the written sources.[6] Volcanic activity, however, offers both an exceptionally clear physical signal and well-known climate implications. The impact of severe winters on the agrarian civilization of the time insures that such anomalies found their way into the written records, especially the annals and chronicles that proliferated then, which have long been mined by historians of climate and famine.[7] But severe winters also can be detected in other kinds of written sources, and more extensive research will likely expand significantly the written evidence for the first millennium beyond the letters that we use here for the first time.[8]

It is worth stressing that global volcanic activity is not a constant: some periods show more, some less. According to the volcanic signals recorded in the GISP2, the first 500 years or so of the first millennium seem relatively calm with respect to volcanic activity. The period from ca. 700 to ca. 1000 was more active (see Fig. 1). Combined with the surge in record generation and preservation that attended the Carolingian revival, this makes the two centuries from 750 to 950 a propitious period to compare the natural scientific and historical records for evidence of volcanic climate forcing. This has rarely been done before, and never this closely for the first millennium.[9]

1. Volcanoes, Climate, and the Climatic Conditions of Carolingian Europe

Severe winters in western Europe arise from different and sometimes complex causes, yet volcanic eruptions are one of the most unambiguous causes of unusual

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record survival over time and space, but this surely must be the consensus of experienced scholars working over the broader period. For some considerations that sustain this point of view, see Michael McCormick, *Origins of the European Economy: Communications and Commerce, A.D. 300–900* (Cambridge, Eng., 2001), pp. 155 n. 19, 157 n. 12, and 433–36.

[6] Rudolf Brázdil, Christian Pfister, et al., "Historical Climatology in Europe—the State of the Art," *Climatic Change* 70 (2005), 363–430; M. V. Shabalova and A. F. V. van Engelen, "Evaluation of a Reconstruction of Winter and Summer Temperatures in the Low Countries, AD 764–1998," *Climatic Change* 58 (2003), 219–42; A. F. V. van Engelen, J. Buisman, and F. Ijnsen, "A Millennium of Weather, Winds, and Water in the Low Countries," in *History and Climate: Memories of the Future?* ed. P. D. Jones et al. (New York, 2001), pp. 101–17; and C. Pfister, J. Luterbacher, et al., "Winter Air Temperature Variations in Western Europe during the Early and High Middle Ages (AD 750–1300)," *Holocene* 8 (1998), 535–52.

[7] Michael McCormick, *Les annales du haut moyen âge,* Typologie des Sources du Moyen Âge Occidental 14 (Turnhout, 1975), p. 55.

[8] See below, pp. 879–80, on papal and other letters. Careful scrutiny of series of records, such as the property conveyances that survive in abundance from monasteries such as Fulda, Lorsch, and St. Gall, might also turn up indirect evidence of severe climate anomalies.

[9] A. E. J. Ogilvie, L. K. Barlow, and A. E. Jennings, "North Atlantic Climate AD 1000: Millennial Reflections on the Viking Discoveries of Iceland, Greenland and North America," *Weather* 55 (2000), 34–45, do have the merit of using written sources along with scientific proxy data, but the data in their written sources, essentially derived from the early Icelandic sagas, are considerably more general in nature.

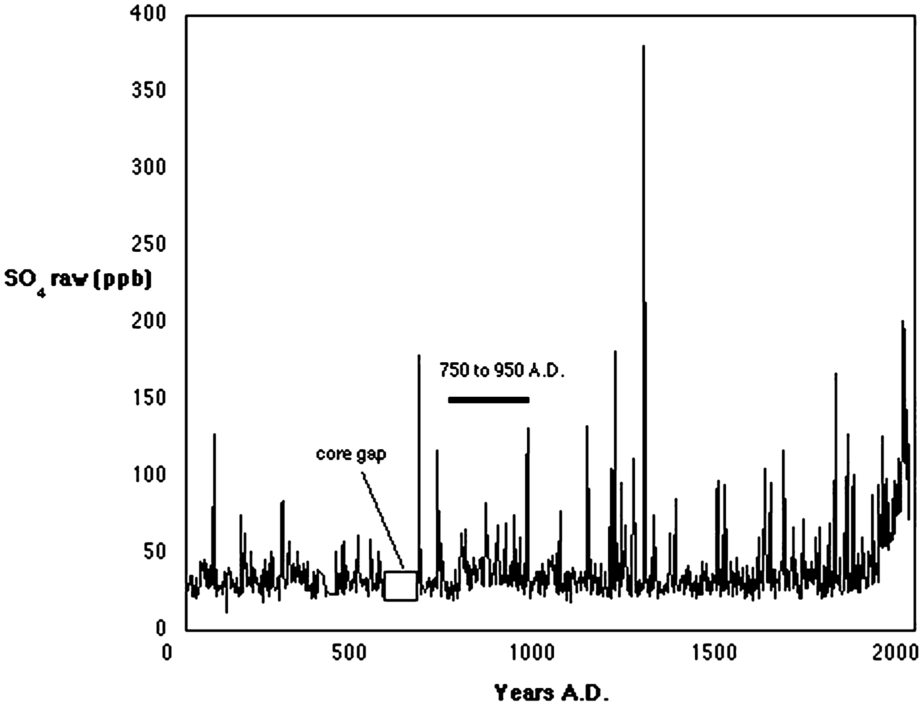

Fig. 1. GISP2 peaks in raw sulfate deposits, A.D. 1–2000. The gap shortly after A.D. 500 refers to a gap in the ice core.

cooling. No less a figure than Benjamin Franklin proposed the link between volcanic emissions and climate cooling.[10] That discovery has been refined and deepened, especially with the advent of modern climate science and the growing evidence of past global atmospheric conditions. Most notably, but not exclusively, glacier ice cores preserve a record of the atmosphere derived from the ancient snowfalls that created the ice.[11] The volcanic mechanism that cools the atmosphere is fairly straightforward.[12] Since the heat of the earth's surface derives ultimately

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[10] Joyce E. Chaplin, *The First Scientific American: Benjamin Franklin and the Pursuit of Genius* (New York, 2006), p. 304. Franklin connected the atmospheric pattern with a recent eruption of Mount Hecla in Iceland.

[11] Thomas J. Crowley, "Causes of Climate Change over the Past 1000 Years," *Science* 289 (2000), 270–77, esp. p. 271.

[12] For quick and clear introductions to the basic concepts and topics touched on in this section see, under the appropriate headings, Stephen Henry Schneider, ed., *Encyclopedia of Climate and Weather* (Oxford, 1996). For volcanoes and climate, see first and foremost the discussion of Lamb, *Climate, History and the Modern World,* pp. 62–66; also Michael J. Mills, "Volcanic Aerosol and Global Atmospheric Effects," in *Encyclopedia of Volcanoes,* ed. Haraldur Sigurdsson (San Diego, Calif., 2000), pp. 931–43. For more detailed explanations, see the relevant articles in Thomas D. Potter and Bradley Roy Colman, eds., *Handbook of Weather, Climate, and Water: Atmospheric Chemistry, Hydrology, and Societal Impacts* (Hoboken, N.J., 2003).

from solar radiation, anything that affects insolation, the arrival of solar radiation on the earth, affects temperature. A violent volcanic eruption expels massive amounts of tephra, particles of volcanic origin, into the atmosphere. Microscopic particles, if lifted into the stratosphere as an aerosol—solid or liquid particles suspended in a gas, in this case, the atmosphere (e.g., a cloud)—may diminish the global temperature by blocking solar radiation. This in turn will work various and complex effects on atmospheric and oceanic circulation. Furthermore, volcanic aerosols increase nucleation sites for water. The resultant cloud condensation nuclei can produce precipitation. Volcanic emissions are typically rich in sulfur dioxide (SO_2), which is converted to sulfuric acid (H_2SO_4). In addition to reflecting solar radiation back into space and thereby cooling the earth, the aerosols also fall to the earth. The resultant sulfate (SO_4) particles are preserved in the millennial record of atmospheric deposits—snow—in the great Greenland glaciers, and, through mass spectroscopy, the particles can be measured in parts per billion (ppb) in the annual layers of ice. Volcanic aerosols appear in the glacier record as sudden surges above the lower, background deposit levels of SO_4, which in the preindustrial era derived from other natural sources of SO_4, such as the biological activity of sea plankton and the weathering of rocks rich in sulfur (see Fig. 1).[13] Given the complexities of atmospheric circulation over seasons and space, it seems at present difficult to draw a linear relation between the volume of volcanic SO_4 deposited in Greenland and the degree of concomitant cooling.[14] For instance, the largest sulfate deposit by far in the period under review reflects the proximity of the volcanic source rather than the global impact of the aerosol.[15] Those same complexities mean that not every volcanic deposit in Greenland will translate directly into climate impact on the European continent, for instance, if an eruption occurred on Iceland at a moment when atypical atmospheric circulation conditions carried the aerosol westward toward Greenland.[16]

The Greenland record results from an undertaking of the U.S. and European scientific communities from 1987 to 1994 to seek in the annual snow deposits of Greenland an extensive palaeoclimate record for the Northern Hemisphere: the Greenland Ice Core Project (GRIP) and the Greenland Ice Sheet Project Two (GISP2). Our study relies on the three-kilometer-long core GISP2 (1987–93), which preserves a nearly continuous record for 110,000 years and which has so far proved more productive for the climate of the last few millennia. Each year's snowfall trapped snow, atmospheric gases, and particles and thus provides a remarkable record of past atmospheric chemistry. In addition to sulfate, *n*on-*s*ea-*s*alt potassium ions (nssK+), *s*ea *s*alt sodium ions (ssNa+), and *n*on-*s*ea-*s*alt calcium ions ($nssCa^{+2}$) are important components of the glaciochemical record for

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[13] G. A. Zielinski, P. A. Mayewski, et al., "Record of Volcanism since 7000 B.C. from the GISP2 Greenland Ice Core and Implications for the Volcano-Climate System," *Science* 264 (1994), 948–52.

[14] Crowley, "Causes of Climate Change," p. 271, for one discussion of the factors.

[15] That is the 939 deposit discussed below, p. 888.

[16] Standard reference works frequently identify particular volcanoes as the specific source of SO_4 peaks detected notably in the Greenland ice cores. Our experience suggests that unless such identifications are specifically justified by the chemical signature of tephra deposits, they should be treated with caution. See also below, n. 79, on the eruption of Eldgjá.

our purposes. Simplifying greatly, the nssK+ dust appears to originate from storms in central Asia, while ssNa+ arises from spray in ocean turbulence. NssCa+^{2} seems to be transported to Greenland from western Canada; increased deposition has been associated with strengthened westerlies. Deposit of nssK+ increases with a strengthening of the Siberian High pressure zone; deposit of ssNA+ rises with a deepening of the Icelandic Low pressure zone. These pressure zones are two of the main determinants of wind circulation, temperature, and moisture in the Northern Hemisphere as it affects Europe. Comparison of the glaciochemical indicators with the instrumental record for 1899–1987 revealed strong correlations between nssK+ and ssNa+ deposits and sea-level atmospheric pressure and sea surface temperature, as well as with patterns in wind circulation. Years with high nssK+ deposition are associated with spring strengthening of the high over Siberia (~3mb), the coldest air mass in the Northern Hemisphere. When it is strong, the Siberian High brings very cold winds from Siberia into Europe.[17] The annual stratification of the GISP ice core allows a highly resolved chronology. The accuracy of the chronological resolution of individual strata for our period is 2.5 years to either side of the proposed calendar year. The *maximum* possible *absolute* dating error for our period in this core is approximately six years. However, within any section of the core, say 100–200 years, the *relative* internal error is much less, since absolute error accumulates with depth. The closer the annual layer is to a securely identified volcanic event, the more likely the error is zero.[18] The sampling rate of the ice core was every 2.5 years.[19] Taken together, these glaciochemical indicators allow a preliminary characterization of the broader climate picture of Europe. From 750 to 950 the sulfate deposits indicate eight major volcanic events—two look to be multiyear in length or double events—that could have affected the climate of Europe.

There are some indications that a fairly quiet climate characterized the first millennium of our era, compared with the second millennium with its RCCs, including the present warming. The two major RCCs of interest to medievalists are those dubbed the "Medieval Warm Period" and the "Little Ice Age." In the former, Northern Hemispheric temperatures may have been similar to portions of the last century but lower than the last two decades; in the latter, conditions abruptly changed around 1400 such that the average temperature was approxi-

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[17] Loren David Meeker and Paul A. Mayewski, "A 1400-Year High-Resolution Record of Atmospheric Circulation over the North Atlantic and Asia," *Holocene* 12 (2002), 257–66. For more on the dust and salt proxies for atmospheric circulation, see P. A. Mayewski and K. A. Maasch, "Recent Warming Inconsistent with Natural Association between Temperature and Atmospheric Circulation over the Last 2000 Years," *Climate of the Past Discussions* 2 (2006), 327–55, at pp. 331–32 and 337.

[18] For the multiple stratigraphical dating methods and error parameters, see D. A. Meese, A. J. Gow, et al., "The GISP2 Depth-Age Scale: Methods and Results," *Journal of Geophysical Research* 102 C12 (1997), 26411–24.

[19] This was the state of the art when the GISP2 was obtained and analyzed in the 1990s. Today it is possible to take multiple samples, commonly 10 to 50, within one year, which seems obviously preferable when dealing with climatic events of the high chronological resolution allowed by the ancient and medieval written records; measurement error rate of the SO_4 deposits was 2 ppb.

mately 1°C lower than today.[20] GISP2 ice-core data broadly confirm these two medieval RCCs (see Fig. 2). There the patterns of deposit of non-sea-salt potassium ions (nssK+), sea-salt sodium ions (ssNa+), and non-sea-salt calcium ions (nssCa+^{2}) that allow reconstructions of past atmospheric circulation (see Fig. 3) all clearly differentiate the two RCCs and compare well with the reconstructions of Northern and Southern Hemisphere temperatures developed by Michael Mann and Philip Jones. As identified from Mann and Jones, the earliest major warming of the last 2,000 years for the Northern Hemisphere occurred around A.D. 800 (Fig. 2). The warming continued until roughly 900. A brief cooling from ca. 900 to 950 was followed by warming until ca. 1100, and then temperature declined

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[20] When the "Medieval Warming Period" began and ended is defined very differently by scientists and historians, who analyze the diverse data with different methods and chronological smoothing scales and techniques. Furthermore, while historians' professional background makes them extremely sensitive to chronological precision on the yearly, if not finer, scales, climate scientists often work in thousands, hundreds of thousands, or even millions of years and hence may sometimes seem rather more casual toward a historical time scale. According to Michael E. Mann and Philip D. Jones, "Global Surface Temperatures over the Past Two Millennia," *Geophysical Research Letters* 30 (2003), 1820–24, here p. 1823, "the broad period from approximately AD 800–1400 is observed to be moderately warmer than multi-century periods both preceding and following it." They used 23 proxy records deriving from tree-ring temperature reconstructions, lake sediments, ice cores, and fossil shells. Anders Mosberg, Dmitry Sonechkin, et al., "Highly Variable Northern Hemisphere Temperatures Reconstructed from Low- and High-Resolution Proxy Data," *Nature* 433 (2005), 613–17, detected two warm peaks, one around A.D. 1000 and one around A.D. 1100, and attributed the differences with Mann and Jones to differing mathematical procedures and calibration of the proxy records. See below, n. 21, on glacier fluctuations. Further complications arise insofar as discussion does not always distinguish the geographic frame of reference: global, Northern or Southern Hemispheric, and European patterns will not be identical. Reduced sea ice has been deduced for the North Atlantic ca. 800 to 1100: Ogilvie, Barlow, and Jennings, "North Atlantic Climate AD 1000." Although they explicitly limit the significance of their findings to the North Atlantic, such reduced sea ice would not be inconsistent with warmer conditions in western Europe. Jan Esper, Edward R. Cook, and Fritz H. Schweingruber, "Low-Frequency Signals in Long Tree-Ring Chronologies for Reconstructing Past Temperature Variability," *Science* 295 (2002), 2250–53, at p. 2252, use corrected dendrodata for the extratropical Northern Hemisphere to suggest that the medieval warm period "may have begun in the early 900s" and that the "warmest period covers the interval 950–1045." The ensuing discussion emphasized the potential for error arising from the smaller numbers of trees available for analysis before ca. A.D. 1300: Michael E. Mann, Malcolm K. Hughes, et al., "Tree-Ring Chronologies and Climate Variability," *Science* 296 (2002), 848–49. Using a completely different method based on rating numerically winters and summers mentioned in written sources, van Engelen, Buisman, and Ijnsen, "A Millennium of Weather," extrapolate temperature series that become colder in the ninth century and warmer in the tenth and the eleventh, which, at least for the ninth-century sources we know, may be rather bold, especially in light of the relativizing effect that is likely to have affected recording (see below, p. 876); see also the overview in Brázdil, Pfister, et al., "Historical Climatology," here pp. 388–96. Paul A. Mayewski, Eelco E. Rohling, et al., "Holocene Climate Variability," *Quaternary Research* 62 (2004), 243–55, place the warming period to ca. 800 to 1000. Most recently, Timothy J. Osborn and Keith R. Briffa, "The Spatial Extent of 20th-Century Warmth in the Context of the Past 1200 Years," *Science* 311 (2006), 841–44, review and test various proxy series and conclude that they provide a significant signal of a positive temperature anomaly from about 890 to 1170. See also Willie Soon, Sallie Baliunas, et al., "Reconstructing Climatic and Environmental Changes of the Past 1000 Years: A Reappraisal," *Energy and Environment* 14 (2003), 233–96. For detailed discussion of the start of the late-medieval cooling period, see J. M. Grove, "The Initiation of the 'Little Ice Age' in Regions round the North Atlantic," *Climatic Change* 48 (2001), 53–82, who notes that Swiss glacier advances point to the thirteenth century and that it was certainly well under way around the North Atlantic in the fourteenth.

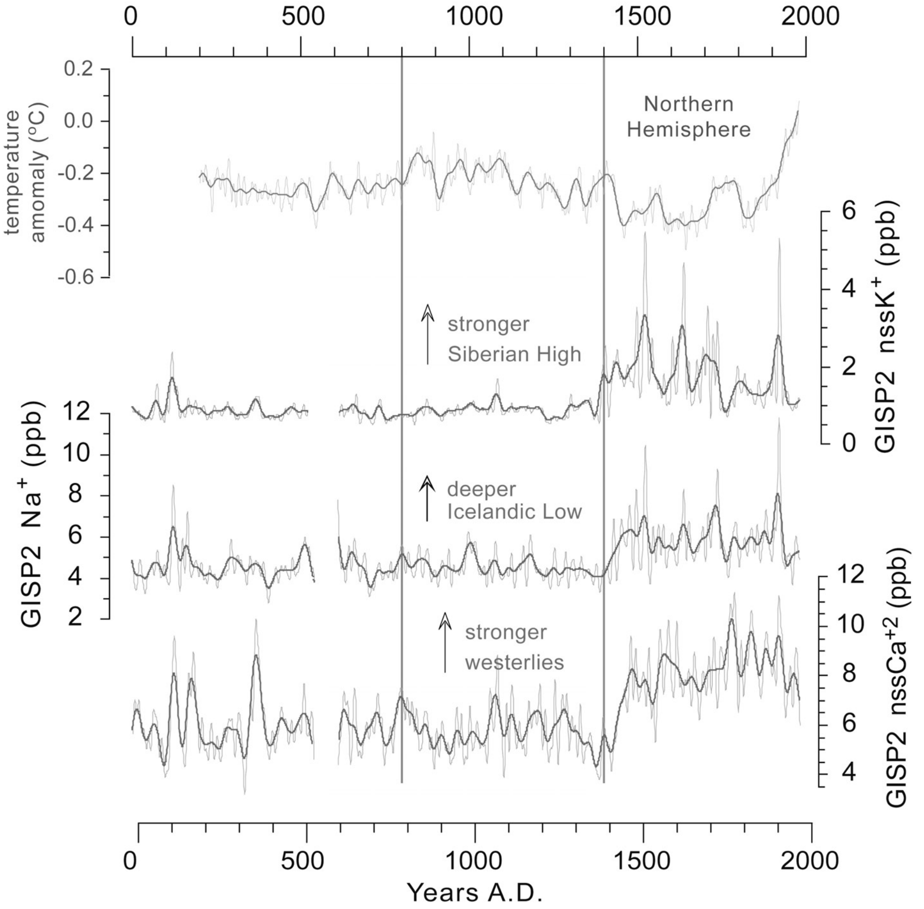

Fig. 2. Reconstructed climate trends in the last two millennia:
temperature anomalies and GISP2 ion records.
The thick line shows the same data with the <30-year signal removed from the temperature and circulation series in Figure 2 to allow comparison of multidecadal-scale features.

slightly to the onset of abrupt cooling at the start of the Little Ice Age around 1400. The GISP2 proxy indicators—nssK+, ssNa+, nssCa+²—for Northern Hemisphere atmospheric circulation as indicated by the Siberian High and Icelandic Low weaken after A.D. 200; the westerlies do likewise around A.D. 400. Both seem notably to precede temperature change and do not intensify again until ca. 1400 and the onset of the Little Ice Age (Fig. 2). In sum, the atmospheric circulation deduced from the GISP2 proxy indicators points to conditions consistent with warming some time after 400 and before 1400, notwithstanding potential relative changes within this period, which could have been significant.

Further insight comes from the completely independent data of Swiss glaciers,

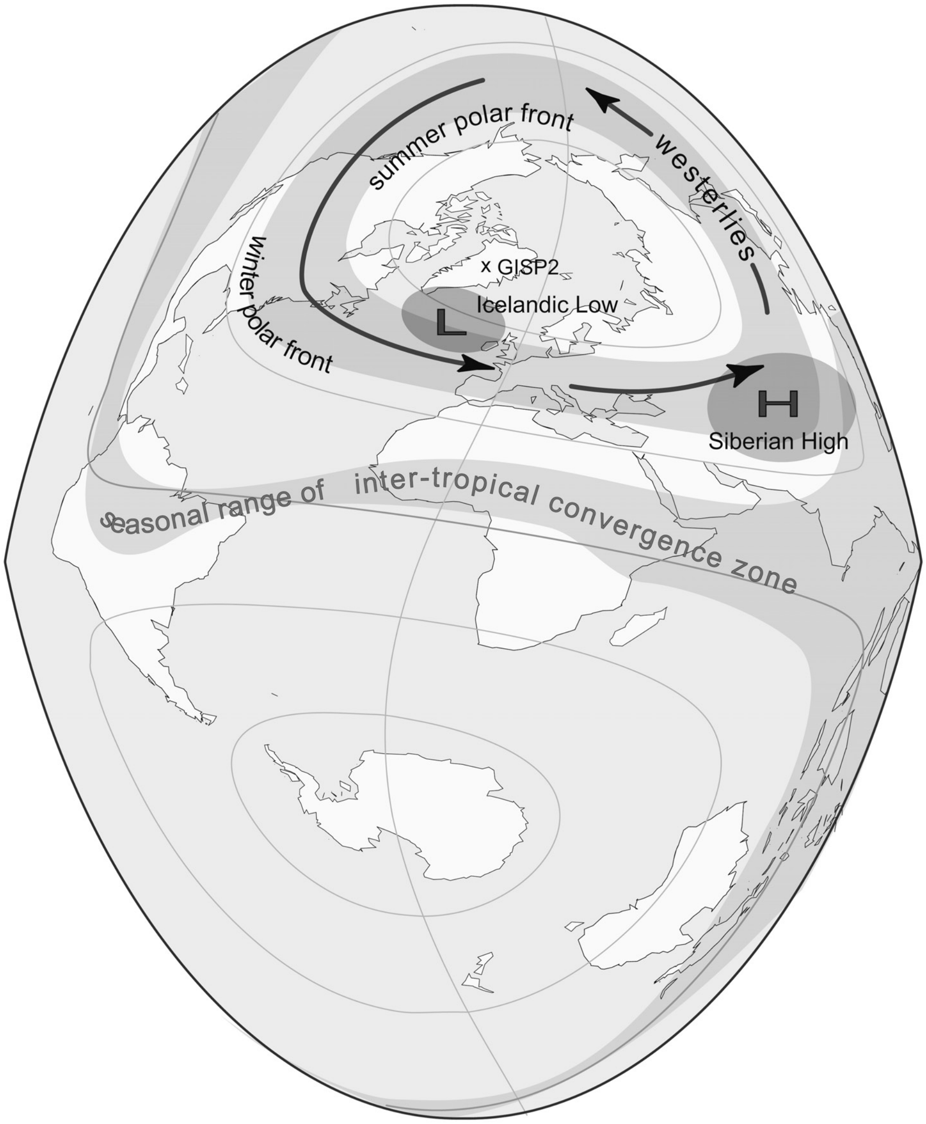

Fig. 3. Reconstructed general circulation patterns of the atmosphere, ca. 750–950. Location of GISP2 ice core.

whose location in the midst of the Carolingian empire makes them of particular interest (see Fig. 4). Recent advances in determining dendrochronologically the life spans of trees that sprouted at known dates in places where glaciers retreated and that were ripped out of the earth at similarly known dates when glaciers advanced allow an increasingly refined and absolute chronology for glacier advances and retreats. Cold *and/or* wet conditions promote glacier advances, while dry *and/or* warm conditions promote their retreat; larger glaciers react more slowly (ca. 20–25 years) to changed conditions than smaller ones ("a few years").[21] Judged the best document in the Swiss Alps for the medieval warming and cold periods, the Gorner Glacier remained small from the second half of the eighth century to the late thirteenth century, broadly defining the "Medieval Warm Period." From the Grosser Aletsch Glacier, radiocarbon dating detects periods of short-term glacier advance also, very approximately, from A.D. 600 to 700 and again around A.D. 900 or in the ninth century.[22] An early dendrochronological insight from the data indicates that the Gorner's retreat, and therefore warming, had certainly begun before A.D. 774, and probably before A.D. 748.[23] Finally, the much smaller and more sensitive Lower Grindelwald Glacier may provide important additional insight into ninth-century conditions, as we shall see.

From the perspective of how today's scientists reconstruct the climate of the last 2,000 years, the GISP2 data can be construed to suggest that the Northern Hemisphere experienced from about 800 to 900 the warmest period in the last 2,000 years, with the sole exception of the last few decades of our own time. More specifically, for Europe, the proxy indicators for the climate indicate that the Siberian High would have been weak. The Siberian High is a vast accumulation of cold air (see Fig. 3). When it is strong, the Siberian High brings very cold winds from Siberia into Europe. The Icelandic Low would have been deep. This low-

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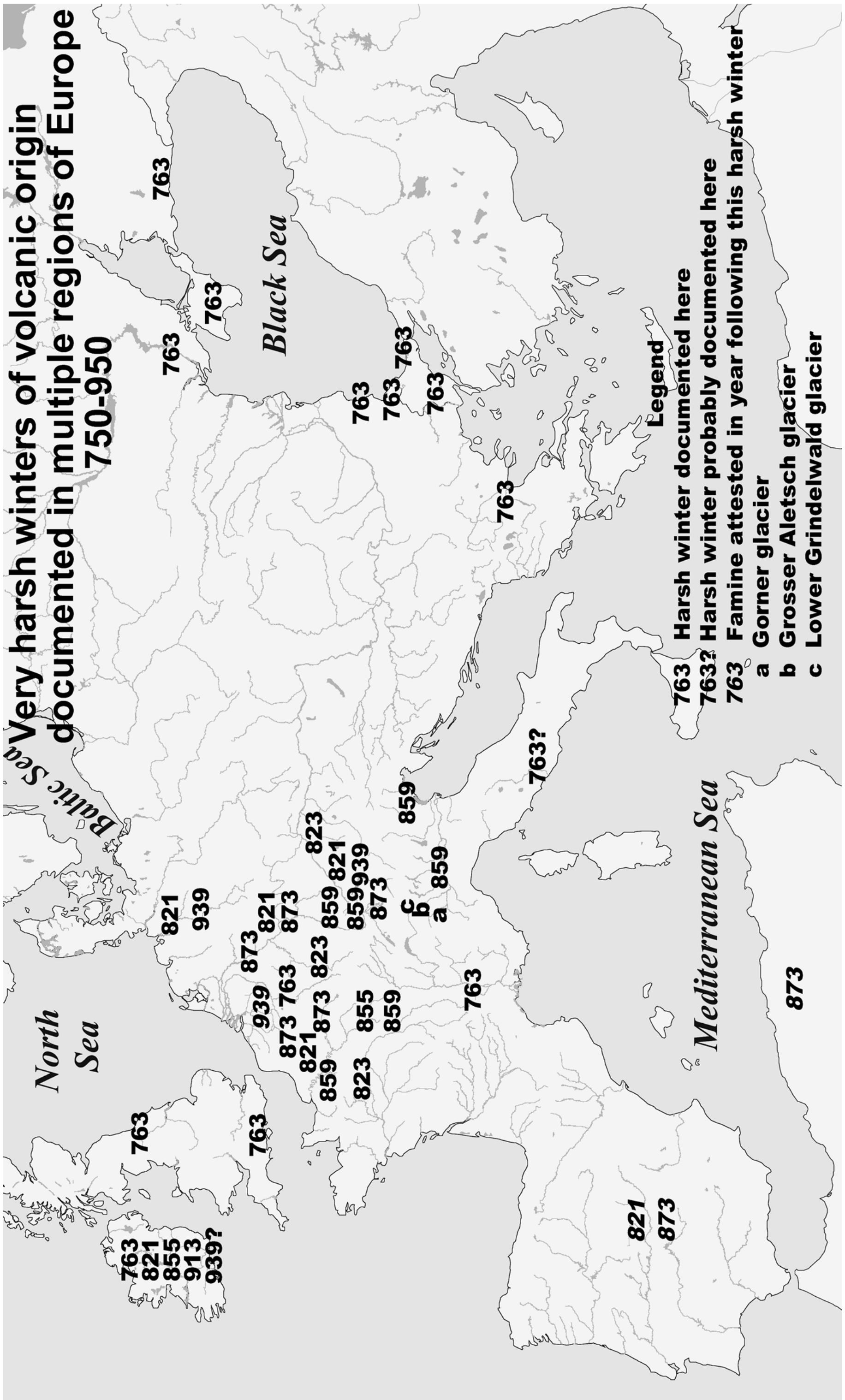
[21] For glacier size and the precipitation/temperature signals, which appear to be difficult to distinguish, see Hanspeter Holzhauser, Michel Magny, and Heinz J. Zumbühl, "Glacier and Lake-Level Variations in West-Central Europe over the Last 3500 Years," *Holocene* 15 (2005), 789–801, here p. 792. It is essential to stress that radiocarbon datings offer only a broad dating framework compared with the absolute annual date supplied by dendrochronology. Thus Holzhauzer cites two trees whose dendrochronology shows they died in the same year yet whose "radiocarbon dates differ from each other by as much as 265 years": Hanspeter Holzhauser, "Fluctuations of the Grosser Aletsch Glacier and the Gorner Glacier during the Last 3200 Years: New Results," in *Glacier Fluctuations during the Holocene,* ed. Burkhard Frenzel et al., ESF Project "European Palaeoclimate and Man," special issue 16 (Stuttgart, 1997), pp. 35–58, at p. 45. Unfortunately, he supplies no details on the type of radiocarbon analysis or calibration.

[22] Holzhauser, "Fluctuations of the Grosser Aletsch Glacier," pp. 42–45, with fig. 1, where the advance is dated ca. 900, and Holzhauser, Magny, and Zumbühl, "Glacier and Lake-Level Variations," p. 794, for judgment and radiocarbon dating to the ninth century. Their fig. 2 accordingly displays this smaller advance of the Grosser Aletsch and the Gorner as uncertain. See the previous note on the broad margins of error and lack of detailed information on the exact radiocarbon procedures used in these studies; on ninth-century conditions and the Lower Grindelwald, see further below, p. 883.

[23] Hanspeter Holzhauser, "Dendrochronologische Auswertung fossiler Hölzer zur Rekonstruktion der nacheiszeitlichen Gletschergeschichte," *Schweizerische Zeitschrift für das Forstwesen* 153 (2002), 17–28, at p. 23 with n. 4. This larch was destroyed in 1327, one of many that the glacier's rapid advance uprooted in the decades when the Little Ice Age was getting under way. The tree was certainly alive in 774 and is estimated to have germinated in 748, ± 5 years. It appears to have taken between 5 and 20 years for a larch to be able to grow up after a glacier had retreated from a spot: ibid., p. 22.


Very harsh winters of volcanic origin
documented in multiple regions of Europe
750-950
North Sea
Baltic Sea
Black Sea
Mediterranean Sea
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821
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939?
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763?
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763
763
763
763
763
821
873
873
Legend
763 Harsh winter documented here
763? Harsh winter probably documented here
763 Famine attested in year following this harsh winter
a Gorner glacier
b Grosser Aletsch glacier
c Lower Grindelwald glacier

Fig. 4.

pressure system is centered between Iceland and Greenland; it is the northern pole of the important oceanic weather component known as the North Atlantic Oscillation (whose southern pole is the Azores High). When it is deeper and closer to Europe, the Icelandic Low brings maritime and relatively mild conditions to parts of Europe. Ca. 800, the westerlies generally strengthened with respect to Europe. In fact, this should have been one of the periods of the most intensified westerly winds between 600 and 1300. Similar to the Icelandic Low, the intensified westerlies bearing on Europe would have brought much air and moderate conditions from the Atlantic into Europe, reflected in relatively warm temperatures and the circulation of mild weather patterns. In the half century or so before 800, those climate proxy indicators show a ramping into the mild phase that prevailed from ca. 800; in the half century or so after 900, the same indicators suggest a ramping into a somewhat cooler phase.[24]

2. Volcanic Activity and Severe Winters: Glaciochemical and Carolingian Historical Data Compared

One of us used GISP2 to identify in the ice core the volcanic events of most indubitable importance between 750 and 950. Independently, two of us sifted the numerous written records to identify and agree on the most unambiguous cases of extreme multiregional winters. We then compared the results and identified a number of correlations. For climatologists the value of this approach is twofold, if our correlation between natural phenomena and the written record of early-medieval Europe is accepted: it yields irreplaceable insight into the impact on human societies of natural events and phenomena as we believe we can detect them from chemical and other signals in the physical evidence; and it allows a more precise and absolute dating of those signals. In six of eight cases, the written sources specify the years of the phenomena with complete certainty; in two more there is some slight ambiguity in which of two years the phenomenon occurred, arising from the fact that winters span two calendar years for most reckoning styles used in western Europe in this period.[25] Figure 5 summarizes the results of these investigations.

Early-medieval reports of climate events, principally climate anomalies, are necessarily subjective: what struck the observer as unusual and worthy of recording was what appeared nonhabitual, according to the observer's own life experience of the climate. The events recorded were being gauged, implicitly, against the climate patterns of the preceding decades in the area(s) where the observer lived. Thus a "harsh" winter in a period of cold temperatures would likely have been considerably harsher in objective terms than a winter similarly qualified as "harsh" after a period of mostly milder temperatures, a factor that should figure in efforts to develop serial data on climate trends purely from written records. Early-medieval

[24] See in general Meeker and Mayewski, "A 1400-Year High-Resolution Record."

[25] Because of the way of recording events, there is some slight ambiguity whether the winter recorded as "913" was the one that began in 913 and ended in 914 or the one that began in 912 and ended in 913. For a similar problem with the winter of 939–40, see below, p. 888.

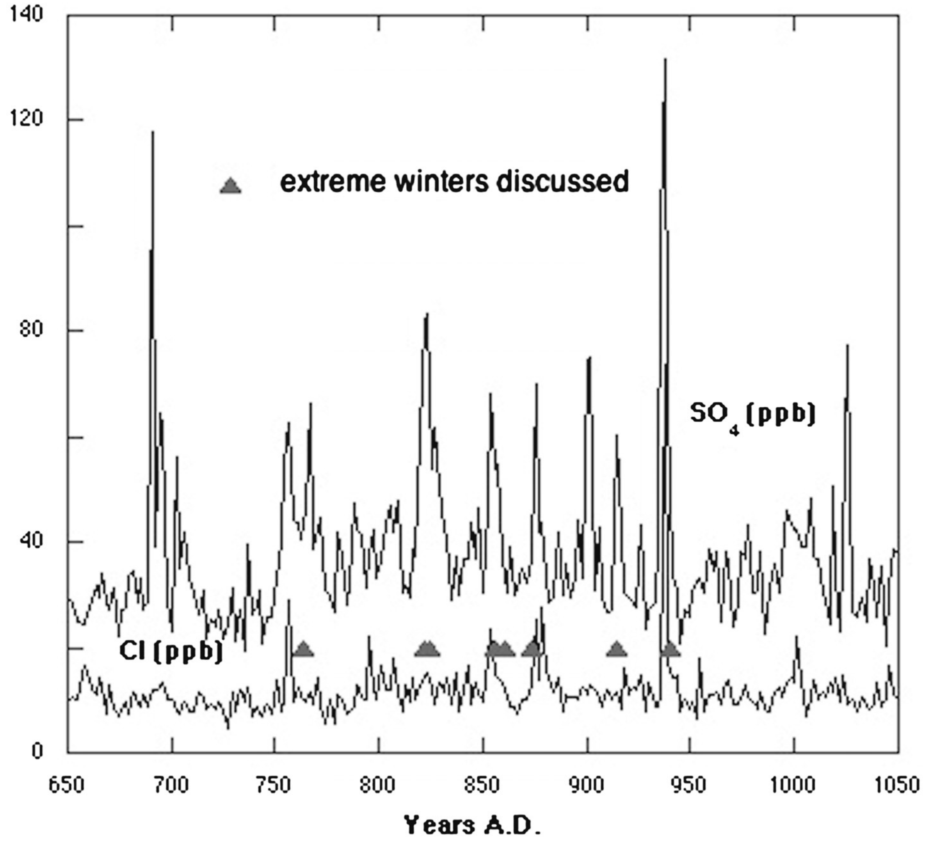

Fig. 5. GISP2 (see Fig. 3 for location) ice core SO_4^+ and Cl^- time series covering the period A.D. 650–1050 and historically documented multiregional climate anomalies between 750 and 950, as discussed in the text.
Spikes in sulfate series are identified as volcanic events, and spikes in chloride (Cl^-) are either associated with expanded sea-ice extent in the North Atlantic (hence cold conditions) or emission from volcanic events. Volcanic forcing of climate is attributed to shielding of incoming solar radiation by sulfate aerosols. While the winter events are absolutely dated unambiguously, as discussed, the date of the volcanic events is exact to 2.5 years.

qualifications of winters must be reckoned as highly relative, which does not facilitate easy translation into modern, measured equivalents. Similarly, considerable regional variation in ancient and modern weather conditions encouraged us to avoid isolated mentions of a "harsh" winter when there was no serious evidence that the anomaly was transregional. Firsthand examination of a wide range of Latin and Greek original sources, as well as consultation of the various repertories of climate and other events in early-medieval written records, nevertheless led us to identify nine truly major winter anomalies in the period between 750 and 950.[26]

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[26] Most useful for this period are the works of F. Curschmann, *Hungersnöte im Mittelalter: Ein*

We accepted only those winters that were described as being exceptionally severe, because of cold, length, or snowfall, *and* that also appear to be documented in more than one region of Europe and in more than one independent source. As it turned out, this made sense in terms of climate forcing by volcanic aerosols, which normally would spread through the stratosphere and affect broad swaths of the earth's surface.[27] Notwithstanding the unevenness of the written records across the 200 years and several thousand kilometers between Ireland and the Byzantine Empire, some of these events were so imposing that they were recorded across that space. All of our unusually severe winters are attested in multiple regions of the European continent; four or five are documented as far to the west as Ireland; one is even documented as far east as southern Russia and Asia Minor.[28] We present them in chronological order, followed in each case by the ice core and other data with which we propose to correlate them.

Event 1:
The terrible winter of 763–64 across Europe and western Asia Minor

From Ireland to the Black Sea, the winter of 763–64 was so extreme that the normally laconic historical and other records of the mid-eighth century refer abundantly to it and offer exceptional details about it and its consequences. The Irish annalistic tradition records that terrible winter as "a great snowfall which lasted almost three months."[29] Compiled from earlier annals at the southern court of

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Beitrag zur deutschen Wirtschaftsgeschichte des 8. bis 13. Jahrhunderts, Leipziger Studien aus dem Gebiet der Geschichte 6/1 (Leipzig, 1900); Curt Weikinn, *Quellentexte zur Witterungsgeschichte Europas von der Zeitwende bis zum Jahre 1850,* 1: *Quellensammlung zur Hydrographie und Meteorologie* (Berlin, 1958); J. Buisman and A. F. V. van Engelen, *Duizend jaar weer, wind en water in de Lage Landen,* 1 (Franeker, 1995); and Ioannes G. Teleles, *Meteorologika phainomena kai klima sto Vyzantio,* 2 vols. (Athens, 2004). The first two in particular require careful verification.

[27] The mechanisms and variations in tropospheric and stratospheric transport of aerosols are only beginning to be elucidated. For a clear overview, see Lamb, *Climate, History and the Modern World,* pp. 64–66; for more details, see, e.g., D. D. Davis, G. Chen, and M. Chin, "Atmospheric Sulfur," in *Handbook of Weather, Climate, and Water* (above, n. 12), pp. 125–56; Kenneth E. Pickering, "Convective Transport," ibid., pp. 157–78; and John H. Seinfeld, "Aerosols: Formation and Microphysics in the Troposphere," ibid., pp. 215–25.

[28] Dutton and McCormick independently compiled their lists of climate anomalies and then met, compared, and critiqued each other's lists to arrive at the most exceptional severe winters. This was done before we encountered the valuable studies of van Engelen, Buisman, and Ijnsen. Those scholars, in "A Millennium of Weather," p. 109, presumably because of their focus on the Low Countries, rate as severe ten winters that we had noticed but excluded, almost always because we could not establish that the winter affected multiple regions: 811, 815 (a mild winter by our information), 843, 845, 872, 880, 881, 887, 894, and 917. They rated the winter of 855–56 as just above normal for the Low Countries, an opinion our reading of the sources does not authorize for much of Europe (see below, Event 4). These evaluations generally reflect the discussions of Buisman and van Engelen, *Duizend jaar weer, wind en water,* 1:193–94 and 196. They curiously deduce a harsh winter from two unexpected thawings of the ice on the Elbe in 815; see pp. 210–11, 219 (872, solely supported by what is probably a misdated entry in a later compilation, the Annals of Stavelot, on which see below, n. 67), 222–23, and 225. They also classify the severity of the winters of 894 and 917 as questionable: pp. 226 and 229.

[29] Annals of Ulster, a late-medieval compilation of lost early annals of Ireland, a. 764.1: "Nix magna .iii.bus fere mensibus," ed. and trans. Seán Mac Airt and Gearóid Mac Niocaill, *The Annals of Ulster*

Wessex around 892, the Anglo-Saxon Chronicle remembers it as "the great winter."[30] In northern England the abbot of Wearmouth-Jarrow apologized to the bishop of Mainz for not sending more books to Germany on account of the impact "of the past winter, which very horribly oppressed the island of our people by cold and freezing and storms of winds and rain." The freezing weather had slowed even the hand of the scribe.[31]

On the Continent eighth-century minor annals record the severe winter in the area from which they drew their information, Austrasia. This was the power center of the new Carolingian dynasty around the Meuse and Moselle rivers and west of the Rhine. In this region that "worst freeze" began on 14 December 763 and continued until 16 March 764.[32] A generation later, the royal court still remembered the winter for its unprecedented bitter cold.[33] About that time someone in the same or a related milieu wrote up the most detailed record, in the *Chronicon Moissiacense*. It observes under the year 762 that the freeze reached as far as the western provinces of the Byzantine Empire: "A great freeze oppressed the Gauls, Illyricum and Thrace and, wasted by the freeze, many olive and fig trees withered; the sprouts of the crops withered, and in the following year, hunger oppressed

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(to A.D. 1131), 1 (Dublin 1983), available online at CELT (The Corpus of Electronic Texts), http://www.ucc.ie/celt/published/G100001A/index.html, accessed on 4 May 2006. The Annals of Ulster are universally regarded as an important and authoritative source for this period: Kathleen Hughes, *Early Christian Ireland: Introduction to the Sources* (Ithaca, N.Y., 1972), pp. 99–107. Although the Annals of Ulster, a.763.5, record: "Sol tenebrosus in hora .iii. diei," which might be construed to refer to a volcanic veiling of sun, Dan McCarthy and Aidan Breen, "An Evaluation of Astronomical Observations in the Irish Annals," *Vistas in Astronomy* 41 (1997), 117–38, at p. 123, identify it with the solar eclipse of 4 June 764, which would have been visible in central Ireland in the fourth and fifth hour. Under 762 the Annals of Ulster a. 762.1 (and of Tigernach presumably) report, "Nix magna et luna tenebrosa": from CELT, as above, and http://curia.ucc.ie/published/G100002/index.html, accessed on 26 July 2006. This has been identified as the partial lunar eclipse visible in central Ireland at 3:38 UT on 25 December 763: McCarthy and Breen, "Astronomical Observations," p. 123.

[30] E.g., Parker and Laud manuscripts, a. 761: "Her waes se mycla winter," ed. Charles Plummer and John Earle, *Two of the Saxon Chronicles Parallel,* 2 vols. (Oxford, 1892–99), 1:50–51.

[31] Gutberct of Jarrow and Wearmouth to Lul of Mainz, *Die Briefe des heiligen Bonifatius und Lullus* 116, ed. Michael Tangl, MGH Epp. sel. 1 (Berlin, 1916), p. 251.

[32] *Annales Sancti Amandi,* a. 764, ed. Georg Heinrich Pertz, MGH SS 1 (Hannover, 1826), p. 10: "tunc fuit ille gelus pessimus, et coepit 19. Cal. Ianuarii, et permansit usque in 17. Cal. Aprilis" (then was that worst freeze, and it started on 19 Kalends of January [i.e., 14 December 763], and it lasted up to 17 Kalends of April [i.e., 16 March 764]); cf. the almost identical wording of the *Annales Petaviani,* a. 764, ibid., p. 11. On this set of annals and their origins, see Norbert Schröer, *Die Annales S. Amandi und ihre Verwandten: Untersuchungen zu einer Gruppe karolingischer Annalen des 8. und frühen 9. Jahrhunderts,* Göppinger akademische Beiträge 85 (Göppingen, 1975). It was a "hiemps grandis et dura" (a great and harsh winter), according to the *Annales Alamannici,* a. 764, MGH SS 1:28; cf., e.g., *Annales Guelferbytani* or the *Annales Nazariani,* a. 764, ibid., p. 29; *Annales Mosellani,* a. 764, ed. I. M. Lappenberg, MGH SS 16 (Hannover, 1859), p. 496; and the *Annales ex annalibus Iuvavensibus antiquis excerpti,* a. 763, ed. H. Bresslau, MGH SS 30/2 (Leipzig, 1934), pp. 732–33.

[33] The *Annales regni Francorum,* a. 763, compiled in the royal court milieu in the 790s, called it the "strong winter" ("Et facta est hiems valida," ed. F. Kurze, MGH SS rer. Germ. [6] [Hannover, 1895], p. 22). When those annals were revised in the same milieu a few decades later, the winter was called "so strong and harsh, that it seemed to be comparable to no winter of earlier years for its enormous cold" ("Facta est autem eo tempore tam valida atque aspera hiems, ut inmanitate frigoris nullae praeteritorum annorum hiemi videretur posse conferri": *Annales Einhardi,* a. 763, ibid., p. 23).

these regions very severely, such that many people died from scarcity of bread."[34] In response to the Frankish king's request for news about the papal and royal ambassadors whose return from Byzantium he had expected earlier, Pope Paul I protested that "it has assuredly not escaped you that because of the very cruel harshness of this winter season, no one is coming from those parts" with news of the envoys. In fact, the pope's unusually specific expression of relief that the king himself, the queen, and their three children were "healthy and safe and unharmed" probably reflects the receding terrors of that extreme winter.[35] The special processions that King Pippin enjoined on the bishop of Mainz for God's mercy for "the great and marvelous consolation and abundance of the fruit of the earth" after the terrible "tribulation for our sins" surely reflects the return to normalcy in 765.[36] The economic impact on the Carolingian kingdom was serious enough to force Pippin to suspend his long-standing effort to conquer Aquitaine.[37]

Some 2,000 kilometers to the southeast, a well-informed observer at Constantinople recorded that great and extremely bitter cold settled on the Byzantine Empire and the lands to the north, west (confirming the *Chronicon Moissiacense*'s statement concerning Illyricum and Thrace), and east. The north coast of the Black Sea froze solid 100 Byzantine miles out from shore (157.4 km). The ice was reported to be 30 Byzantine "cubits" deep, and people and animals could walk on it as on dry land.[38] Drawing on the same lost written source, another contempo-

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[34] Ed. Georg Heinrich Pertz, MGH SS 1:294: "gelu magnum Gallias, Illyricum et Thraciam deprimit, et multae arbores olivarum et ficulnearum decoctae gelu aruerunt; sed et germen messium aruit; et supervenienti anno praedictas regiones gravius depressit fames, ita ut multi homines penuria panis perirent."

[35] Pope Paul I writing to King Pippin III in the winter of 763–64: *Codex Carolinus* 29, ed. W. Gundlach, MGH Epp. 3 (Berlin, 1892), p. 534, line 41–p. 535, line 3: ". . . dum profecto vobis incognitum non est, quod pro tam saeva huius hiemalis temporis asperitate, nullus de illis partibus adveniens nobis adnuntiavit, qualiter circa eis agatur. . . ." Royal family's health: ibid., p. 533, lines 24–30, at line 26: ". . . sani atque sospites et inlesi existentes sitis simul. . . ." This emphatic wording is without parallel in the ninety-nine letters of papal correspondence preserved in the codex; spelling out the members of the royal family is also unusual. Paul's letter furthermore strongly suggests what we would otherwise expect, that the winter was also harsh in Italy. For the date and the suggestion that the *Chronicon Moissiacense*'s unparalleled weather report on the Byzantine Empire is somehow connected with this embassy, which was trapped en route home by the early winter, see McCormick, *Origins of the European Economy,* p. 873 n. 38.

[36] As Michael Tangl astutely observed: Boniface of Fulda, ep. 118, ed. Tangl, *Die Briefe des heiligen Bonifatius und Lullus,* p. 254 with n. 2.

[37] See above, n. 2.

[38] Theophanes, *Chronographia,* A.M. 6255, 2 vols., ed. C. De Boor, 1 (Leipzig, 1883), p. 434, lines 6–17; *The Chronicle of Theophanes Confessor: Byzantine and Near Eastern History, A.D. 284–813,* trans. Cyril A. Mango, Roger Scott, and Geoffrey Greatrex (Oxford, 1997), pp. 600–601. The Greek text has *pècheis* (cubits), which has the same biblical resonance in Greek as in English, for it recurs many times in the Septuagint. The same term recurs in the nearly identical account of Nicephorus's *Short History* (see next n.). If Theophanes' source—in this section both historians are drawing on the same lost source—is using the term literally, it probably refers to the Byzantine construction measure of one and a third Byzantine feet, i.e., 46.8 cm, for a total of 14 m in depth. If he is misusing the term as a kind of biblical echo in the sense of the Byzantine foot, the unit would measure 31.23 cm, for a total depth of 9.37 m. See on these measures Erich Schilbach, in the *Oxford Dictionary of Byzantium,* 3 vols. (Oxford, 1991), 3:1614 and 1708. These conditions prevailed from Zichia (in the area southeast of the Sea of Azov) to Mesembria (modern Nesebŭr, Bulgaria) and Medeia (ancient Salmydessos,

rary, the patriarch of Constantinople, Nicephorus I, emphasized that it particularly affected the "hyperborean and northerly regions," as well as the many great rivers that lay north of the Black Sea.[39] Twenty cubits of snow accumulated on top of the ice, making it very difficult to discern where land stopped and sea began, and the Black Sea became unnavigable.[40] In February the ice began to break up and flow into the Bosporus, entirely blocking it. Theophanes' account recalls how, as a child, the author (or his source's author) went out on the ice with thirty other children and played on it and that some of his pets and other animals died. It was possible to walk all over the Bosporus around Constantinople and even cross to Asia on the ice. One huge iceberg crushed the wharf at the Acropolis, close to the tip of Constantinople's peninsula, and another extremely large one hit the city wall, shaking it and the houses on the other side, before breaking into three large pieces; it was higher than the city walls. The terrified Constantinopolitans wondered what it could possibly portend.[41]

At 66 ppb, the spike in the GISP2 sulfate deposit on Greenland dated 767 is the highest recorded for the eighth century (see Fig. 5) and shows that this terrible winter in Europe and western Asia was connected with a volcanic aerosol that left marked traces on Greenland.

Events 2 and 3:
Two unusually harsh winters in 821–22 and 823–24

The 820s began very inauspiciously, with two very wet summers in a row, according to the annalist and contemporary eyewitness at the court of the Frankish emperor Louis the Pious. That of 820 certainly affected almost every part of the kingdom of the Franks, which covered most of western Europe bounded by the Atlantic, the Baltic, the Elbe, and the Pyrenees and Alps. The summer of 821 also

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modern Midye or Kıyıköy, Turkey, about 100 km up the Thracian coast from the Bosporus), that is to say, across the entire northwestern coast of the Black Sea. Cf. the entries on this winter in Teleles, *Meteorologika phainomena,* 1:342–50, no. 271, and the detailed discussion of the Greek sources in Ioannis Telelis and Evangelos Chrysos, "The Byzantine Sources as Documentary Evidence for the Reconstruction of Historical Climate," in *European Climate Reconstructed from Documentary Data: Methods and Results,* ed. Burkhard Frenzel, Christian Pfister, and Birgit Gläser (Stuttgart, 1992), pp. 17–31.

[39] *Nikephoros, Patriarch of Constantinople, Short History* 74, ed. and trans. Cyril Mango, Corpus Fontium Historiae Byzantinae 13 (Washington, D.C., 1990), pp. 144–49, here pp. 144, lines 1–16, and 147; for his relation to Theophanes, e.g., ibid., p. 12. Nicephorus further refers to the icebergs and solid freezing of the Bosporus as one of the signs of divine anger with the Iconoclast emperors, in his *Refutatio et eversio definitionis synodalis anni 815,* 23, ed. J. M. Featherstone, CCSG 33 (Turnhout, 1997), p. 50, lines 35–41.

[40] Nicephorus, p. 146, lines 16–27; cf. Theophanes, 1:434, lines 13–17. Twenty cubits equals 9.36 or 6.25 m, depending on the term's meaning here (see above, n. 38).

[41] Theophanes, 1:434, line 17–435, line 5; trans. Mango et al., pp. 600–601; for the possibility that Theophanes was copying the eyewitness statement from his source, ibid., p. lviii; cf. Telelis and Chrysos, "The Byzantine Sources," pp. 26–27. The mention of a great drought that follows in this entry of Theophanes, 1:435, line 8, seems inconsistent with the precipitation just described; it may indeed be a misplaced reference to the great drought narrated in A.M. 6258 (A.D. 765–66), as Mango et al. observe, *Chronicle,* p. 602 n. 14; see also Teleles, *Meteorologika phainomena,* 1:351–52, no. 272.

seems to have been cool: the wine harvest was sharply reduced, and what grapes could be collected yielded a harsh wine because of the lack of warmth during the growing season. In some places low-lying lands inundated by flooded rivers prevented the sowing of the winter crop until the next spring.[42] The rains returned or continued in the autumn of 821 in some unspecified areas of the empire such that the autumn sowing of the winter crop was impossible. The heavy rains of 820 and 821 are probably those that disrupted the production of sea salt around this time and that drove at least one purchaser to turn to inland salt works.[43] The summer cooling of 821 announced a winter so long and harsh that it froze even the Rhine, Danube, Elbe, and Seine, as it did the other rivers that flowed across Gaul and Germany to the Atlantic. The ice was deep and hard enough that for thirty or more days carts could cross the great rivers as if on bridges. When the ice melted and flowed downriver, it damaged settlements along the Rhine.[44] One suspects no coincidence when Adalhard, abbot of Corbie, decided in that awful January of 822 to compose a detailed handbook for managing the resources—including the food supply—of his monastery.[45] The freezing cold reached as far west as Ireland, since the Old Irish Annals of Ulster record, "Abnormal ice; the seas, lakes and rivers froze and herds of horses and cattle, and loads, were brought across them."[46] The terrible winter from Ireland to central Europe may well have affected Spain also, since a great famine struck Muslim Spain in year

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[42] *Annales regni Francorum,* a. 820, p. 154: "Hoc anno propter iuges pluvias et aerem nimio humore resolutum magna incommoda contigerunt. Nam et hominum et boum pestilentia tam inmane longe lateque grassata est, ut vix ulla pars totius regni Francorum ab hac peste inmunis atque intacta posset inveniri. Frumenta quoque et legumina imbrium adsiduitate corrupta vel colligi non poterant vel collecta conputrescebant. Vinum etiam, cuius parvus proventus eodem anno fuit, propter caloris inopiam acerbum et insuave fiebat." Louis the Pious and his court spent most of the year at Aachen, although they made a trip into northeastern France: Johann Friedrich Böhmer, Engelbert Mühlbacher, et al., *Die Regesten des Kaiserreichs unter den Karolingern, 751–918,* 3rd ed., Regesta Imperii 1 (Hildesheim, 1966), nos. 709a–731. By this date, the court was regularly apprised of developments around the vast empire. The climatic anomalies of these years may well have been remembered as signs of divine disfavor: see below, n. 82.

[43] Jeremiah, archbishop of Sens, wrote to Bishop Frotharius of Toul requesting his help in buying salt, presumably from the long-established works along the Seille river: *La correspondance d'un évêque carolingien* 28, ed. Michel Parisse, Josiane Barbier, et al. (Paris, 1998), pp. 140–42, dated there 817–20 to 828: "Preterea contigit in nostra provincia presenti anno sal fore carissimum, eo quod propter pluvias in areis maritimis, ubi fieri solebat, non potuisset perfeci usque in hoc tempus. . . ." For the salt works of the Seille see Alan M. Stahl, *The Merovingian Coinage of the Region of Metz,* Publications d'Histoire de l'Art et d'Archéologie de l'Université catholique de Louvain 30 (Louvain-la-Neuve, 1982), pp. 122–25.

[44] *Annales regni Francorum,* a. 821, p. 157: "Cui hiems in tantum prolixa successit et aspera, ut non solum minores rivi ac mediocres fluvii, verum ipsi maximi ac famosissimi amnes, Rhenus videlicet ac Danubius Albisque ac Sequana caeteraque per Galliam atque Germaniam oceanum petentia flumina, adeo solida glacie stringerentur, ut tricenis vel eo amplius diebus plaustra huc atque illuc commeantia velut pontibus iuncta sustinerent; cuius resolutio non modicum villis iuxta Rheni fluenta constitutis damnum intulit." See also the *Annales Xantenses,* a. 821, ed. B. von Simson, MGH SS rer. Germ. [12] (Hannover, 1909), p. 6, line 15: ". . . et hiemps erat valde dura."

[45] *Statuta seu breuia,* ed. J. Semmler, Corpus Consuetudinum Monasticarum 1 (Siegburg, 1963), p. 365, lines 2–3.

[46] Annals of Ulster, a. 822.2, as accessed at http://www.ucc.ie/celt/published/T100001A/index.html on 5 May 2006.

207 of the Hegira (27 May 822–16 May 823).[47] One year later, after widespread hail and electrical storms damaged the harvest in many regions of the Carolingian empire, with ensuing epidemic deaths of men and beasts, a very harsh winter recurred.[48] The Annals of St. Emmeram, from Regensburg in Bavaria, specify that, in addition to famine and a great drought, 823 witnessed "a big winter."[49] This was surely the winter of 823–24, for very early in their entry for 824, and right before the description of a lunar eclipse on 5 March 824, the Royal Annals also describe the winter as "harsh and very long, and the extreme cold extinguished animals, as well as some humans."[50] The ensuing famine was still raging (implicitly in the summer) and forced the emperor to postpone until the autumn the campaign he had planned against the Bretons.[51]

In the Greenland ice-core layers dated to "822 and 823," GISP2 offers a peak reading of 83 ppb of SO_4, the highest sulfate deposit of the ninth century. Because those layers fall within the 2.5 year chronological resolution of the individual strata, they must be considered as reflecting the same event. Even more significantly, a second sulfate peak at 62 ppb occurs in the GISP2 ice layer assigned to "827," demonstrating that the volcanic aerosol was a multiyear phenomenon (see Fig. 5). Conceivably, but not necessarily, the entire sequence from 820 to 824 could represent the fluctuations in one long period of some volcano's activity. In other words, not only is the short interval since the preceding volcanic event and its correlate in the written sources correct within the margin of error of the GISP2 dating at this depth, but so, too, is its duration as a phenomenon of multiple events approximately spanning four years, with a decline in the middle.

The concurrence of the GISP2 evidence for multiple volcanic aerosols and cooling, combined with the written evidence for unusual precipitation and cold, gains more power in light of the most recent evaluation of the development of the Lower Grindelwald Glacier in Switzerland. According to the combined testimony of GISP2 and the medieval written records, the period from 820 to 824 was marked by an exceptional succession of wet and cool summers in 820 and 821, followed by very cold winters in 821–22 and 823–24. In other words, in connection with

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[47] Ibn al-Athīr, *Annales du Maghreb et de l'Espagne,* trans. E. Fagnan (Algiers, 1901), p. 198; Muhammad Ibn Idhārī, *Historia de al-Andalus,* trans. Francisco Fernández González (Malaga, 1999), p. 116; cf. Teleles, *Meteorologika phainomena,* 1:386, no. 309. The deduction that harsh climate conditions also caused the unexplained famine in Muslim Spain is strengthened by the fact that al-Athīr typically does not mention the weather in this section of his work.

[48] *Annales regni Francorum,* a. 823, pp. 163–64: "Et in Saxonia in pago, qui vocatur Firihsazi, viginti tres villae igne caelesti concrematae, et fulgora sereno atque interdiu de caelo cadentia" and "Et in multis regionibus fruges grandinis vastatione deletae atque in quibusdam locis simul cum ipsa grandine veri lapides atque ingentis ponderis decidere visi; domus quoque de caelo tactae hominesque ac caetera animalia passim fulminum ictu praeter solitum crebro exanimata dicuntur. Secuta est ingens pestilentia atque hominum mortalitas, quae per totam Franciam inmaniter usquequaque grassata est et innumeram hominum multitudinem diversi sexus et aetatis gravissime seviendo consumpsit."

[49] *Annales S. Emmerammi maiores,* a. 823, ed. H. Bresslau, MGH SS 30/2:741.

[50] *Annales regni Francorum,* a. 824, p. 164: "Hiemps aspera valdeque prolixa facta est, quae non solum caetera animalia, verum etiam homines quosdam inmanitate frigoris extinxit." For the date in 823–24, see also Böhmer, Mühlbacher, et al., *Die Regesten des Kaiserreichs,* no. 783a.

[51] *Annales regni Francorum,* a. 824, p. 165: "propter famem, quae *adhuc* praevalida erat" (our emphasis); see also Böhmer, Mühlbacher, et al., *Die Regesten des Kaiserreichs,* no. 790b.

one or more volcanic aerosols, western Europe experienced the conditions of increased moisture *and* increased cold that were optimal for glacier advance. This is precisely what happened at the sensitive Lower Grindelwald Glacier, which offers dendrodated evidence of an advance between 820 and 834, an advance that should reflect increased precipitation and/or cold within "a few years" of those dates.[52]

Events 4 and 5:
The harsh winters of 855–56 and 859–60

Two remarkably cold winters struck Europe over the period 855–60. Reports from both France and Ireland document the cold and dry winter of 855–56. The winter of 859–60 appears to have been much harsher still, affecting France, Germany, and northern Italy in extreme fashion. The description of celestial phenomena that are consistent with volcanic aerosols in the atmosphere reinforces the link of the 859–60 winter with a volcanic eruption.[53]

Prudentius, bishop of Troyes, reports that the winter of 855–56 was "most harsh and dry" and accompanied by a strong infection, which killed a big part of the population.[54] Ireland received so much lasting snow and ice that between 23 November and 7 January "the principal lakes and rivers of Ireland could be crossed by people on foot and on horseback."[55] The Annals of Fulda, composed in this period in the Rhine-Main area and reflecting the concerns of the eastern Frankish kingdom, describe the weather of 855 as stormy, inclement, and changeable, with numerous electrical storms in June and July, but say nothing about the winter.[56]

The winter of 859–60 was extraordinarily long and cold across western Europe. The bishop of Troyes reports a strange celestial phenomenon evoking lines of battle, so that it looked as bright as day from the east to the north night sky;

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[52] Holzhauser, Magny, and Zumbühl, "Glacier and Lake-Level Variations" (above, n. 21), at p. 794, with dendrodates from, apparently, twelve trees, according to their fig. 2.

[53] Abundant recent cases of celestial phenomena linked to volcanic aerosols and comparable to those referred to below by Prudentius of Troyes (see below, n. 57) are documented in Lindsay McClelland, Tom Simkin, et al., *Global Volcanism, 1975–1985: The First Decade of Reports from the Smithsonian Institution's Scientific Event Alert Network (SEAN)* (Englewood Cliffs, N.J., 1989), pp. 581–612.

[54] *Annales de Saint-Bertin,* ed. Félix Grat, Jeanne Vielliard, Suzanne Clémencet, and Léon Levillain (Paris, 1964), a. 856, p. 72: "Hiems asperrima et sicca, pestilentia valida qua magna pars hominum absumitur."

[55] Annals of Ulster, a. 856.1. Cf. *Chronicon Scotorum,* a. 856, ed. and trans. William M. Hennessy, *Chronicum Scotorum,* Rolls Series 46 (London, 1866), pp. 154–55, which preserves an abbreviated but generally superior version of the Annals of Tigernach between 765 and 973: Hughes, *Early Christian Ireland,* pp. 106–7.

[56] *Annales Fuldenses,* a. 855, ed. F. Kurze, MGH SS rer. Germ. [7] (Hannover, 1891), p. 45: "Aeris insolita commotio turbinibus ac tempestatibus plagisque grandinum multis damnum intulit. Fulminum ictibus aedes plurimae crematae sunt, inter quas basilica sancti Kiliani martyris Nonis Iuniis clero laudes vespertinas celebrante repentino ictu percussa atque succensa est. . . . Fertur etiam quendam in illis regionibus hominem ita caelesti igne combustum, ut consumpto corpore vestis ab igne remaneret inlaesa. Sequentis vero mensis die octava, instante sollempnitate natalis eiusdem sancti martyris, muros aecclesiae, quos prius caelestis non consumpsit ignis, subito terribilis exorta tempestas funditus evertit; quam ruinam mors episcopi Gozbaldi subsecuta est, qui tercio dehinc mense, id est XII. Kal. Octobris, praesentem vitam finiens Arnum discipulum suum sibi successorem reliquit."

blood red columns extended from it in different directions. This went on during August, September, and October.[57] Then a terrible, long winter set in: snowfalls and freezing were unremitting from November until April.[58] From their Rhine-Main perspective, the Fulda Annals observed that the winter was very harsh, longer than usual and very harmful to the crops and tree fruit. Furthermore, bloody red snow was found to have fallen in many places. The Adriatic Sea froze solid, such that merchants who had hitherto traveled there only by boat now frequented Venice on horseback or moved their merchandise in wagons. The Rhineland observation is confirmed by the tenth-century Venetian chronicle attributed to John the Deacon, which seems to reckon this winter unique over the two-hundred-year period recorded in that work.[59] Similar testimony comes from Swabia: "a great winter, and a dying of animals."[60] According to Andrew of Bergamo, so much snow fell in Italy that it persisted in the plains for a hundred days; the freeze was so bad that many seeds were killed, vines withered, and wine froze in its containers.[61] At Rouen the freeze began on 30 November and continued to 5 April.[62]

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[57] *Annales de Saint-Bertin,* a. 859, p. 81: "Acies in caelo mense augusto, septembri et octobri nocturno tempore uisuntur, ita ut diurna claritas ab oriente usque in septentrionem continue fulserit et columnae sanguineae ex ea discurrentes processerint."

[58] Ibid., a. 860, p. 82: "Hiems diutina et continuis niuibus ac gelu dira, a mense uidelicet nouembri usque ad aprilem." "Continuis niuibus" could mean either "unremitting snowfalls" or "lasting snows." Prudentius further notes a partial obscuring of the moon in the night of 4–5 April and of the sun on 8 April, neither of which seems to correspond to eclipses: a. 860, p. 83, "Pridie nonas aprilis nocte sequenti, nona uidelicet luna iam inchoata, fertur quaedam obscuritas corniculata, eodem scemate quo luna splendebat, per medium eiusdem lunae apparuisse, ita ut hinc inde luceret, sed in medio obscuraretur. Similiter dicitur VIII idus aprilis sol ortus quandam in medio sui orbe tenebrositatem passus, qua ad inferiora eius delabente, mox alia a superioribus eius ingruerit eiusque orbem usque ad infima similiter percucurrerit, et hoc luna Xma." For the ninth-century solar and lunar eclipses, see http://sunearth.gsfc.nasa.gov/eclipse/SEcat/SE0801-0900.html and http://sunearth.gsfc.nasa.gov/eclipse/LEcat/LE0801-0900.html, as well as D. Justin Schove and Alan Fletcher, *Chronology of Eclipses and Comets, A.D. 1–1000* (Woodbridge, Eng., 1984), pp. 173–209.

[59] *Annales Fuldenses,* a. 860, p. 54: "Hibernum tempus asperum nimis et solito prolixius erat frugibusque et arborum proventibus pernoxium; nix quoque sanguinulenta in plerisque locis cecidisse reperta est. Mare etiam Ionium glaciali rigore ita constrictum est, ut mercatores, qui numquam antea nisi vecti navigio, tunc in equis quoque et carpentis mercimonia ferentes Venetiam frequentarent." *Giovanni Diacono Istoria Veneticorum* 2.56, ed. Luigi Andrea Berto (Bologna, 1999), p. 128: "Eo vero anno talis glacies apud Veneciam dicitur fuisse, qualis nec antea nec postea visa est." The Xanten annalist, whose vantage point in this period reflects the lower Rhine, also mentioned the "extremely long winter": *Annales Xantenses,* a. 861, p. 19, line 14: "Eo anno hiemps longissima . . . ," under the incorrect year, on which see Ernst Dümmler, *Geschichte des ostfränkischen Reiches,* 2nd ed., 3 vols. (Leipzig, 1887), 1:459 n. 2. On the Xanten annalists, see Heinz Löwe, "Studien zu den Annales Xantenses," *Deutsches Archiv* 8 (1951), 59–99, and on the incorrect year p. 63.

[60] *Annalium Alammanicorum continuatio Sangallensis prima,* a. 860: "Hiems magna, et mortalitas animalium," ed. Georg Heinrich Pertz, MGH SS 1:50; on this local historical work, see, e.g., Robert Holtzmann, Wilhelm Wattenbach, and Franz Josef Schmale, *Deutschlands Geschichtsquellen im Mittelalter: Die Zeit der Sachsen und Salier,* 2nd ed., 3 vols. (Darmstadt, 1967), 1:226–27.

[61] *Historia* 10, ed. Georg Waitz, MGH SS rer. Lang. (Hannover, 1878), p. 227, lines 5–9: ". . . tanta quidem nivem Italia cecidit, ut per centum dies in planis locis teneret; fuit gelus gravissimus, multa semina mortua fuerunt, vitae pene omnibus in planis locis siccaverunt, et vinum intra vascula glaciavit, quae aetiam per foramen spinarum nihil exiebat, donec rumperetur ipsa glatia cum fuste ab ante ipsa spina. Hoc fuit tempus domni Hludowici imperatori anno 10, ind. octava."

[62] *Annales Rotomagenses,* a. 859, ed. O. Holder-Egger, MGH SS 26 (Hannover, 1882), p. 494; this

Comparison with sulfate sediments in GISP2 strongly suggests that both cold winters reflect volcanic emissions, conceivably, but not necessarily, from one long period of some volcano's activity (Fig. 5). The ice core provides a strong parallel, with a 68 ppb peak in SO_4 in the layer dated to "854" and continuing with a high SO_4 level at a maximum of 55 ppb in the layers assigned to "856" and "858." Because those layers fall within the chronological resolution of individual strata, we consider them as reflecting the same event. Both the historical and glaciochemical records indicate multiyear phenomena.

Event 6:
An exceptionally long and hard winter in western Europe in 873–74 and possibly in Spain and North Africa

After a terrible plague of locusts in Germany, Gaul, and Spain in the late summer of 873, a long and harsh winter followed.[63] Hincmar of Reims, who certainly would have remembered the winter of 859–60, declared that the winter of 873–74 was "long and strong, and the snow was spread about in a quantity such as no one could ever remember seeing."[64] The Fulda annalist recorded that the winter was very harsh and longer than usual. Snow fell continuously from 1 November 873 to the vernal equinox, that is, around 20 March 874, making it very difficult for people to collect firewood; many people and animals died from the cold. The Rhine and the Main were frozen solid for a long time and entirely crossable.[65] The famine and infection that ensued across all of Gaul and Germany, the Fulda annalist asserted, killed about a third of the population.[66] In the lower Rhine region, probably around Cologne, the snow completely covered the ground from

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work, compiled at Rouen in the eleventh century, draws on the Annals of St. Bénigne of Dijon and on local annals that appear to be lost. The report on the winter does not occur in the Annals of St. Bénigne and therefore presumably testifies to conditions in western France. On the *Annales Rotomagenses* see Wilhelm Wattenbach, Wilhelm Levison, and Heinz Löwe, *Deutschlands Geschichtsquellen im Mittelalter: Vorzeit und Karolinger,* 6 vols. (Weimar, 1952–90), 5:584.

[63] Locust plagues appear to require fairly precise and complex meteorological conditions. See "World Meteorological Organization, Expert Meeting on Meteorological Information for Locust Control (Geneva, Switzerland, 18–20 October 2004)" at http://www.wmo.ch/web/wcp/agm/Meetings/milc-geneva/mtgreport-MILC.pdf, accessed on 17 August 2006. On the locust plague of 873, see *Annales de Saint-Bertin,* a. 873, p. 192 with n. 2; the detailed description in *Annales Fuldenses,* a. 873, p. 79, says the locusts appeared with the new crops ("Tempore vero novarum frugum)," came from the east, and devastated Germany and Italy for two months. In one hour they ate their way through 100 *iugera* near Mainz. *Annales Xantenses,* a. 873, p. 33, places the plague in the middle of August.

[64] *Annales de Saint-Bertin,* a. 873, p. 195: "Hiems prolixa et fortis, et nix tanta fuit nimietate perfusa quantam nemo se uidisse meminerit." The following summer was dry and yielded a shortfall of hay and harvest in general: ibid., p. 196.

[65] *Annales Fuldenses,* a. 874, p. 81: "Hiems aspera nimis et solito prolixior; nix quoque inmensa a Kalendis Novembris usque in aequinoctium vernale sine intermissione cadens magnum hominibus fecit impedimentum silvas petere lignaque colligere. Unde accidit, ut non solum animalia, verum etiam homines plurimi frigore perirent. Sed et Rhenus et Moenus glaciali rigore constricti longo tempore se sub vestigiis incedentium calcabiles praebuerunt."

[66] Ibid., a. 874, p. 83: "Hoc anno fame et pestilentia per universam Galliam et Germaniam grassantibus pene tercia pars humani generis consumpta est."

1 November to 15 February.[67] At Reims a set of local annals echoed Hincmar's evaluation of "snow such as no one could remember ever having seen, whence a great proportion of the cattle and sheep died."[68] Whether the terrible famine recorded for North Africa, the Maghreb, and Spain in A.H. 260 (27 October 873–16 October 874) was connected with the weather and/or the locusts, or something else, remains to be determined.[69]

For "876" GISP2 shows a very steep peak to 70 ppb in SO_4 sediment (Fig. 5), signaling a volcanic aerosol deposit on Greenland; the date falls within the ±2.5 years bracket. In this case, then, the precision of the written sources works to fix the less precise GISP2 chronology.

Event 7:
Dark and rainy years and harsh winter in 913 in Ireland, Switzerland, and France

For our purposes, the early tenth century is less well documented in western Europe, since the major Carolingian annals all ceased and with them their broader geographical horizons and regular interest in weather anomalies. Nevertheless, small but sturdy written evidence shows a climatic anomaly in 913. Unless one is a mistaken repetition, two identical entries in the Annals of Ulster document that, in Ireland, both 912 and 913 were "dark and rainy" years.[70] At the abbey of Reichenau, overlooking Lake Constance, an annalist recorded that the winter of 913 (presumably that of 913–14) was a "very big" one.[71] The situation was similar in France, to judge from the Annals of Saint-Quentin in Vermandois, which recorded "a very great freezing" this year.[72]

GISP2 shows a 61 ppb peak in SO_4 sediment in "913–14," which corresponds

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[67] *Annales Xantenses,* a. 873, p. 33, lines 12–15: "Item in Kalendis Novembris usque ad sexagesimam nix totam superficiem terrae cooperuit, et diversis plagis Dominus assiduę populum suum afflixit. . . ." On this segment of *Annales Xantenses* and Cologne, see Löwe, "Studien zu den Annales Xantenses," at pp. 76–82. Andrew of Bergamo refers to strange precipitation on Easter of 873 (not 872, as the editor writes, for the locust plague occurred in the same year in August), *Historia* 17, p. 229, lines 8–9: "In ipsa pascha Domini per arbores vel reliqua folia et loca parebat quasi terra pluvisset." A local tradition from the Ardennes is presumably preserved, one year off, in the eleventh-century Annals of Stavelot's record of a "most serious winter:" *Annales Stabulenses,* a. 872, ed. Georg Waitz, MGH SS 13 (Hannover, 1881), p. 42, lines 29–30: "Hoc anno ⟨lacuna⟩ hyems gravissima, aquarum inundatio, terrae motus, in quibusdam locis pestilentia locustarum"; cf. P. Fransen and H. Maraite, *Index scriptorum operumque Latino-Belgicorum medii aevi/Nouveau répertoire des œuvres médiolatines belges: XIe siècle* (Brussels, 1976), p. 99.

[68] *Annales S. Dionysii Remenses,* a. 873 or 874, ed. Georg Waitz, MGH SS 13:82.

[69] Ibn al-Athīr, trans. Fagnan, p. 244: "En 260 . . . , une famine terrible ravagea l'Ifrîk'iyya, le Maghreb, et l'Espagne et s'étendit même partout. Elle fut suivie de la peste et de violentes épidémies qui enlevèrent beaucoup de monde." See also Ibn Idhārī, *Historia de al-Andalus,* p. 138. Cf. Teleles, *Meteorologika phainomena,* 1:421, no. 348.

[70] Annals of Ulster, a. 912.8 and a. 913.7: "Pluuialis atque tenebrosus annus."

[71] *Annales Augienses,* a. 913, ed. Georg Heinrich Pertz, MGH SS 1:68: "Hiemps magna nimis." On this source, see Holtzmann, Wattenbach, and Schmale, *Deutschlands Geschichtsquellen im Mittelalter,* 1:228.

[72] *Annales S. Quintini Veromandensis,* a. 913, ed. Ludwig Bethmann, MGH SS 16 (Hannover, 1859), p. 507, line 26: "Hoc anno gelum maximum."

to this winter (Fig. 5). Ireland's increased precipitation and dark could certainly correlate with the presence of volcanic aerosols by virtue of their capacity to act as cloud condensation nuclei.

Event 8:
A very harsh winter in Germany and Switzerland, and possibly the Low Countries and Ireland, in 939–40

A "most harsh winter," which caused a bad famine, is attested for Germany and Switzerland in 939–40. Whether this was the winter of 939–40 or 940–41 is not perfectly clear. The contemporary witness Widukind of Corvey, in north-central Germany, situates that winter immediately after the death of dukes Eberhard and Giselbert in the fall of 939, so that the winter by implication was that of 939–40.[73] In the foothills of the Alps it was, according to the Annals of St. Gall, "a hard year, and the crops were insufficient."[74] Herman of Reichenau, under 940, recorded a "cruel winter, followed by an animal pestilence."[75] The harsh winter may have affected the area of present-day Belgium as well, for the annalistic tradition of Lobbes and Liège recorded a famine under the year 941.[76] An Irish source could actually bear witness to the volcanic plume.[77] The severe winter may have been felt even in Ireland, for annals there record "unusual frost" and freezing of the rivers and a battle on ice under the year 941 or 939.[78]

The GISP2 layers assigned to "936," "938," and "939" show the highest spike in sulfate deposits in the two hundred years under review, 132 ppb (Fig. 5). We consider them to reflect the same event, since they fall within the 2.5 year chronological resolution of individual strata. In this case, tephra have been used to identify chemically the volcano from which the sulfate very probably originated:

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[73] "Necem ducum asperrima hiemps hiememque secuta est fames validissima," *Res gestae Saxonicae* 2.26, ed. H.-E. Lohmann and Paul Hirsch, *Die Sachsengeschichte des Widukind von Korvei,* MGH SS rer. Germ. [60], 5th ed. (Berlin, 1935), p. 89, lines 8–9. Emil von Ottenthal and Hans H. Kaminsky, *Die Regesten des Kaiserreichs unter Heinrich I. und Otto I., 919–973* (Hildesheim, 1967), no. 78d, place this winter in 939–40.

[74] *Annales S. Galli maiores,* a. 940, ed. Georg Heinrich Pertz, MGH SS 1:78: "Annus durus et deficiens fructus."

[75] *Chronicon,* a. 940, ed. Georg Heinrich Pertz, MGH SS 5 (Hannover, 1844), p. 113: "Hiems saeva hoc anno facta, et pestis animalium subsecuta."

[76] Although they connect the famine with the comet of 941, e.g., *Annales Laubienses,* a. 941, "Cometes apparuit et fames subsecuta," and similarly *Annales Leodienses,* both ed. Georg Heinrich Pertz, SS 4 (Hannover, 1841), p. 16.

[77] *Chronicon Scotorum,* a. 939, ed. and trans. William M. Hennessy, *Chronicum Scotorum: A Chronicle of Irish Affairs* (London, 1866), pp. 202–3; see the identification with the plume and discussion in McCarthy and Breen, "Astronomical Observations" (above, n. 29), p. 125.

[78] Annals of the Four Masters, a. 939.11 (available online at CELT [above, n. 29]): "Unusual frost, so that the rivers and lakes were passable; and the foreigners plundered Inis-Mochta on the ice." Annals of Ulster, a. 941.1: "Severe frost so that the ice on lakes and streams was passable." Against the 939 date, the chronological reliability of the Annals of Ulster is superior to that of the Four Masters, which stems from a tradition of regnal chronologies that began only in the eleventh century: D. P. McCarthy, "Irish Chronicles and Their Chronology" at https://www.cs.tcd.ie/Dan.McCarthy/chronology/synchronisms/annals-chron.htm, accessed on 17 August 2006. The *Chronicon Scotorum,* whose chronology is generally good, mentions that battle on ice in 941: pp. 202–3.

Eldgjá, on Iceland. The proximity of the Greenland ice sheet to Eldgjá explains the exceptionally high levels of sediment connected with this eruption, for they could well stem from localized tropospheric transport (i.e., lower in the atmosphere) rather than the stratospheric transport, which typically has the most powerful cooling effect.[79] If it is correct that the *Chronicon Scotorum* preserves an eyewitness account of this eruption's plume in 939, then the connection and the date seem confirmed.

3. Conclusions and Discussion

Eight of the nine harshest winters we identified in the written record for western Europe between 750 and 950 have analogues (allowing for the margin of error in dating the ice core's annual layers) right where they would be predicted on the basis of the sulfate deposit levels of the Greenland ice core analyzed by GISP2. Eight of the ten sediment peaks—two of which are in fact multiple or multiyear events—correspond to eight of the nine harshest winters recorded by written sources for this period.

Three cases of noncorrelation occur between 750 and 950. The written sources document one exceptionally severe winter that affected Europe and western Asia at least as far east as Baghdad in 927–28 but that does not correspond to a major surge in SO_4 deposits in GISP2.[80] Conversely, the written sources do not record exceptionally harsh winters for two peaks in GISP2 SO_4 deposits around "757" and "900–902" (see Fig. 5). These cases do not suffice to weaken the relationship between documented volcanic activity and climate forcing in western Europe in the other instances. With respect to 927–28, volcanic forcing is, of course, not the only reason Europe might experience unusually harsh winters. The silence of the Greenland ice core indicates that this terrible winter was not owed to volcanic forcing but to other causes, for instance, an above-average number of invasions of Siberian air over western Eurasia.

The "757" volcanic event (63 ppb; see Fig. 5) occurred as the written records were just beginning to improve, so the silence could possibly reflect the thin surviving historical narratives from this decade. That is not likely the case for the layers assigned to "900–902" (75 ppb; Fig. 5). In any event, large sulfate deposits

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[79] G. A. Zielinski, M. S. Germani, et al., "Evidence of the Eldgjá (Iceland) Eruption in the GISP2 Greenland Ice Core: Relationship to Eruption Processes and Climatic Conditions in the Tenth Century," *Holocene* 5 (1995), 129–40.

[80] As Fig. 5 shows, GISP2's "926" SO_4 deposit does rise above the background level to 45 ppb. However, on our present understanding, it is unclear whether a rise of this level reliably signals a volcanic aerosol. As we stated at the outset, at this early stage of investigation, we judged it preferable to concentrate on unambiguous signals, whether in the natural scientific or in the written evidence. For the terrible winter of 927–28, see, e.g., in western Europe, *Annales Augienses,* a. 927, MGH SS 1:68: "Hiemps magna nimis." In Constantinople the ground froze for 120 days, and there was terrible famine; see, e.g., Symeon Magister, ed. I. Bekker, *Leonis Grammatici chronographia* (Bonn, 1842), p. 318, line 23–p. 320, line 8, on which source see Alexander P. Kazhdan, in the *Oxford Dictionary of Byzantium,* 3:1982–83, while in Baghdad, wine and oil froze in cellar storage, and trees withered: *The Chronography of Gregory Abû'l Faraj . . . Bar Hebraeus,* trans. Ernest A. Wallis Budge, 2 vols. (Oxford, 1932), 1:155; cf. Teleles, *Meteorologika phainomena,* 1:443–8, no. 373.

in Greenland, which certainly signal a volcanic aerosol and cold temperature in Greenland, do not inevitably correspond to harsh winters in Europe. General circulation patterns could arise that might block the westerly transmission beyond Greenland of the aerosol itself. In the absence of the analysis of the tephra associated with these depositions in the ice core, it would also be unwise to rule out the possibility of a purely local event, for instance, another volcanic explosion on (relatively) nearby Iceland, which might not have affected the hemispheric climate to the extent that it did Greenland's. In fact, volcanologists have connected Icelandic eruptions with the SO_4 at this depth in the ice core.[81] It is also possible that the volcanic eruptions responsible for "757" and "900–902" occurred in a time or place when the general circulation patterns distributed the aerosols in a way that did not affect western Europe or that they did so, for instance, in the summer and so escaped the threshold of written recording that prevails in the period. In sum, these absences of correlation do not weaken the correlations that have been drawn.

We historians and archaeologists rarely subject to rigorous statistical testing the correlations we detect in our evidence, although this is standard procedure in the natural and quantitative social sciences. Because our findings will interest scientists as well as more typical readers of *Speculum,* we have sought expert advice on whether the association we have observed between the glaciochemical and written records appears statistically significant. Our colleague Dr. Nick Patterson of the M.I.T.–Harvard Broad Institute kindly devised the test that we publish below as an Appendix. Complications arise from the fact that ice-core data have a resolution of more than one year and are not precisely aligned to calendar time. Patterson modeled the overall displacement between the historical record (H) and the ice-core record (I), as well as the sampling rate and concomitant potential variance of ice-core year assignment; he proceeded to calculate a Pearson correlation (a standard test of the correlation of two variables) and deduce a statistic measuring the association of H and I that fits well with what we know of the ice-core data variation. In order to estimate the statistical significance, he generated random data by permuting the values of H (i.e., year dates). A correlation as high as that observed in the real data is obtained with probability .0047. This provides strong statistical evidence of an association between the historical and ice-core data. For full details, the reader may consult the Appendix.

Scrutiny of Europe's historical written records and the GISP2 glaciochemical record of volcanic aerosols establishes a clear correlation between exceptionally severe winters that affected multiple regions of Europe and volcanic activity between 750 and 950. That one of those volcanically forced RCC events can also be detected in a Swiss glacier suggests the fruitfulness of more intensive compar-

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[81] Gudrun Larsen, "Recent Volcanic History of the Veidivötn Fissure Swarm, Southern Iceland—an Approach to Volcanic Risk Assessment," *Journal of Volcanology and Geothermal Research* 22 (1984), 33–58, at p. 46, hypothesized it was Vatnaöldur, based on Hammer's earlier ice core; Zielinski, Mayewski, et al., "Record of Volcanism," p. 949, table 1, identify this deposit with another Icelandic volcano, Bárdarbunga. It appears that a southerly wind that was blowing at the time of the Vatnaöldur eruption shifted toward the northwest and west in the course of the eruption, i.e., directly toward Greenland and the site of the ice core: Larsen, "Recent Volcanic History," at pp. 43–46.

ative scrutiny of the Greenland ice cores and Swiss glacier movements. We expect that comparison of these climate signals with the other high-resolution climate data, such as those available from varves and tree rings, should yield interesting results on the local effects of such RCC events for the regions they document. The written records deepen our understanding of the interaction between global climate systems and human history by allowing us for the first time to observe the impact of these particular volcanic aerosols on specific human societies. They also invite volcanologists and climate specialists to intensify their study of the tephra associated with particular sulfate deposits in order to clarify the volcanic source of each deposit and, where possible, the season of eruption. This may in turn shed light on the differing size of differing aerosol deposits in Greenland and their relations with the severity of climate impact on Europe. Although such investigations are no longer possible with the GISP2 samples, these findings suggest the value of a new Greenland ice-core project that could deploy recent refinements in methods and instrumentation that allow multiple samples in each year's deposit. Its potential would be considerable for clarifying at a commensurately higher chronological, even seasonal, resolution critical features of Eurasia's historical climate and the forces that drive it. The accelerating disappearance of the world's glaciers under the impact of global warming is yet another incentive for returning to this unique record before it is definitively destroyed.

We have chosen to limit our investigation to the complex historical records of regions and periods with which we have long experience. Beyond the annals and chronicles on which most investigations of earlier medieval weather have focused, we have detected these climate anomalies in a broader range of written records than has hitherto been appreciated, particularly in Carolingian letters and administrative records, and we have no doubt that there is more to be found. Our self-imposed limitation is in no way meant to imply that the RCCs discussed here were necessarily limited to those regions, for general atmospheric circulation and climate conditions are hemispheric, indeed global, phenomena. We hope that colleagues expert in the languages and criticism of the relevant primary sources will examine their own evidence for the climatic impact of these volcanic aerosols in the Arabic, Chinese, Japanese, or other records for the appropriate regions. It would, of course, be worthwhile to expand the scrutiny of potential volcanic forcing of European climate events to the rest of the first millennium and beyond. The high proportion of aerosol deposits that resulted in severe winters, food-production shortfall, and even famine in the relatively well documented period we have studied also has implications for less well documented periods. We suspect that a similarly high proportion of GISP2 aerosol deposits from those periods will correspond to exceptionally severe winters (see Figs. 1 and 5) that may have left little or no written tracks in the scarce documents from those periods.

Some of the best medieval economic history has tended to focus on getting inside systems, understanding how they developed, changed, or collapsed, in terms of their structural components: agrarian or trading technology, crop complexes, social organization, economic incentives, rising or falling supply and demand, market development, political pressures, or institutional frameworks. This paper offers a salutary reminder that exogenous factors have a word to say in the changing economic performance of systems; how different systems were capable of responding, or not, to unforeseen challenges remains nevertheless a crucial part of the story. If we look beyond system to economic conjuncture or fluctuation, we observe that volcanic climate forcing's cruel blows to food production were not regularly distributed over time (and possibly also not over space).

In terms of experienced time, the devastating impact of exceptionally severe winters—which echo through the pope's relief that his indispensable patrons and protectors, the Frankish royal family, had escaped the horrors of 763–64—was no more equally or fairly distributed in the life span of the Carolingian empire. A child born in 765 could die at the ripe old age of fifty-five without having lived through such a winter. One born in 820 would experience five such crises in the same span. Charlemagne was more than vigorous and smart: he was, with respect to volcanic aerosols and rapid climate change, a very lucky ruler. Not so his son Louis the Pious, who, perhaps not entirely coincidentally, in August 822, after the terrible winter of 821–22, ostentatiously expiated before his assembled magnates his and his father's sins.[82] Unfortunately, his act of public penance would have little effect on the volcanic aerosol that produced yet another terrible winter, famine, and disruption but a year later. The reigns of his sons Louis the German and Charles the Bald would suffer from three such bad climate years each; in between two of them, Louis invaded Charles's kingdom.

Volcanic emissions, of course, do not explain the crises that faced the Carolingian empire in the ninth and early tenth century. But they had real impact on the climate, and that affected the production of food and the survival of man and beast. As our discussion has shown, six of the harsh winters were explicitly recorded to have caused an immediate mortality increase, by killing humans, animals, or both in 763–64, 823–24, 855–56, 859–60, 873–74, and 939–40. The impact went beyond human demography, for the deaths of the animals represented real economic losses of capital goods, food supply, and traction power.[83] And that was not the end of it, for subsequent famines surely entailed mortality increases after exceptionally hard winters. Our contemporary witnesses observed and explicitly recorded famines in 763–64, 823–24, 873–74, 939–40, even leaving aside mentions of crop failures that likely implied food shortages. The stark consequences of climate anomalies will have added to the cascading power of events and economic change.

Just as volcanic aerosols and the climate forcing they entail are not evenly distributed over the Carolingian period, nor are they evenly distributed over human history. As Figure 1 shows, the GISP2 record of volcanic activity differs considerably across the 2,000 years of our era. The second half of the first millennium

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[82] *Annales regni Francorum,* a. 822, p. 158. In fact, Paschasius Radbertus may be referring precisely to these climate anomalies as the "inclemencies of the weather" that, among other signs, announced God's displeasure with the sins of the Franks: "Radbert's Epitaphium Arsenii," ed. Ernst Dümmler, *Abhandlungen der Königlichen Akademie der Wissenschaften zu Berlin,* 1899–1900 (Berlin, 1900), at p. 61.

[83] See David Stone, *Decision-Making in Medieval Agriculture* (Oxford, 2005), pp. 45–46, on possible links between deteriorating climate conditions and late-medieval murrains; cf. pp. 54 and 196 on frequency and impact. For the military implications of horse mortality under the Carolingians, see Carroll Gillmor, "The 791 Equine Epidemic and Its Impact on Charlemagne's Army," *Journal of Medieval Military History* 3 (2005), 23–45.

appears to be more volcanically active than the first half; a period of intense volcanic activity also occurs early in the second millennium. The Roman Empire faced few such RCCs of volcanic origin until late in its life span; so, too, the civilization of late-medieval Europe. Unfortunately, the playing field of history is not level. Although few would maintain that volcanically caused climate anomalies determined the course of empires and civilization, they certainly were capable of playing a role that we would do well to integrate into our efforts to observe, untangle, and integrate the mounting arrays of data old and new about the human past.

Perhaps the single most important methodological conclusion of this study concerns the detecting of intelligible patterns of cause and effect in what has hitherto been viewed as unintelligible, or at least patternless: the occurrence of a climate anomaly with serious economic and human consequences. Some years ago the distinguished American historian Bernard Bailyn anticipated the growing integration of what he called "latent" and "manifest" history.[84] "Latent" events are deep developments whose effects contemporaries felt but of which they were unconscious. "Manifest" events, like our extreme winters and famines, are those that contemporaries perceived. This study illustrates how the new data from the science of the past can recover that latent history and how it might be integrated into our established narrative of manifest history. Although the exact timing of volcanic eruptions somewhere on the globe is, so far as we know, unpredictable, the mechanism and nature of the impact of those distant events on the peasants working the fields of early-medieval Ireland, France, Thrace, or Germany are not. In light of the advances of biomolecular archaeology, it is not too much to hope that some day archaeologists who analyze the health history of those peasants' childhoods from their remains will be able to detect a crisis signal from the nutritional deficiency caused by these global disturbances in the formation of their dental enamel, and so fill in another panel in the breathtakingly detailed portrait of medieval society that is beginning to emerge from advanced research, even as they produce demographic data of unmatched chronological resolution.[85]

Although the specific volcanoes specialists have hypothesized as causing the Greenland deposits have not, for the most part, been chemically verified, there is no doubt that there are legitimate candidates. They erupted as nearby as Iceland

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[84] Bernard Bailyn, "The Challenge of Modern Historiography," *American Historical Review* 87 (1982), 1–24, here p. 11.

[85] For the method see Simon Hillson and Daniel Antoine, "Ancient Bones and Teeth on the Microstructural Level," in *Decyphering Ancient Bones: The Research Potential of Bioarchaeological Collections,* ed. Gisela Grupe and Joris Peters, Documenta Archaeobiologiae 1 (Rahden, Germany, 2003), pp. 141–57. Essentially, one would expect to see, e.g., two defects in the development of the tooth enamel (hypoplasia) at the appropriate distance (resolvable almost to the day) corresponding to severe biological stress in the microstructure of enamel formation of most individuals aged between birth and ca. twelve years in the affected regions in the period 855–56 and 859–60. The remarkable by-product of such an observation would be an absolute dating of the birth years of all individuals so marked and therefore, of course, of that part of a cemetery's activity. Especially after the end of the deposit of significant grave goods by the eighth century, such dating is usually possible only within the broad error margins of the radiocarbon method. Hillson described precisely such cases from the later Middle Ages in a workshop held at Harvard University in December 2006.

and as far away as Japan.[86] Far from the intentions and mental horizons of early-medieval people, the global climate system prepared rude blows for men, women, and children across Europe. Fifteen years ago, detecting this would have been impossible. In the future historians and archaeologists will gain further new insights from the advances of the natural sciences. This connection makes clear in a very unexpected way that, here too, the historical experience of Europe was anchored in global realities, even in the early Middle Ages. Combining the discoveries of twenty-first-century science with the extraordinarily deep and varied historical and archaeological record of medieval Europe promises a rich harvest of new insights for specialists of the global present, no less than of the human past.

Appendix
A Statistical Analysis
By Nick Patterson

1. Introduction

We first coded the data of Figure 5 as follows:

1. We made a vector H indexed by the years 750–949 (200 years in all), setting a coordinate 1 when there was a "harsh winter" in the historical record, with other coordinates set 0.
2. We then made a similar vector I for the ice-core data.

In both cases when a range of years is given, we took just the last year of the range. We must deal with the issue that the ice-core data have a resolution of more than a year and are not precisely aligned to calendar time. We introduced two variables, s (displacement) and σ (uncertainty). The displacement will model an overall offset between H and I, while the uncertainty reflects imprecision in an individual measurement. Given σ define a probability distribution $P(x;\sigma)$, $x = -10 \ldots 10$, as

$$P(x;\ \sigma) = \frac{N(x/\sigma)}{\sum_{y=-10}^{10} N(y/\sigma)}$$

and N() is the standard normal distribution function. $P(x;\sigma)$ is a probability density centered on 0 with standard deviation approximately σ. We try values of the displacement s from the range $-3 \ldots 3$ and values of $\sigma = 0.1 \ldots 3(0.1)$. For each choice of s, σ we form a new vector V from I by setting

$$V(i) = \sum_{j:|j+s-i|<10} I(j)P(j + s - i;\ \sigma)$$

V is a vector with "bell-shaped" peaks centered on the years $\{j+s : I(j) = 1\}$ with the peak width depending on σ. We now compute the Pearson correlation $\rho(s, \sigma)$ between H and σ and form $z(s, \sigma) = \sqrt{200}\rho(s, \sigma)$.

If z, σ are fixed, then $z(s, \sigma)$ will be roughly distributed as a standard normal.

Finally we compute

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[86] Tom Simkin, Lee Siebert, and R. J. Blong, *Volcanoes of the World: A Regional Directory, Gazetteer, and Chronology of Volcanism during the Last 10,000 Years,* 2nd ed. (Tucson, Ariz., 1994), p. 187.

$$Z = \max_{s,\sigma} z(s, \sigma)$$

Z is a statistic measuring the association of H and I.

2. Results and Significance

When we carry this out on the data of Figure 2, we obtain

$$Z = 4.443 \text{ for } s = -1, \sigma = 2.2$$

We regard these "best-fitting" values for s, σ as encouraging.

The score for $s = 0$, $\sigma = 2.2$ is only slightly worse ($z = 4.310$), and the uncertainty of 2.2 years fits well with the knowledge of ice-core data described earlier in the article. Our Z score corresponds to a "nominal" p-value of 4×10^{-6}. This is, of course, uncorrected for the choice we have made of s, σ. To calculate a more appropriate significance level, we resort to *permutation testing,* randomly permuting the coordinates of H 100,000 times and for each permutation computing Z. The resulting Z (using a random permutation) equaled or exceeded the Z-statistic on the actual data 470 times out of 100,000. This yields a p-value of .0047—strong statistical evidence of an association between the historical and ice-core data.

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