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Ice core evidence for a second volcanic eruption around 1809 in the Northern Hemisphere

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[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_2SO_4 loading of 34 to 68 $\times$ 10^{12} 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_4^{2-} peaks in ice cores can provide information on the source volcano responsible for an eruption. Tephra associated with the 1809 SO_4^{2-} 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_4^{2-} 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

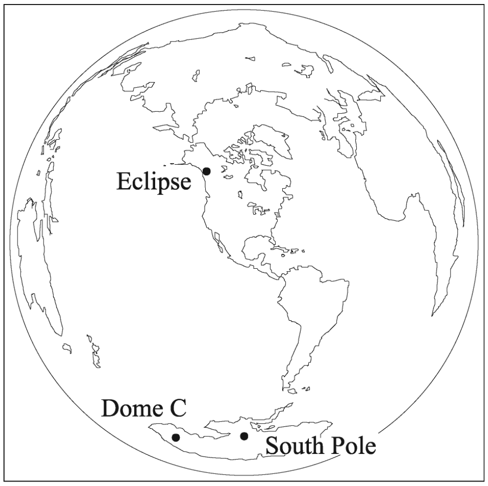

Figure 1. Location of the Eclipse, Dome C, and South Pole ice cores.

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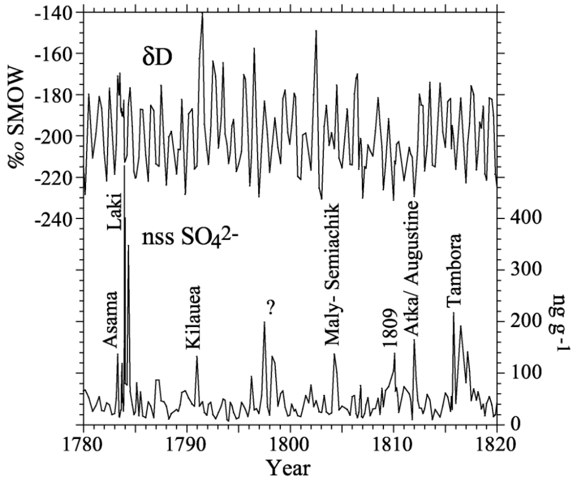

Figure 2. The δD (top) and non-sea-salt SO_4^{2-} (bottom) records from the Eclipse ice core for the period 1780 to 1820. Possible sources of volcanic SO_4^{2-} signals are indicated.

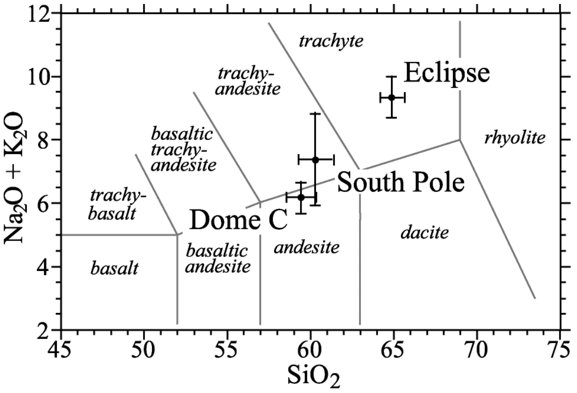

Figure 3. Chemical classification of 1809 ice core tephras using a total alkali (Na_2O + K_2O) versus silica variation diagram. Error bars represent the 95% confidence interval estimated from the standard error and observed mean of each tephra set.

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 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 Al_2O_3 (Table 2). Conversely, the t-test detects no significant difference between the South Pole and Dome C tephras, except for 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, Aniakchak, 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[a]

Sample	SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	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 et al.* [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 et al.* [1985]

[a] 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 Tephras[a]

Sample Sets	df	SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O
Eclipse 1809 - SP1809	16	**7.51**	**3.64**	0.50	**5.87**	n.a.	**4.74**	**6.62**	n.a.
Probability <		0.001	0.01		0.001		0.001	0.001	
Eclipse 1809 - Dome C 1809	21	**9.48**	**5.21**	1.17	**17.18**	n.a.	**5.80**	**8.80**	4.74
Probability <		0.001	0.001		0.001		0.001	0.001	0.001
SP 1809 - Dome C 1809	19	1.24	**1.91**	0.98	1.59	1.24	0.02	0.39	n.a.
Probability <			0.1						

[a]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_4^{2-} signal in Arctic ice cores. We investigated this by calculating the SO_4^{2-} flux for the 1809 eruption at Eclipse and compared our results to those calculated from other ice cores. To separate volcanic SO_4^{2-} from other SO_4^{2-} 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_4^+) reveals that EOF 5 is loaded solely with SO_4^{2-} and describes 5.3 % of the total variance in the dataset, but 20.3% of the variance in the SO_4^{2-} time series. Volcanic eruptions have been identified as the source of this SO_4^{2-} [*Yalcin et al.*, 2003]. Total SO_4^{2-} deposition, or flux, for the 1809 event was calculated as the product of the volcanic SO_4^{2-} 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_4^{2-} flux ratio of the 1809 eruption relative to Tambora [*Cole-Dai et al.*, 1997].

[9] The volcanic SO_4^{2-} flux from the unknown 1809 and Tambora eruptions at Eclipse was 3.69 and 7.08 $\mu g\ cm^{-2}$, 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_4^{2-} 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^{-2}) From the 1809 Eruption Relative to Tambora[a]

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

[a]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.

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References

Castellano, E., S. Becagli, M. Hansson, M. Hutterli, J. R. Petit, M. R. Rampino, M. Severi, J. P. Steffensen, R. Traversi, and R. Udisti (2005), Holocene volcanic history as recorded in the sulfate stratigraphy of the European Project for Ice Coring in Antarctica Dome C (EDC96) ice core, *J. Geophys. Res.*, *110*, D06114, doi:10.1029/2004JD005259.

Chenoweth, M. (2001), Two major volcanic cooling episodes derived from global marine air temperature, AD 1807–1827, *Geophys. Res. Lett.*, *28*, 2963–2966.

Clausen, H. B., C. U. Hammer, C. S. Hvidberg, D. Dahl-Jensen, J. P. Steffensen, J. Kipfstuhl, and M. Legrand (1997), A comparison of the volcanic records over the past 4000 years from the Greenland Ice Core Project and Dye 3 Greenland ice cores, *J. Geophys. Res.*, *102*, 26,707–26,723.

Cole-Dai, J., E. Mosley-Thompson, and L. Thompson (1991), Ice core evidence for an explosive tropical eruption 6 years preceding Tambora, *J. Geophys. Res.*, *96*, 17,361–17,366.

Cole-Dai, J., E. Mosley-Thompson, and L. Thompson (1997), Annually resolved Southern Hemisphere volcanic history from two Antarctic ice cores, *J. Geophys. Res.*, *102*, 16,761–16,771.

Cole-Dai, J., E. Mosley-Thompson, S. Wight, and L. Thompson (2000), A 4100-year record of explosive volcanism from an East Antarctic ice core, *J. Geophys. Res.*, *105*, 24,431–24,441.

Crowley, T. J., T. R. Quinn, F. W. Taylor, C. Henin, and P. Joannot (1997), Evidence for a volcanic cooling signal in a 335-year coral record from New Caledonia, *Paleoceanography*, *12*, 633–639.

De Angelis, M., L. Fehrenbach, C. Jehanno, and M. Maurette (1985), Micrometer-sized volcanic glasses in polar ice and snows, *Nature*, *317*, 52–54.

Delmas, R. J., S. Kirchner, J. M. Palais, and J. R. Petit (1992), 1000 years of explosive volcanism recorded at the South Pole, *Tellus*, *44*, 335–350.

Keenan, D. J. (2003), Volcanic ash retrieved from the GRIP ice core is not from Thera, *Geochem. Geophys. Geosyst.*, *4*(11), 1097, doi:10.1029/2003GC000608.

Kohno, M., and Y. Fujii (2002), Past 220-year bipolar volcanic signals: remarks on common features of their source eruptions, *Ann. Glaciol.*, *35*, 217–223.

Langway, C. C., K. Osada, H. B. Clausen, C. U. Hammer, and H. Shoji (1995), A 10-century comparison of prominent bipolar volcanic events in ice cores, *J. Geophys. Res.*, *100*, 16,241–16,247.

LeBas, M. J., R. W. Maitre, A. Strickeisen, and B. Zanettin (1986), A chemical classification of volcanic rocks based on the total alkali-silica diagram, *J. Petrol.*, *27*, 745–750.

Legrand, M., and R. J. Delmas (1987), A 220 year continuous record of volcanic H_2SO_4 in the Antarctic ice sheet, *Nature*, *327*, 671–676.

Miller, T. P., R. G. McGimsey, D. H. Richter, J. R. Riehle, C. J. Nye, M. E. Yount, and J. A. Dumoulin (1998), Catalog of the historically active volcanoes of Alaska, *U.S. Geol. Surv. Open File Rep., 98-582*, 104 pp.

Moore, J. C., H. Narita, and N. Maeno (1991), A continuous 770-year record of volcanic activity from East Antarctica, *J. Geophys. Res.*, *96*, 17,353–17,359.

Palais, J. M., S. Kirchner, and R. J. Delmas (1990), Identification of some global volcanic horizons by major element analysis of fine ash in Antarctic ice, *Ann. Glaciol.*, *14*, 216–220.

Palmer, A. S., V. I. Morgan, M. A. J. Curran, T. D. Van Ommen, and P. A. Mayewski (2002), Antarctic volcanic flux rations from Law Dome ice cores, *Ann. Glaciol.*, *35*, 329–332.

Scott, W., C. Gardner, G. Devoli, and A. Alvarez (2006), The A.D. 1835 eruption of Volcán Cosiguina, Nicaragua: A guide for assessing local volcanic hazards, in *Volcanic Hazards in Central America*, edited by W. I. Rose et al., *Spec. Pap. Geol. Soc. Am.*, in press.

Simkin, T., and L. Siebert (1994), *Volcanoes of the World*, Geosci. Press, Tucson, Ariz.

Stenni, B., R. Caprioli, L. Cimmino, C. Cremisini, O. Flora, R. Gragnani, A. Longinelli, V. Maggi, and S. Torcini (1999), 200 years of isotope and chemical records in a firn core from Hercules Neve, northern Victoria Land, Antarctica, *Ann. Glaciol.*, *29*, 106–112.

Yalcin, K., C. P. Wake, and M. Germani (2003), A 100-year record of North Pacific volcanism in an ice core from Eclipse Icefield, Yukon, Canada, *J. Geophys. Res.*, *108*(D1), 4012, doi:10.1029/2002JD002449.

Yalcin, K., C. P. Wake, S. Whitlow, and K. Kreutz (2006), A 1000-year record of forest fire activity from Eclipse Icefield, Yukon, Canada, *Holocene*, *16*, 200–209.

Zielinski, G. A. (1995), Stratospheric loading and optical depth estimates of explosive volcanism over the last 2100 years derived from the GISP2 Greenland ice core, *J. Geophys. Res.*, *100*, 20,937–20,955.

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