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# New ice core evidence for a volcanic cause of the A.D. 536 dust veil

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[1] New and well-dated evidence of sulphate deposits in Greenland and Antarctic ice cores indicate a substantial and extensive atmospheric acidic dust veil at A.D. 533–534 ± 2 years. This was likely produced by a large explosive, near equatorial volcanic eruption, causing widespread dimming and contributing to the abrupt cooling across much of the Northern Hemisphere known from historical records and tree-ring data to have occurred in A.D. 536. Tree-ring data suggest that this was the most severe and protracted short-term cold episode across the Northern Hemisphere in the last two millennia, even surpassing the severity of the cold period following the Tambora eruption in 1815. **Citation:** Larsen, L. B., et al. (2008), New ice core evidence for a volcanic cause of the A.D. 536 dust veil, *Geophys. Res. Lett.*, *35*, L04708, doi:10.1029/2007GL032450.

## 1. Introduction

[2] In the year A.D. 536 a widespread dust veil event caused dimming and cooling across much of the Northern Hemisphere [*Stothers and Rampino*, 1983; *Weisburd*, 1985; *Rampino et al.*, 1988]. This mysterious event is known from both historical records and tree-ring data [*Baillie*, 1991, 1994]. The cooling effect of the dry-cloud might even have been a contributing cause of the Justinian Plague [*Baillie*, 1991].

[3] During the past decades the cause of the historically observed dimming of the sun in the year 536 has been widely debated [*Stothers and Rampino*, 1983; *Stothers*, 1984; *Baillie*, 1994, 1999; *Keys*, 1999; *Rigby et al.*, 2004]. The lack of a contemporaneous volcanic deposit in ice cores to explain the dust veil [*Clausen et al.*, 1997] has long been enigmatic and has even led to speculation that the event was caused by an impact from an extraterrestrial object [*Baillie*, 1999; *Rigby et al.*, 2004].

[4] Adding to the confusion, a previously identified $SO_4^{2-}$ deposit in the Dye-3 ice core was given a 535 date [*Herron*, 1982]. However, this was based on a preliminary timescale established by combining the counting of only 300 annual layers with ice flow modelling. This modelling was subsequently found to be oversimplified and more extensive annual layer counting shifted the date to 516 [*Clausen et al.*, 1997].

[5] Here we show new and well-dated evidence of sulphate deposits in Greenland and Antarctic ice cores that indicate the existence of a substantial and extensive atmospheric acidic veil at A.D. 533–534 ± 2 years. This is strong evidence that a large explosive, near equatorial volcanic eruption caused the observed dimming and cooling, removing the need for an extraterrestrial explanation.

## 2. Data

### 2.1. Tree-Ring Chronologies

[6] The tree-ring chronologies (Figure 1 and Table 1) are expressed here in high-pass filtered form. This is achieved by first fitting a 60-year spline to each constituent measurement series and dividing the measurement data by the fitted values to yield dimensionless index data for each tree. These are then averaged in correct calendrical alignment to produce a mean chronology series. The appropriate section of this series is then divided back into each measurement series and the new residuals fitted with the 60-year smoothing spline. This process is repeated six times so that the ultimate fit of the smoothing splines (which define the multidecadal and longer variability to be removed from the chronology) is not locally distorted by the presence of any abrupt shifts in the chronology (such as represented by the cooling in 536). A detailed description of this process is given by *Melvin and Briffa* [2008].

### 2.2. Measurements of Chemical Impurities in the Greenland Ice Cores

[7] The samples for ion chromatographic measurements were decontaminated manually with a microtome knife in a laminar flow bench. 143 samples from Dye-3 and 76 samples from GRIP were cut in the cold lab in Copenhagen. Samples from NGRIP were cut in the field (see Table 2 for drill site locations). All samples were measured in Copenhagen. Each sample was melted prior to measurement and decanted into 5-mL vials for automatic injection into the ion chromatograph. The University of Copenhagen ion chromatograph is a DIONEX 500 equipped with a two-

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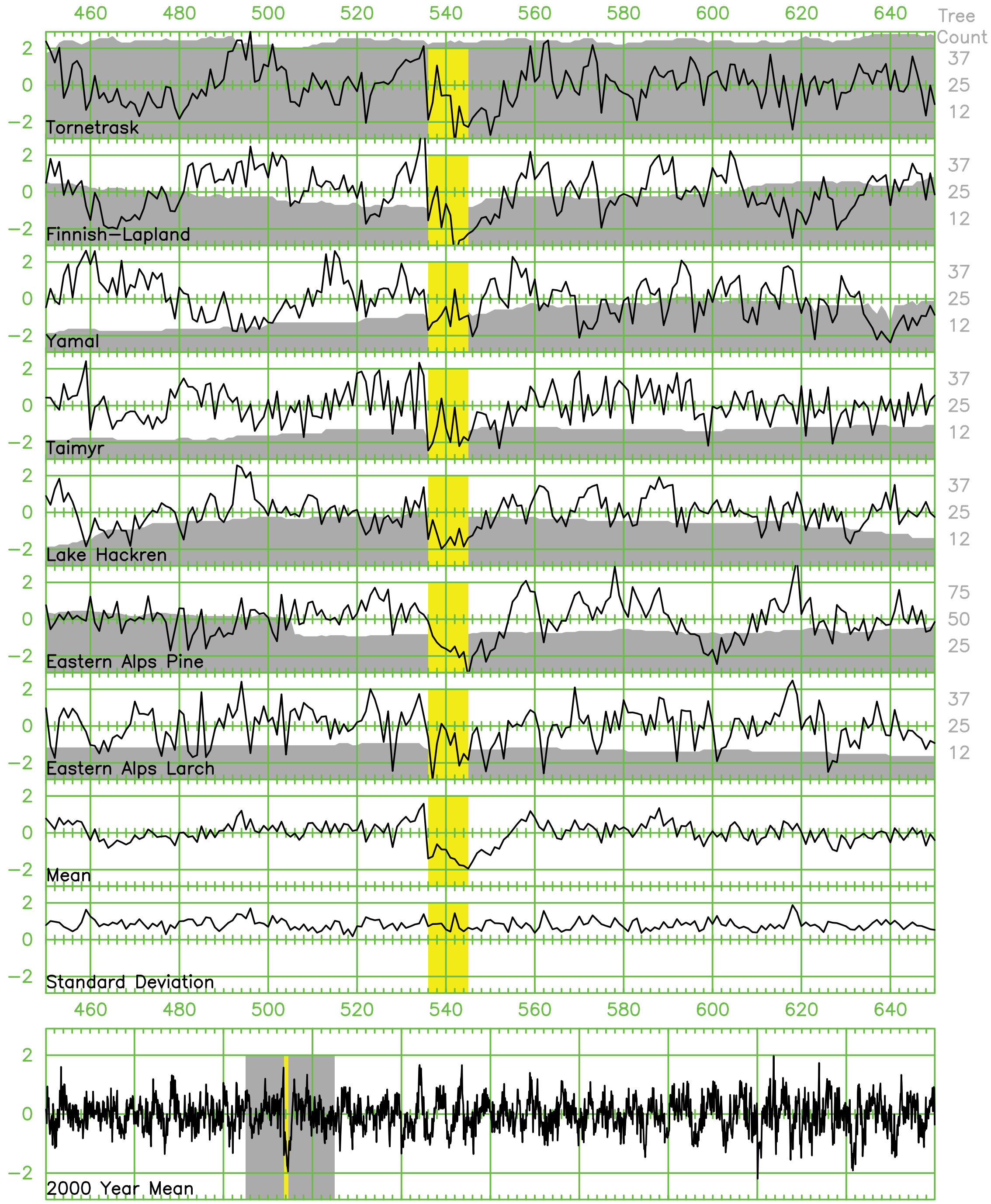

**Figure 1.** High-pass filtered index chronologies for Tornetrask, Finish-Lapland, Yamal, Taimyr, Lake Hackren and the Austrian Alps (two species). All chronologies are standardised over the common period A.D. 1 to 800 and plotted for the period 450–650 with dark grey shaded areas indicating sample counts. The series of means and standard deviations of these chronologies are also shown for the period 450–650. The mean series over the period 1 to 1999 is shown in the bottom panel. Low tree-ring indices can be seen during the period 536 to 545 (indicated by the yellow vertical column).

channel setup, where anions and cations are measured at the same time. Chromatograms were integrated by Peaknet 5.1 software.

## 3. The 536 Event in Tree-Ring Chronologies

[8] The severity of the summer cooling across wide areas of the Northern Hemisphere beginning in 536 is evident in the low growth shown in a number of long tree-ring chronologies, located in cool and relatively moist sites at high latitudes or high elevations in north and central Sweden, Finland, Russia and Austria (Table 1 and Figure 1). Averaging chronologies from these regions, after high-pass filtering to remove background climate trends (Figure 1 (bottom)) reveals the extent of severely reduced tree growth

**Table 1.** Site Details of Tree-Ring Chronologies

| Name | Species | Elevation, m a.s.l. | Latitude, °N | Longitude, °E | Reference |
|---|---|---|---|---|---|
| Tornetrask | *Pinus sylvestris* | 300–600 | 68.2 | 19.8 | *Grudd et al.* [2002] |
| Finnish-Lapland | *Pinus sylvestris* | 100–465 | 69.8 | 28.0 | *Eronen et al.* [2002] |
| Yamal | *Larix sibirica* | 10–60 | 67.5 | 70.0 | *Hantemirov and Shiyatov* [2002] |
| Taimyr | *Larix gmelinii* | 200–300 | 72.0 | 101.0 | *Naurzbaev et al.* [2002] |
| Lake Hackren | *Pinus sylvestris* | 560–830 | 63.2 | 13.3 | *Gunnarson et al.* [2003] |
| Eastern Alps Pine | *Pinus cembra* | 1830–2430 | 47.0 | 11.0 | *Nicolussi et al.* [2005] |
| Eastern Alps Larch | *Larix decidua* | 1950–2230 | 46.7 | 10.7 | Nicolussi (unpublished, 2007) |

and, by inference, summer cold lasting from 536 to at least 550. While biological persistence in the tree-ring series may extend the apparent duration of the cooling signal somewhat, the severity of the event is still more marked than the widely recognized volcanically induced coolings starting in 1601 (at least in part associated with the eruption of Huaynaputina [*de Silva and Zielinski*, 1998]) and 1810 (associated with a low latitude eruption in 1809 and the Tambora eruption in 1815 [*Harrington*, 1992; *Briffa et al.*, 1998; *Briffa*, 2000]). These results suggest an eruption in 535 (or successive eruptions in and shortly after 535) of unparalleled magnitude in the last two millennia. Reduced tree growth or wood anatomical evidence in the form of "frost rings" also indicate severe cold in the western United States and Mongolia in 536 [*Scuderi*, 1990; *D'Arrigo et al.*, 2001; *Salzer and Hughes*, 2007].

[9] The very few long temperature sensitive chronologies in the Southern Hemisphere [*Cook et al.*, 2006] do not indicate any significant cooling in either 536 or the decade of the 540s, but neither do they show a great decline following the 1601, 1809 or the Tambora eruptions.

## 4. The 536 Event in Greenland and Antarctic Ice Cores

### 4.1. Greenland Evidence

[10] Here we present measurements of chemical impurities in three Greenland ice core records: Dye-3, GRIP and NGRIP. These measurements reveal a hitherto underestimated acidity signal that is consistent with a volcanic cause for the 536 event (Figure 2b). This $SO_4^{2-}$ deposit has been dated to 533–534 ± 2 in a recently completed dating effort in which annual layer counting was carried out in the Dye-3, GRIP and NGRIP ice core records simultaneously [*Vinther et al.*, 2006]. This dating is furthermore anchored by tephra from the historically dated A.D. 79 Vesuvius eruption.

[11] The 533–534 ± 2 $SO_4^{2-}$ deposit is preceded by an even larger $SO_4^{2-}$ deposit in the three Greenland ice cores, dated to 529 ± 2 (Figure 2b). This $SO_4^{2-}$ deposit may have been caused by the mid 6th century plinian Haruna eruption (VEI = 5), Japan [*Soda*, 1996], as its pattern of $SO_4^{2-}$ deposition shows striking similarities to that stemming from two 17th century Japanese volcanic eruptions (Figure 2c). While the reason for the similarities is poorly understood, it is interesting that archaeological evidence strongly suggests that the Haruna eruption took place in early summer [*Soda*, 1996], i.e. at almost the same time of year as the two 17th century Japanese volcanic eruptions shown in Figure 2c (relevant summers are indicated with "S" in Figure 2). It is

**Table 2.** Site Details for Greenland Ice Cores

| Drill Site | Latitude, °N | Longitude, °W | Elevation, m a.s.l. | Accumulation, m ice/year |
|---|---|---|---|---|
| NGRIP | 75.10 | 42.32 | 2917 | 0.19 |
| GRIP | 72.58 | 37.64 | 3230 | 0.23 |
| Dye-3 | 65.18 | 43.83 | 2480 | 0.56 |

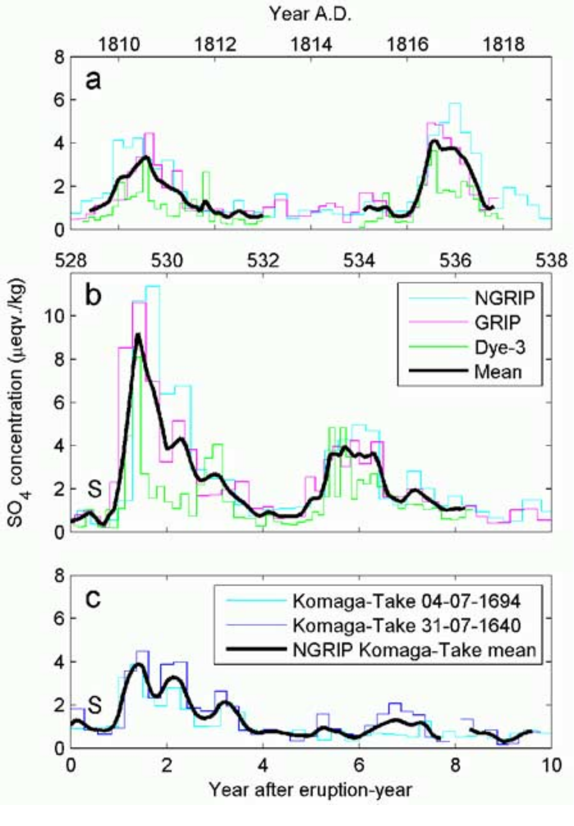

**Figure 2.** Volcanic $SO_4^{2-}$ deposits as registered in the Greenland ice cores. (a) The deposits following the 1809 eruption (unknown source) and the 1815 Tambora eruption. (b) The deposits from what is believed to be the Haruna (Japan) eruption (left) and the eruption that caused the 536 dust veil (right). (c) The deposits in the NGRIP ice core following two eruptions of Komaga-Take (Japan) in the 17th century. The summers during which both the Komaga-Take eruptions occurred and that when the Haruna eruption is believed to have taken place are marked with "S". The summers have been determined directly from the stable isotope data that were used for the ice core dating.

**Table 3.** Selected Volcanic $H_2SO_4$ Deposits From Well-dated Greenland and Antarctic Ice Cores

| Eruption | Greenland Peak $H_2SO_4$ Dating,[a] A.D. | Dye-3 $H_2SO_4$,[b] kg/km$^2$ | GRIP $H_2SO_4$,[b] kg/km$^2$ | NGRIP $H_2SO_4$,[b] kg/km$^2$ | Antarctica Peak $H_2SO_4$ Dating,[c] A.D. | DML05 $H_2SO_4$,[d] kg/km$^2$ | DML07 $H_2SO_4$,[d] kg/km$^2$ |
|---|---|---|---|---|---|---|---|
| Haruna? | 529 ± 2 | 104 ± 5 | 101 ± 3 | 97 ± 3 | - | - | - |
| 536 event | 533/534 ± 2 | 100 ± 7 | 61 ± 4 | 57 ± 4 | 542 ± 17 | 29.2 ± 6.3 | 43.9 ± 15.6 |
| 1809 event | 1810 | 44 ± 5 | 29 ± 2 | 38 ± 3 | 1809 ± 3 | 15.4 ± 9.3 | 27.5 ± 3.4 |
| Tambora | 1816 | 63 ± 4 | 39 ± 2 | 46 ± 2 | 1816 ± 1 | 32.5 ± 7.0 | 54.6 ± 5.5 |

[a] Greenland ice core dating from *Vinther et al.* [2006].

[b] The natural $H_2SO_4$ background has been subtracted from all data. The uncertainties in deposited $H_2SO_4$ are a direct consequence of the uncertainties in the determination of the $H_2SO_4$ background.

[c] Antarctic ice core dating from DML cores [*Traufetter et al.*, 2004].

[d] DML data from *Traufetter et al.* [2004].

therefore conceivable that the seasonally recurring large scale atmospheric flow patterns could yield similar depositional patterns for eruptions happening at the same time of year.

[12] The A.D. 533/34 ± 2 deposits and the 1815 Tambora deposits also show some similarities, with Dye-3 having an early $SO_4^{2-}$ peak followed by broader signals in GRIP and NGRIP $SO_4^{2-}$ (Figures 2a and 2b) [*Clausen et al.*, 1997; *Langway et al.*, 1995]. Another striking similarity between the Tambora $SO_4^{2-}$ signals and the 533–534 ± 2 $SO_4^{2-}$ signals is their spatial distribution across Greenland. In both cases the Dye-3 $SO_4^{2-}$ loading (measured in kg $H_2SO_4$ per km$^2$) is 40–50% larger than the $SO_4^{2-}$ loading at GRIP/NGRIP (Table 3). This is consistent with the observed depositional pattern over Greenland for radioactive fallout released by low latitude (∼11°N) thermonuclear-bomb tests in the early 1950s [*Clausen and Hammer*, 1988]. For the 529 ± 2 event the Dye-3 $SO_4^{2-}$ loading is of the same magnitude as the GRIP and NGRIP loading, indicating a more northerly source eruption [*Clausen and Hammer*, 1988], thus providing additional support for a mid to high latitude eruption being the likely cause of the 529 ± 2 $SO_4^{2-}$ deposit.

### 4.2. Antarctic Evidence

[13] If the 533–534 ± 2 $SO_4^{2-}$ deposit originates from a tropical eruption, then a deposit should also be detectable in Antarctic ice cores. Up until a few years ago the dating uncertainty for the Antarctic ice core records that reached more than 1500 years back in time was about 5% or more [*Cole-Dai et al.*, 2000; *Steig et al.*, 2000; *Taylor et al.*, 2004], which is too high (more than ±70 yr at 536) to safely assign any peak to the 536 dust veil event, as all records would have one or two deposits that would be consistent with just about any age. Recent efforts to improve dating and quantify $SO_4^{2-}$ deposits have, however, resulted in a new chronology of $SO_4^{2-}$ deposition from Dronning Maud Land (DML), Antarctica, with a dating uncertainty of just ∼1% [*Traufetter et al.*, 2004]. This new chronology reveals an $SO_4^{2-}$ deposit at 542 ± 17 (Table 3). The deposit has been detected in three shallow ice cores from Dronning Maud land [*Traufetter et al.*, 2004] as well as in the EPICA DML and EPICA Dome C deep ice cores [*Severi et al.*, 2007]. It should be noted that while the deposit is identifiable in the EPICA Dome C $SO_4^{2-}$ record [*Severi et al.*, 2007] its magnitude was not sufficient to exceed the volcanic detection limit applied by *Castellano et al.* [2005].

[14] Hence the 536 dust veil event can be linked to $SO_4^{2-}$ deposits in both hemispheres if a slight shift in the Greenland and Antarctic ice core dating is accepted. A perfect match would require the Antarctic DML ice core dating to be shifted 6 years back in time while the Greenland ice core dating should be shifted 2–3 years forward in time. Interestingly, such a shift in chronologies would line up two more $SO_4$ deposits in Greenland and Antarctica to within 1–2 years: The DML deposits at 578 ± 16 and 684 ± 14 [*Traufetter et al.*, 2004], and Greenland deposits at 567–568 ± 2 and at 674–675 ± 2 observed in all three Greenland ice cores on their common time scale. It is very hard to believe that this near-perfect accord between Greenland and Antarctic $SO_4^{2-}$ is coincidental given the current narrow dating constraints on these ice cores. Therefore, these recently well-dated ice core data from both hemispheres provide a consistent indication of an equatorial volcanic eruption as the most likely cause of the 536 dust veil.

### 4.3. Magnitude and Impact of the 536 Event

[15] The Greenland ice core data suggests that the eruption associated with the 536 dust veil caused ∼40% more $SO_4^{2-}$ deposition than the Tambora eruption, while the Antarctic ice core data suggest that the eruption had a deposition some 15% smaller than Tambora. However, the uncertainty of the Antarctic $SO_4^{2-}$ deposition estimates are too large to draw any firm conclusions. The fact that the 536 dust veil is associated with 40% more $SO_4^{2-}$ deposition in Greenland than brought by the 1815 Tambora eruption is in accord with historical observations from Europe, China and Mesopotamia that the 536 dust veil event was more severe and produced more protracted dimming than was observed after the Tambora eruption [*Stothers*, 1984].

[16] While an equatorial eruption is consistent with the observed dust veils and the rapid climatic downturn in 536, it is not clear to what extent the eruption directly contributed to the prolonged nature of the apparent growth anomaly seen in Figure 1. The general variability of interdecadal temperatures implied in Figure 1 indicates that internal climate variability could also have contributed to the persistence of the growth anomaly. The 567–568 ± 2 and 674–675 ± 2 events apparently did not cause a pronounced impact on NH tree growth, but this could at least partly be due to the smaller magnitude of these events (their Greenland $SO_4^{2-}$ deposits are 10–30% smaller than the Tambora deposit).

## 5. Conclusion

[17] The improvement in ice core dating and the increasing availability of high quality $SO_4^{2-}$ measurements from ice cores from both hemispheres allow us to conclude that a

tropical volcanic eruption of somewhat larger magnitude than the Tambora eruption most likely caused the 536 dust veil. This removes the apparent mystery that has surrounded the 536 dust veil and emphasizes the value of joint analyses of carefully dated tree-ring and ice core records in reconstructing the magnitude, timing and effects of volcanism in the past.

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