

7-29-2006

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Yalcin, Kaplan; Wake, Cameron P.; Kreutz, Karl J.; Germani, Mark S.; and Whitlow, Sallie I., "Ice Core Evidence for a Second Volcanic Eruption Around 1809 in the Northern Hemisphere" (2006). *Earth Science Faculty Scholarship*. 44.  
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## Ice core evidence for a second volcanic eruption around 1809 in the Northern Hemisphere

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Received 9 February 2006; revised 10 April 2006; accepted 14 June 2006; published 29 July 2006.

[1] A volcanic signal observed in ice cores from both polar regions six years prior to Tambora is attributed to an unknown tropical eruption in 1809. Recovery of dacitic tephra from the 1809 horizon in a Yukon ice core (Eclipse) that is chemically distinct from andesitic 1809 tephra found in Antarctic ice cores indicates a second eruption in the Northern Hemisphere at this time. Together with the similar magnitude and timing of the 1809 volcanic signal in the Arctic and Antarctic, this could suggest a large tropical eruption produced the sulfate and Antarctic tephra and a minor Northern Hemisphere eruption produced the Eclipse tephra. Nonetheless, the possibility that there were coincidental eruptions of similar magnitude in both hemispheres, rather than a single tropical eruption, should not be discounted. Correctly attributing the source of the 1809 volcanic signal has important implications for modeling the magnitude and latitudinal distribution of volcanic radiative forcing. **Citation:** Yalcin, K., C. P. Wake, K. J. Kreutz, M. S. Germani, and S. I. Whitlow (2006), Ice core evidence for a second volcanic eruption around 1809 in the Northern Hemisphere, *Geophys. Res. Lett.*, 33, L14706, doi:10.1029/2006GL026013.

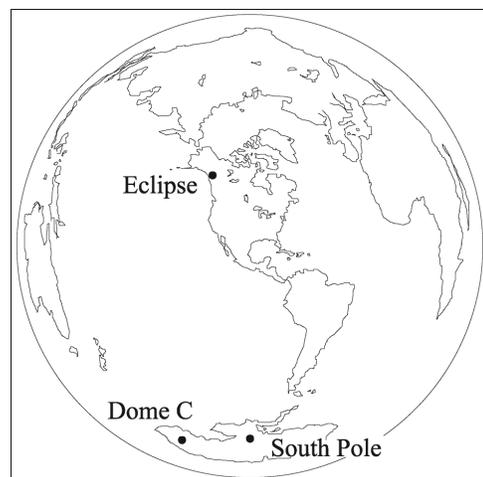
### 1. Introduction

[2] Explosive volcanic eruptions in the tropical latitudes can perturb climate on a global scale; unfortunately an incomplete record of volcanism complicates investigations of the influence of such eruptions on past climate. Large eruptions of global influence may have gone unnoticed as recently as the 1809 eruption known only in ice core records from Greenland [Cole-Dai *et al.*, 1991; Zielinski, 1995; Langway *et al.*, 1995; Clausen *et al.*, 1997; Kohno and Fujii, 2002] and Antarctica [Legrand and Delmas, 1987; Cole-Dai *et al.*, 1991, 1997, 2000; Moore *et al.*, 1991; Delmas *et al.*, 1992; Langway *et al.*, 1995; Stenni *et al.*, 1999; Palmer *et al.*, 2002]. Assuming a tropical source of the eruption, Zielinski [1995] calculated a stratospheric H<sub>2</sub>SO<sub>4</sub> loading of 34 to 68 × 10<sup>12</sup> g and an optical depth of 0.11 to 0.28 from the GISP2 ice core, placing the 1809 eruption among the largest of the last few centuries.

A latitude between 20° N and 10° S and an eruption column height of at least 25 km (Volcanic Explosivity Index (VEI) 5 or greater) are requirements for a volcanic signal to be seen in both Greenland and Antarctica [Kohno and Fujii, 2002]. However, no eruption with a VEI > 3 is reported in the historical volcanism record between 1801 and 1812 [Simkin and Siebert, 1994].

[3] Analysis of tephra associated with volcanic SO<sub>4</sub><sup>2-</sup> peaks in ice cores can provide information on the source volcano responsible for an eruption. Tephra associated with the 1809 SO<sub>4</sub><sup>2-</sup> peak has been found in ice cores from South Pole [Palais *et al.*, 1990] and Dome C, Antarctica [De Angelis *et al.* [1985]; reinterpreted to be from the 1809 horizon by Legrand and Delmas [1987]] (Figure 1). Palais *et al.* [1990] suggested the source of the tephra found in the South Pole and Dome C ice cores was Cosiguina, Nicaragua, based on the similar chemical compositions of the Antarctic 1809 tephra and Cosiguina 1835 eruption products and a March 1809 eruption date for Cosiguina [Simkin and Siebert, 1994]. However, recent work on Cosiguina has not uncovered any geologic evidence for an eruption around 1809 [Scott *et al.*, 2006] and the 1809 eruption date for Cosiguina is now regarded as spurious (S. Self, personal communication, 2004).

[4] In this paper we present evidence for a second eruption in the Northern Hemisphere in 1809 using tephra found in an ice core from Eclipse Icefield. The SO<sub>4</sub><sup>2-</sup> contribution from this eruption to the 1809 volcanic signal in circum-Arctic ice cores is examined to assess the significance of this eruption. We conclude by discussing the



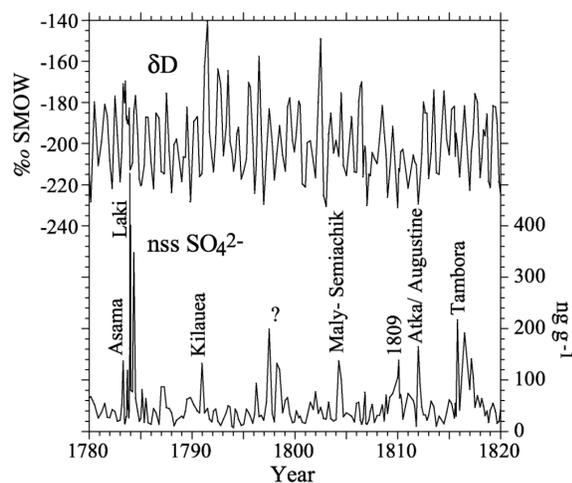
**Figure 1.** Location of the Eclipse, Dome C, and South Pole ice cores.

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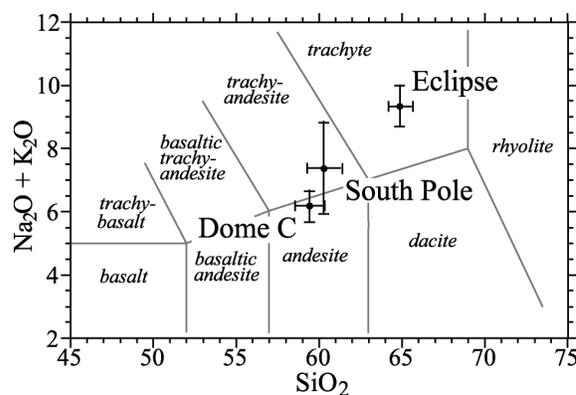
**Figure 2.** The  $\delta D$  (top) and non-sea-salt  $\text{SO}_4^{2-}$  (bottom) records from the Eclipse ice core for the period 1780 to 1820. Possible sources of volcanic  $\text{SO}_4^{2-}$  signals are indicated.

implications of these results in attributing the source of the 1809 volcanic signal.

## 2. Collection and Analysis of 1809 Tephra From the Eclipse Ice Core

[5] The strongest evidence for a tropical location of the unknown 1809 eruption would come from identification of volcanic glass shards of similar composition associated with the 1809 horizon in both Arctic and Antarctic ice cores. However, no analyses of 1809 tephra have been previously reported from Arctic ice cores (including Greenland). Here we present the major oxide composition of tephra found in the 1809 horizon in a 345 m ice core from Eclipse Icefield (Yukon) drilled in 2002 [Yalcin *et al.*, 2006]. This core was analyzed as described for the 1996 Eclipse ice core [Yalcin *et al.*, 2003] and the 1809 horizon dated by annual layer counting with age control provided by identification of the Laki 1783 and Tambora 1815 volcanic sulfate horizons (Figure 2). Tephra was collected by filtering core melt water through a 0.2-micron polycarbonate membrane (no tephra layer was visible in the core). Individual particles greater than four micrometers with glass shard morphology were analyzed for major oxide composition using a Hitachi S-570 scanning electron microscope.

[6] Tephra from the 1809 horizon in the Eclipse ice core has a chemical composition that is distinctly different from 1809 tephra found in the South Pole and Dome C ice cores (Table 1). Following the total alkali-silica classification scheme [LeBas *et al.*, 1986], tephra from the South Pole and Dome C ice cores is andesitic to trachyandesitic, while the Eclipse tephra is trachytic in composition (Figure 3). A Student's *t*-test can be used to evaluate the significance of the



**Figure 3.** Chemical classification of 1809 ice core tephras using a total alkali ( $\text{Na}_2\text{O} + \text{K}_2\text{O}$ ) versus silica variation diagram. Error bars represent the 95% confidence interval estimated from the standard error and observed mean of each tephra set.

compositional differences between the Eclipse, South Pole, and Dome C tephras [Keenan, 2003]. The *t*-test can only be applied for those constituents whose mean divided by standard deviation is greater than 2.5 in both data sets to be compared so that the assumption of a normal distribution is satisfied. For constituents satisfying this assumption, the difference between the Eclipse/South Pole tephras and Eclipse/Dome C tephras is significant at the 99.9% confidence level, except for  $\text{Al}_2\text{O}_3$  (Table 2). Conversely, the *t*-test detects no significant difference between the South Pole and Dome C tephras, except for  $\text{TiO}_2$  at the 90% confidence level. These results demonstrate that the South Pole and Dome C tephras are from the same volcano while the Eclipse tephra is from a different volcano, implying a second eruption around 1809 as the source of the Eclipse tephra.

[7] All identified tephras from the Eclipse ice cores are from high northern latitude volcanoes (Alaska, Kamchatka, or Iceland [Yalcin *et al.*, 2003]). The only volcano in the region known to have been active around 1809 is Bogoslof in the Aleutians, but its products range from basaltic to andesitic in composition [Miller *et al.*, 1998]. Though no eruption is reported around 1809, Aniakhak, Shishaldin, and Okmok volcanoes in Alaska erupt material similar in composition to the Eclipse 1809 tephra [Miller *et al.*, 1998], as do some Kamchatkan volcanoes. Although identifying the volcano which produced the Eclipse 1809 tephra is not possible with the available data, the most likely source is a high northern latitude eruption that had a negligible global climate impact.

## 3. Magnitude of the 1809 Signal From Sulfate Flux Calculations

[8] The eruption responsible for the 1809 tephra at Eclipse, depending on its magnitude, may or may not be a

**Table 1.** Major Oxide Composition of 1809 Ice Core Tephras<sup>a</sup>

Sample	$\text{SiO}_2$	$\text{TiO}_2$	$\text{Al}_2\text{O}_3$	$\text{FeO}$	$\text{MgO}$	$\text{CaO}$	$\text{Na}_2\text{O}$	$\text{K}_2\text{O}$	n	Reference
1809 Eclipse	64.86 (1.10)	1.15 (0.20)	16.13 (0.66)	3.84 (0.71)	1.12 (0.49)	3.56 (0.73)	6.64 (0.77)	2.70 (0.26)	10	this work
1809 South Pole	60.28 (1.41)	0.84 (0.16)	15.80 (1.77)	7.91 (1.86)	2.35 (0.93)	5.45 (0.92)	4.26 (0.75)	3.11 (1.38)	8	Palais <i>et al.</i> [1990]
1809 Dome C	59.44 (1.63)	0.67 (0.24)	16.43 (0.51)	9.00 (0.72)	2.83 (0.73)	5.44 (0.82)	4.14 (0.52)	2.05 (0.40)	13	De Angelis <i>et al.</i> [1985]

<sup>a</sup>Compositions given as weight %, recalculated to a sum of 100%, where n is the number of individual tephra particles analyzed. Values are means for the specified number of particles, with the standard deviation in parentheses.

**Table 2.** Calculated t Statistics and Significance Levels for Comparisons of 1809 Ice Core Tephra<sup>a</sup>

Sample Sets	df	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O
Eclipse 1809 - SP1809	16	<b>7.51</b>	<b>3.64</b>	0.50	<b>5.87</b>	n.a.	<b>4.74</b>	<b>6.62</b>	n.a.
Probability <		0.001	0.01		0.001		0.001	0.001	
Eclipse 1809 - Dome C 1809	21	<b>9.48</b>	<b>5.21</b>	1.17	<b>17.18</b>	n.a.	<b>5.80</b>	<b>8.80</b>	4.74
Probability <		0.001	0.001		0.001		0.001	0.001	0.001
SP 1809 - Dome C 1809	19	1.24	<b>1.91</b>	0.98	1.59	1.24	0.02	0.39	n.a.
Probability <			0.1						

<sup>a</sup>Where df indicates the degrees of freedom and n.a. denotes that the assumption of normal distribution is not satisfied. Probability levels are the chance the sample sets would have observed values so different if they were from the same population.

significant contributor to the 1809 volcanic SO<sub>4</sub><sup>2-</sup> signal in Arctic ice cores. We investigated this by calculating the SO<sub>4</sub><sup>2-</sup> flux for the 1809 eruption at Eclipse and compared our results to those calculated from other ice cores. To separate volcanic SO<sub>4</sub><sup>2-</sup> from other SO<sub>4</sub><sup>2-</sup> sources, we used an empirical orthogonal function (EOF) decomposition to describe the variance in the Eclipse glaciochemical data set. Applying EOF analysis to the suite of ions measured in the Eclipse ice core (excluding NH<sub>4</sub><sup>+</sup>) reveals that EOF 5 is loaded solely with SO<sub>4</sub><sup>2-</sup> and describes 5.3 % of the total variance in the dataset, but 20.3% of the variance in the SO<sub>4</sub><sup>2-</sup> time series. Volcanic eruptions have been identified as the source of this SO<sub>4</sub><sup>2-</sup> [Yalcin *et al.*, 2003]. Total SO<sub>4</sub><sup>2-</sup> deposition, or flux, for the 1809 event was calculated as the product of the volcanic SO<sub>4</sub><sup>2-</sup> concentration and the water equivalent length of the sample (corrected for layer thinning), summed for the samples containing fallout attributable to the event. For comparison with other ice core sites where different mass transfer mechanisms (wet and dry deposition, riming) may vary in importance, we calculated the volcanic SO<sub>4</sub><sup>2-</sup> flux ratio of the 1809 eruption relative to Tambora [Cole-Dai *et al.*, 1997].

[9] The volcanic SO<sub>4</sub><sup>2-</sup> flux from the unknown 1809 and Tambora eruptions at Eclipse was 3.69 and 7.08 μg cm<sup>-2</sup>, respectively. The volcanic flux from the 1809 event at Eclipse, 54% of Tambora, is in good agreement with results from both Greenland (60–78%) and Antarctica (26–60%) (Table 3). This result suggests little additional SO<sub>4</sub><sup>2-</sup> deposition at Eclipse from the eruption whose tephra we recovered, assuming the sulfate fallout in Greenland is from a tropical eruption. Because no tephrochronological evidence exists to link the 1809 fallout in Greenland ice cores to a tropical eruption, the high northern latitude eruption whose tephra we recovered at Eclipse could also be the source of the volcanic sulfate in Greenland.

#### 4. Implications of These Results

[10] The existence of a second eruption in the Northern Hemisphere around 1809 raises the possibility that the bipolar 1809 volcanic signal was the result of coincidental eruptions in the high latitudes of both hemispheres, rather than a tropical eruption that was dispersed to both hemispheres. There are three lines of evidence that suggest a tropical eruption affected both hemispheres in 1809. First, the 1809 signal has a similar magnitude in both hemispheres [Cole-Dai *et al.*, 1991]. Second, there is a close match in the timing of the 1809 event in both Greenland and Antarctic cores [Cole-Dai *et al.*, 1997]. Third, there is both instrumental [Chenoweth, 2001] and proxy [Crowley *et al.*, 1997]

evidence of short-term cooling in the tropics in 1809 and 1810. If these temperature anomalies are volcanic in origin, they suggest a tropical eruption because aerosols from even the largest high latitude eruptions do not reach the tropics.

[11] Our results demonstrate that there were at least two separate volcanic eruptions around 1809. If the Antarctic tephra is also from a high-latitude volcano (but in the Southern Hemisphere), a large tropical eruption is not needed to explain the bipolar volcanic signal. Instead, there could have been volcanic eruptions in the high latitudes of both hemispheres, similar in timing and magnitude, which produced the observed volcanic sulfate deposition in Greenland and Antarctica. This hypothesis could explain why a source volcano has not been identified. First, the eruptions would not need to be as large to account for the observed sulfate deposition if they occurred in the high latitudes. Second, the eruptions could have taken place in comparatively more remote regions at higher latitudes were they went unobserved or unreported.

[12] At present, the available data does not permit unequivocal distinction between these competing scenarios. However, the magnitude and latitudinal distribution of radiative forcing resulting from a large tropical eruption would be very different from that resulting from coincidental high latitude eruptions. For this reason, paleoclimate models for the early 1800's that assume a single 1809 eruption in the tropics and global dispersal may not be simulating the correct volcanic radiative forcing. The pos-

**Table 3.** Ice Core Volcanic Sulfate Fluxes (ug cm<sup>-2</sup>) From the 1809 Eruption Relative to Tambora<sup>a</sup>

Site	fV	fT	fV/fT	Reference
<i>Yukon</i>				
Eclipse	3.7	7.1	0.52	this work
<i>Greenland</i>				
Site T	2.8	4.7	0.60	Cole-Dai <i>et al.</i> [1991]
GRIP	2.5	3.5	0.71	Clausen <i>et al.</i> [1997]
GISP2	2.8	3.6	0.78	Zielinski [1995]
<i>Antarctica</i>				
Dome C	1.0	3.9	0.26	Castellano <i>et al.</i> [2005]
Plateau Remote	0.8	2.2	0.37	Cole-Dai <i>et al.</i> [2000]
Siple (2)	5.4	13.3	0.40	Cole-Dai <i>et al.</i> [1997]
Siple (1)	5.3	12.9	0.41	Cole-Dai <i>et al.</i> [1991]
South Pole (1)	3.0	7.2	0.41	Delmas <i>et al.</i> [1992]
Hercules Neve	0.7	1.7	0.45	Stenni <i>et al.</i> [1999]
South Pole (2)	3.2	6.8	0.47	Delmas <i>et al.</i> [1992]
Law Dome	4.5	8.0	0.56	Palmer <i>et al.</i> [2002]
Dyer	5.4	9.0	0.60	Cole-Dai <i>et al.</i> [1997]

<sup>a</sup>Where fV is the volcanic sulfate flux attributable to the 1809 eruption, fT is the flux from Tambora, and fV/fT is the flux ratio of the 1809 eruption to the Tambora eruption in the same core. For Siple and South Pole, multiple cores are available.

sibility also exists that coincidental eruptions in the high latitudes of both hemispheres in the more distant past produced volcanic signals in both polar regions that are incorrectly inferred to be tropical in origin. Only through tephrochronological evidence can a common source in the tropics be definitively established.

[13] **Acknowledgments.** We thank W. Scott and S. Self for insights concerning eruptive activity at Cosiguina prior to 1835, M. Twickler for the map projection used in Figure 1, and J. Palais, J. Johnson, and an anonymous reviewer for helpful comments that resulted in an improved manuscript. The National Science Foundation Office of Polar Programs funded this research.

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