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SPATIAL RESPONSE TO MAJOR VOLCANIC EVENTS IN OR ABOUT AD 536, 934 AND 1258: FROST RINGS AND OTHER DENDROCHRONOLOGICAL EVIDENCE FROM MONGOLIA AND NORTHERN SIBERIA: COMMENT ON R. B. STOTHERS, ‘VOLCANIC DRY FOGS, CLIMATE COOLING, AND PLAGUE PANDEMICS IN EUROPE AND THE MIDDLE EAST’ (CLIMATIC CHANGE, 42, 1999)

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Abstract. Hypothesized large-scale climatic extremes require verification from distant regions in order to confirm the magnitude and timing of such events. Three of the most massive hypothesized volcanic events of the past two millennia, occurring in or about AD 536, 934 and 1258, had profound climatic and demographic repercussions over much of Europe, the Middle East, and other areas, according to historical accounts recently described in Stothers (1998, 1999, 2000) as well as other research. Here we report on frost ring and other dendrochronological evidence derived from a 1738-year tree-ring chronology from Mongolia and millennial-scale tree-ring data from northern Siberia which demonstrate that these three events may have also impacted conditions in these distant regions.

1. AD 536: Unknown Event

Stothers (1984, 1999) reported historical evidence for dry fog and unusual cold in Europe, the Mediterranean and the Middle East during AD 536-537, and accounts of plague in these areas in AD 541–544. References in Baillie (1994, 1999) cited historical documentation of crop failure, famine and plague in Europe and the Middle East around this time. In AD 536, northern Chinese historical records documented a period of dim sun, summer frosts, loss of crops, severe famine and widespread population losses (Pang and Chou, 1985).

Stothers suggested that these extreme environmental conditions were likely due to a major volcanic event, perhaps the tropical eruption of Rabaul, New Britain (Stothers, 1984) or possibly a northern latitude eruption (Stothers, 1999). Alternatively, it has been theorized that a cosmic phenomenon (asteroid or comet) may explain the unusual climate conditions and other effects at this time (Baillie, 1999).

Acidity peaks from ice cores would support the theory of a volcanic event, and have been sought to provide definitive evidence for the cause of this episode. Yet

Climatic Change **49:** 239–246, 2001.

examination of these data has been inconclusive thus far. Stothers (1984) employed the Crete, Greenland ice core acidity measurements of Hammer (1980), as well as other information, to estimate an optical depth for this episode exceeding that of any other volcanic event, including Tambora (in 1815), in the past three millennia. However Hammer (1984) has since revised his earlier estimated date from AD 540+/-10 to AD 516+/-4. There is a sulfate peak in the GISP ice core, but it is at AD 530+/-2 (Zielinski, 1995). Dates of AD 530 and AD 527 are given in Clausen et al. (1997, pers. comm.) for ice core records from Dye 3 (southeast Greenland) and GRIP (ice cap summit, central Greenland), respectively. Other ice core records either have missing data or are ambiguous (e.g., Zielinski, 1995). Well-dated ice core records from Antarctica may help resolve these ambiguities (Hammer, pers. comm.).

Baillie (1994, 1999) has extensively reviewed tree-ring and other evidence for very unusual conditions in many areas of the globe in the middle 500s. In a multi-millennial Irish oak series, AD 536 was a very narrow ring; but some of the narrowest rings in this record actually occurred in AD 540–541. AD 536 was the second coldest summer in 1500 years in a temperature record from Fennoscandia (Briffa et al., 1992), and there was reduced growth from about AD 536–45 or even later in this and a number of other European chronologies (Baillie, 1999). A temperature-sensitive tree-ring record from North America shows AD 535, 536 and 541 to be the second, third and fourth coldest years over the past two millennia (Scuderi, 1990, 1993). Subnormal growth was also found in western U.S.A. bristlecone pine chronologies (Baillie, 1994, 1999), although there were no frost rings in these records in the middle 500s (LaMarche and Hirshboeck, 1984). A multi-millennial tree-ring record from Chile (Lara and Villalba, 1993) also shows decreased growth at this time, suggesting that this event impacted parts of the Southern Hemisphere. A number of these series show a two-stage decline separated by partial recovery in AD 537–538.

Our chronology from Mongolia extends from AD 262–1999 and was developed from living and relict wood of Siberian pine (*Pinus sibirica* Du Tour) at Solongotyn Davaa (Sol Dav), an elevational timberline site (48°17.51′ N, 98°55.87′ E). The Sol Dav series has been used as an indicator of temperature variability spanning the past two millennia (Jacoby et al., 1996; D’Arrigo et al., 2000, 2001). This temperature-sensitive record contributes new climate information, derived from frost rings, ring widths and latewood density, for a data-sparse, remote region. It can be used to more completely assess the spatial extent and timing of volcanic events and their consequences for climate and humanity.

Frost rings are annual growth increments that have cellular irregularities caused by freeze damage during the growing season. They can signify severely cold conditions related to volcanic and other extreme cold events (LaMarche and Hirschboeck, 1984). Cold air outbreaks or surges are common features in the highly continental Mongolian environment that may cause frost rings to form, even without association with volcanic episodes.

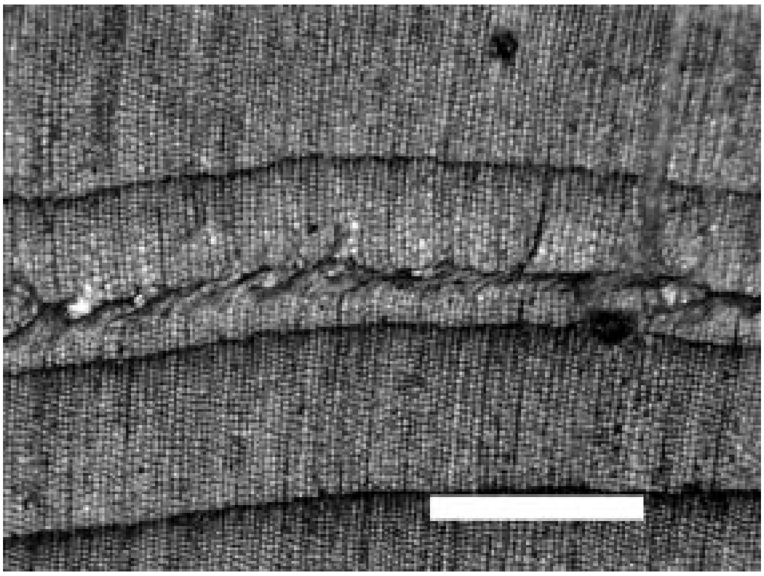

Figure 1. Image of tree core of Siberian pine from Sol Dav, Mongolia showing frost ring in AD 536. Scale bar is one millimeter.

Although climatic effects of volcanism can be more immediate, there can also be delay in manifestation of these effects by several years depending on the nature of a given volcanic eruption (e.g., Robock and Mao, 1995). There may also be a biological lag response in tree growth, particularly for the ring width parameter (e.g., Fritts, 1976, and for Sol Dav, D'Arrigo et al., 2001). Based on our studies of Siberian pine, frost rings appear to show a more immediate response than ring width to hypothesized volcanic cooling. Our observations, although limited, also indicate that latewood frost damage is more likely than earlywood damage to reflect larger-scale (e.g., volcanic episodes) cooling events, as was earlier noted by LaMarche and Hirschboeck (1984). Light density latewood is another parameter which tends to correlate with volcanism, often with a more rapid response than ring width (e.g., Jones et al., 1995; D'Arrigo et al., 1999; Jacoby et al., 1999).

At Sol Dav, three samples of relict wood cover the period around AD 536. Of these, frost damage is observed in the latewood of this year (Figure 1) in two of the samples and although there is no frost damage there is light density latewood in the third.

The ring-width indices for Sol Dav provide additional environmental information. In AD 536 the index value is 0.645, relative to the long-term mean of 1.0. Standard deviation (SD) is 0.204 over the full length of the chronology. This low growth value signals the onset of an overall unusually cold decade (AD 536–545) in which the mean ring-width index is 0.670 (SD 0.240), with a minimum of 0.37 in AD 543. AD 538 shows a brief recovery with an index value of 1.223. As noted, this two-stage pattern is also evident in the European oak and other tree-ring series and may signify a delayed climatic response to one event (as is typical for many volcanic eruptions – e.g., Stothers (2000)) or possibly two separate events (Baillie, 1994, 1999).

The above results for Mongolia are consistent with the observations of summer frosts and snow, crop failure, decreased star visibility and famine documented for northern China in July and August of AD 536–7 (Pang and Chou, 1985). Further indication for a climatic response to this event in Eurasia comes from a cross section of wood from the Taymir Peninsula, Siberia (Jacoby et al. (2000); sites at this location span from 70°37.24′ N–72°27.80′ N and 101°53.50′ E–105°09.46′ E). This sample has several hundred rings which include the middle 500s interval, and was dated through comparison with another Taymir tree-ring series (Naurzbaev and Vaganov, 2000; Briffa, 2000). As for Mongolia, there is an abrupt growth decrease (and light density latewood) in AD 536 followed by a brief recovery and subsequent decline.

The frost ring, ring width and density evidence for low temperatures in Mongolia in the middle AD 500s coincides temporally with the other tree-ring data from the scattered areas noted above. These findings are also remarkably consistent with the historical and archaeological observations of extreme cold, crop failure, plague and famine chronicled by Stothers (1999), Baillie (1999) and other researchers. Our findings from Mongolia and Taymir indicate that the spatial impact of this episode extended further eastward into Eurasia than previously documented.

2. AD 934: Eldgja, Iceland

Stothers (1998) chronicled the massive Eldgja, Iceland volcanic event, considered one of the largest fissure eruptions of the last eleven centuries. He employed historical accounts of dry fog, famine, disease and plague from Iceland, Europe and the Middle East to suggest AD 934 as the most probable date for this event. Very cold winters were documented in AD 934–5 and again in AD 939–40 in Europe and the Middle East, with an intervening period of less severe conditions. Due to its long-lived stratospheric dust veil, Eldgja may have had climatic and demographic impacts up to 5 to 8 years after its eruption, longer than many other events (Zielinski et al., 1995; Stothers, 1998). Estimates from Greenland ice core acidity measurements vary, with dates given of AD 934+/-2 from the Crete ice core (Hammer, 1980, 1984), AD 934+/-3 from Dye 3 (Johnson et al., 1992) and AD 938+/-4 from GISP2 (Zielinski et al., 1995).

Evaluation of tree-ring data from northern Europe and western North America did not show definitive evidence for decreased growth, frost rings or other unusual features associated with this episode (LaMarche and Hirschboeck, 1984; Scuderi, 1990; Zielinski et al., 1995). This lack of consistent findings led Zielinski et al. (1995) to conclude that there may not have been a major cooling following this eruption, although the more recent compilation of historical accounts (Stothers, 1998) seems to indicate otherwise.

Stothers (1998) speculated that Eldgja's sulfuric acid aerosols almost certainly spread much farther (eastward) than northern Europe. Our Siberian tree-ring samples from Taymir, Siberia (Jacoby et al., 2000) do not date through this middle 900s interval. The Taymir chronology of Naurzbaev and Vaganov (2000), which does include this period (and see Briffa, 2000), shows significantly decreased growth in AD 933–5 and again in 940.

At Sol Dav, frost rings are observed in the earlywood of AD 938 in four out of six of the tree-ring samples that date through this period. Yet, ring widths are only slightly below average in 935 (0.969) and in 944–51 (mean 0.853). The prevalence of these frost rings is consistent with the estimates for the timing and subsequent cooling for the Eldgja eruption. However, they could simply indicate a localized outbreak of extreme cold not linked to the Eldgja event.

3. AD 1258: Unknown Eruption

Historical evidence from Europe and the Middle East indicates cold conditions, dry fog, crop damage and pestilence in 1258–1259, and a very cold winter in 1260–1261 (Stothers, 2000). A tropical volcanic event, possibly the most massive eruption of the past millennium, has been postulated to account for these unusual conditions. The historical accounts mention that Europe was very cold from about February–June, 1258, with unusual frost reported in Russia for one day in April 1259. Ice core evidence shows high sulfate values in both Greenland and Antarctica in or about 1259 (e.g., Zielinski, 1995; Clausen et al., 1997). However, the increase in sulfates actually started in 1258 (Hammer et al., 1980), indicating that this was the year that stratospheric injection began.

Reviews of some north temperate tree-ring records (including data from Fennoscandia, Quebec and the western U.S.A.) did not indicate unusual cold in the late AD 1250s or early 1260s (Zielinski, 1995; Stothers, 2000), although there is decreased growth in a series from the Sierra Nevada in 1257 (Scuderi, 1990). There are no frost rings for this event in the LaMarche and Hirschboeck (1984) series.

In the Mongolia tree-ring record there are 5 frost rings (out of 11 samples dating through this period): 3 in the latewood of AD 1258 and 2 in the earlywood of 1259. The ring width index at Sol Dav is about average in 1258 but a decline begins in 1261, with below average growth persisting through 1268. There is a growth minimum in 1262 (0.475). The frost ring evidence supports the contention that this eruption began prior to late summer in 1258. This is not inconsistent with Stothers (2000), who proposes January of 1258 as the eruption's initiation date.

Our Taymir chronology (Jacoby et al., 2000) does not show frost rings but has substantially decreased growth in 1258–1259 (0.744 and 0.345) and 1263-1264 (mean 0.556). The decreased growth departures at Taymir and Sol Dav are in agreement with the historical reports of cold for northern Europe and Russia (Stothers, 2000), and suggest that the greatest climatic impact for this episode may have taken place in Eurasia.

4. Other Major Volcanic Eruptions

We have also examined the tree growth variations in Mongolia and Taymir for possible evidence of unusual growth effects following three of the other most significant eruptions of the past two millennia: in AD 626 (unknown), 1783 (Laki, Iceland) and 1815 (Tambora, Indonesia) (Stothers, 1999).

For Mongolia, we do not find either frost rings, light density latewood or decreased ring widths at Sol Dav around the time of the postulated eruption in AD 626 (Stothers and Rampino, 1983; Stothers, 1999). A frost ring was observed by LaMarche and Hirschboeck (1984) in AD 628 which may relate to this event. The climatic effects of Laki have been described in tree-ring records for Alaska (D'Arrigo et al., 1999; Jacoby et al., 1999), Norway (Jones et al., 1995) and other locations. Demaree et al. (1998) had mentioned that available evidence for unusually cold conditions east of the Altai Mountains was limited to only a few accounts of dry fog and haze in China, possibly suggesting that Laki's impact was diluted in this general area. At Sol Dav, tree growth is not unusually low in 1783. However, two out of sixteen living tree samples at this site do show frost damage. For the 1815 eruption of Tambora, below average growth is observed (index value 0.698).

At Taymir, there is no evidence of unusual growth or frost damage linked to either the AD 626 or 1815 eruptions. However, there is decreased growth (without frost damage) in Taymir in 1783, with an index value of 0.455. There were near normal conditions in 1784–1785 and an index value of 0.257 in 1786 (density values for an adjacent site are slightly below normal), indicating a possible impact in northern Siberia.

Acknowledgements

Research supported by the National Science Foundation, Climate Dynamics and Earth Systems History Programs. This research was aided by the Mongolian Ministry for Nature and the Environment, Institute of Biological Sciences and Hydrometeorological Research Institute. We gratefully acknowledge Drs. Naurzbaev and Vaganov for use of their Taymir tree-ring data and R. Stothers for helpful comments. Lamont-Doherty Earth Observatory Contribution No. 6086.

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