The anomalous winter of 1783–1784: Was the Laki eruption or an analog of the 2009–2010 winter to blame?

Rosanne D'Arrigo,[1] Richard Seager,[1] Jason E. Smerdon,[1] Allegra N. LeGrande,[2] and Edward R. Cook[1]

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[1] The multi-stage eruption of the Icelandic volcano Laki beginning in June, 1783 is speculated to have caused unusual dry fog and heat in western Europe and cold in North America during the 1783 summer, and record cold and snow the subsequent winter across the circum-North Atlantic. Despite the many indisputable impacts of the Laki eruption, however, its effect on climate, particularly during the 1783–1784 winter, may be the most poorly constrained. Here we test an alternative explanation for the unusual conditions during this time: that they were caused primarily by a combined negative phase of the North Atlantic Oscillation (NAO) and an El Niño-Southern Oscillation (ENSO) warm event. A similar combination of NAO-ENSO phases was identified as the cause of record cold and snowy conditions during the 2009–2010 winter in Europe and eastern North America. 600-year tree-ring reconstructions of NAO and ENSO indices reveal values in the 1783–1784 winter second only to their combined severity in 2009–2010. Data sources and model simulations support our hypothesis that a combined, negative NAO-ENSO warm phase was the dominant cause of the anomalous winter of 1783–1784, and that these events likely resulted from natural variability unconnected to Laki. **Citation:** D'Arrigo, R., R. Seager, J. E. Smerdon, A. N. LeGrande, and E. R. Cook (2011), The anomalous winter of 1783–1784: Was the Laki eruption or an analog of the 2009–2010 winter to blame?, *Geophys. Res. Lett.*, *38*, L05706, doi:10.1029/2011GL046696.

1. Introduction

[2] Laki had massive effects on climatic conditions around the Northern Hemisphere and the globe (Text S1 of the auxiliary material) [*Thordarson and Self*, 2003]. It began on June 8, 1783 and continued until Feb. 1784, diminishing over this period. Sulfuric acid aerosols rapidly encircled northern latitudes. Laki's effects devastated ill-prepared populations from famine, crop failure, and livestock loss, and thousands perished. Nevertheless, we argue that besides the undoubtedly profound impacts of Laki, it is likely that the relatively rare, synchronous occurrence of a negative NAO in the Atlantic and an El Niño in the Pacific during the 1783–1784 winter was more fundamentally to blame for the severe conditions over North America and Europe than the waning effects of Laki.

2. Conditions in the Summer of 1783

[3] The consequences of Laki make it one of the greatest natural disasters of the past millennium. In Britain, ~23,000 died from gas fumes, placing the event among the greatest disasters in British history [*Grattan and Brayshay*, 1995]. There were heat waves in northern and western Europe, while in France a priest performed an exorcism of the Laki dust cloud [*White*, 1789]. Laki may even have contributed to the onset of the French Revolution, due to destruction of crops and livestock [*Wood*, 1992]. From Europe, the Laki dust veil spread into Eurasia and around the globe [*Stothers* 1996; *Thordarson and Self*, 2003]. That summer, Japan experienced one of the worst famines in its history, although perhaps partly due to the Asama, Japan eruption [*Thordarson and Self*, 2003]. In North America, severe cold in summer 1783 was inferred from Alaskan tree rings, with a reconstructed temperature four standard deviations below the 400-yr mean [*Jacoby et al.*, 1999]. Inuit legends describe famine and deaths of the Kauwerak peoples, known in local lore as the "summer that did not come". Elsewhere on the continent, conditions in Labrador were also attributed to Laki [*Wood*, 1992].

3. Ensuing Winter of 1783–1784

[4] Following closely on the heels of this anomalous summer, the 1783–1784 winter was extremely cold and snowy around the circum-North Atlantic. European temperatures were ~2°C below average for the late 1700s, and it was among the coldest winters in central England [*Manley*, 1974] (Figure S1). Iceland was ~5°C colder than normal, with the longest period of sea ice ever recorded [*Wood*, 1992]. Cold, frozen soils, icebound watercourses and high snow levels were documented across Europe [*Brazdil et al.*, 2010]. Brief warmings brought some respite from the cold but also flooding from snowmelt. Long European temperature records (Figure S1) show that this winter was one of the more severe in the past 500 years [e.g., *Brazdil et al.*, 2010].

[5] In eastern North America, this winter was among the most severe of the past 500 years [*Ludlum*, 1966]. The eastern USA had its lowest-ever winter temperature: 4.8°C below the 225-yr mean [*Scarth*, 2001]. It was the longest period of cold in New England, and one of the largest ever snow accumulations in New Jersey [*Scarth*, 2001]. Ice bridging on the St. Lawrence River began and persisted for years [*Houle et al.*, 2007]. A harbor frozen enough for skating in Charleston, South Carolina, freezing of the Mississippi

[1]Lamont-Doherty Earth Observatory, Earth Institute at Columbia University, Palisades, New York, USA.
[2]NASA Goddard Institute for Space Studies, New York, New York, USA.

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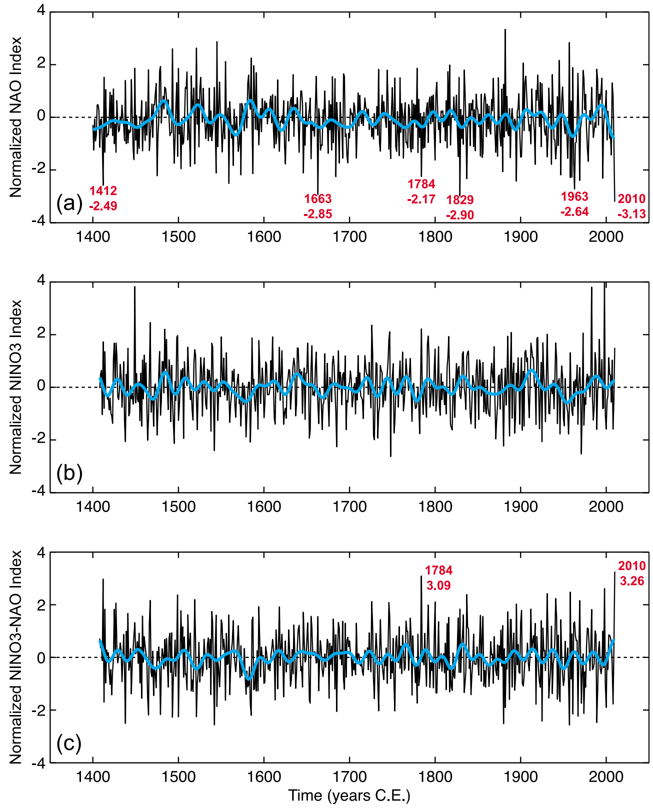

Figure 1. (a) Normalized DJFM NAO reconstruction. (b) Normalized NAO Niño3 SST reconstruction. (c) Paleo-Niño-NAO index based on differencing normalized Niño-3-NAO SST. 2010 and 1784 values 1st and 2nd highest over the past six centuries (Table S1).

River at New Orleans, the longest freeze-over of Chesapeake Bay, and ice floes in the Gulf of Mexico all attest to its severity [*Ludlum*, 1966; *Wood*, 1992]. These conditions seem attributed by *Benjamin Franklin* [1784] to an Icelandic eruption, but with Hekla as the probable source, not Laki (section S2 of Text S1).

4. The 2009–2010 Winter, Combined NAO and El Niño

[6] Similar to the famed winter of 1783–1784, that of 2009–2010 broke records over western Europe and eastern North America. Snows and cold were attributed to a combined negative NAO and El Niño [*Seager et al.*, 2010]. Such a combination can cause increased snow as enhanced storms impact central-southern latitudes of the U.S. during an El Niño, while the NAO provides sufficient cold for the precipitation to fall as snow. Increased snowfall in the southern USA results from a southward-displaced storm track, but farther north (eastern USA, northern Europe), positive snow anomalies arise from the cold of a negative NAO. These dynamical arguments, and NAO and Niño-3 sea surface temperature (SST) indices, were used to conclude that these phenomena were largely responsible for anomalies of winter 2009–2010 (negative NAO conditions have persisted early in this winter (2010–2011), but with a La Niña). Here, we use proxy records, observations, and models to test if a negative NAO-El Niño, as in 2009–2010, could have caused the winter conditions of 1783–1784, even without the eruption of Laki.

5. Data and Methods

[7] Two proxies are used to assess the 1783–1784 winter within the context of the past six centuries (Figure 1): (1) an NAO tree-ring reconstruction [*Cook et al.*, 2002]; and (2) a Niño-3 SST reconstruction [*Cook*, 2000; *D'Arrigo et al.*, 2005] based on tree rings from the SW USA and Mexico, where El Niños are linked with wet winters. The DJFM NAO reconstruction was calibrated with a Gibraltar-Iceland NAO index [*Jones et al.*, 1999] over 1826–1974 (the reconstruction spans 1400–1979 – a subset extends it to 1979 and to 2001 using instrumental data). The Niño-3 reconstruction (1408–1978) is calibrated (1919–78) with DJF SSTs [*Kaplan et al.*, 1998] (5°N–5°S, 90–150°W).

[8] To compare the 1783–1784 event to that of 2009–2010, both reconstructions were updated using instrumental NAO (http://www.cru.uea.ac.uk/~timo/datapages/naoi.htm) and Niño-3 SST indices (http://iridl.ldeo.columbia.edu/SOURCES/.Indices/.nino/.EXTENDED/), after adjusting (reducing) instrumental values to the mean and variance of the reconstructions during their common period to reflect lost variance due to regression. This allows the recent event (only represented in the instrumental data) to be compared with 1783–1784 (only available from the proxies). The two updated reconstructions were normalized and their difference used to develop a paleo-Niño-3-NAO index (Figure 1), representing the combined effect of these two phenomena.

6. Results

[9] For the 2009–2010 winter, the instrumental NAO anomaly [*Seager et al.*, 2010] was −2.4, the lowest in the Climate Prediction Center's NDJF NAO since 1950 (http://www.cpc.noaa.gov/products/precip/CWlink/daily_ao_index/history/method.shtml); based on rotated PCA applied to 500mb-height anomalies. A similar value, −2.54, is found in the updated DJFM NAO index [*Jones et al.*, 1999] based on Gibraltar-Iceland sea-level-pressure or SLP (http://www.cru.uea.ac.uk/~timo/datapages/naoi.htm), the lowest in this ~190-year record.

[10] We compare this latter NAO anomaly with that for winter 1783–1784 using the NAO reconstruction (Figure 1). Adjusting for the mean and variance of the reconstruction, the instrumental value is revised to –2.29 (normalized –3.13; Table S1). We infer that the 2009–2010 value was the lowest since ~AD 1400. The 1784 reconstructed NAO value is –1.62 (normalized –2.17), noteworthy but less severe than in 2009–2010 (section S3 of Text S1).

[11] The instrumental DJF Niño-3 SST anomaly was 1°C in 2009–2010 [*Seager et al.*, 2010]. Updating the Niño-3-SST reconstruction (after adjustment as described for the NAO reconstruction) reveals a 1784 Niño-3-SST value of 1.21 (normalized 2.22), indicating a somewhat stronger El Niño than for 2009–2010 (for which the adjusted Niño-3-SST value is 0.85, normalized 1.50) (Table S1, Figures 1 and 2, and sections S4 and S5 of Text S1).

[12] Comparing the NAO and Niño-3-SST reconstructions reveals 18 years when negative NAO and positive Niño-3 SST anomalies *both* exceed +/− 1.0 during the common period. Of these, only one, the winter of 1783–

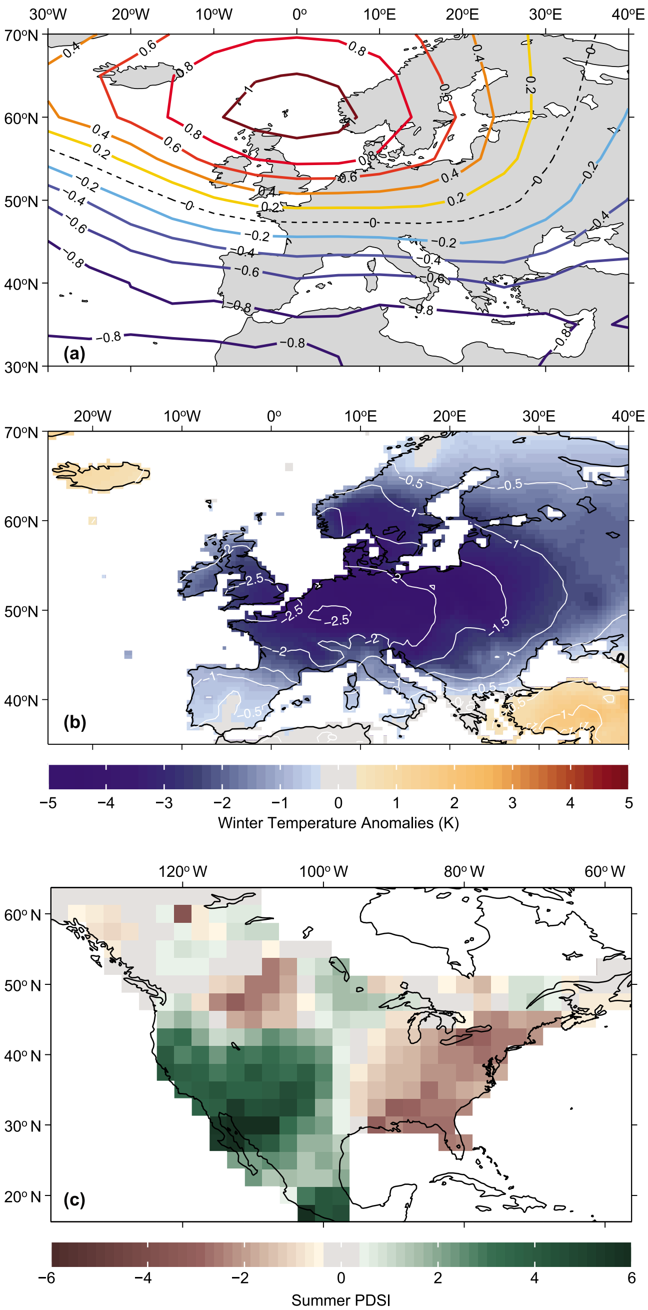

Figure 2. (a) Normalized reconstructed 1783–1784 European winter (DJF) SLP anomalies (relative to 1900–1999; normalized units given in contours) [*Luterbacher et al.*, 2002a, 2002b, 2004]. (b) Reconstructed 1783–1784 European winter (DJF) surface air temperatures (SAT): 25°W–40°E; 35°N–70°N, 0.5 by 0.5°. Colors: winter (DJF) temperature anomalies (relative to 1900–1999); contours normalized to same period. (c) Reconstructed PDSI, summer (JJA) 1784 [*Cook and Krusic*, 2004].

1784, has normalized anomalies in *both* negative NAO and positive Niño-SST over +/− 2.0 during the 600-yr period (Table S1 and Figure 1). Computing the Niño-NAO index yields the combined effect, for which the original 2009–2010 value was 2.4. After adjustment, the 2009–2010 value is 3.26, the most severe in 600 yr, with 1784 being second (3.09).

[13] Independent reconstructions of European temperatures and SLP support a negative NAO in winter 1783–1784 [*Luterbacher et al.*, 2002a, 2002b, 2004] (Figure 2). Similarly, a summer North American Palmer Drought Severity Index reconstruction [PDSI, derived from precipitation and temperature [*Palmer*, 1965; *Cook and Krusic*, 2004], indicates a strong El Niño in summer 1784 (Figure 2), lending credence to the occurrence of a negative NAO and an El Niño during 1783–1784.

[14] Atmosphere-only model simulations determined the impact of sulfate injections consistent with the Laki eruption [*Oman et al.*, 2005, 2006a, 2006b], and we have examined subsequent seasons (Figure S2 and section S5 of Text S1). By fall 1783, solar radiation and temperature perturbations were simulated to be small. Ensemble mean SLP response shows a weak positive NAO. For DJF 1783–1784, there is no evidence of a negative NAO. The ensemble mean has weak cooling over Europe and stronger cooling over northeastern North America, but this is clearly not directly radiatively forced and, if it were a response to Laki, would have had to arise from a multi-stepped lagged response. More likely it arises from internal variability and sampling error in the modestly-sized 10-member simulation ensemble, or other forcings not considered here. Thus, impacts of Laki's injection were largely or entirely gone by winter, and the model results don't support it as the sole or even dominant cause of the extremes at that time.

7. Summary

[15] We have tested the hypothesis that negative-NAO-El Niño conditions, as in 2009–2010, can explain winter 1783–1784 conditions, without attributing them to Laki. Our paleo-index had the 2nd highest value of the past 600 years in 1783–1784, with the most severe in 2009–2010. Conditions were thus more likely due to the rare occurrence of these events, neither of which can be clearly linked to Laki. Our results suggest that Franklin and others may have been mistaken in attributing winter conditions in 1783–1784 mainly to Laki or another eruption, rather than unforced variability. Similarly, conditions during the 2009–2010 winter likely resulted from natural NAO-ENSO variability, not tied to greenhouse gas forcing. The 2009–2010 El Niño was unremarkable, and links between ENSO and greenhouse forcing are widely debated. Models suggest that rising greenhouse gases should force a positive, not negative, NAO [*Intergovernmental Panel on Climate Change*, 2007], despite Arctic sea ice loss creating a tendency to a negative NAO [*Seierstad and Bader*, 2009]. A solar minimum may have shifted the system towards a negative NAO [*Lockwood et al.*, 2010], but it is unclear whether this could account for such a negative episode. Evidence thus suggests that these winters were linked to the rare but natural occurrence of negative NAO and El Niño events.

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E. R. Cook, R. D'Arrigo, R. Seager, and J. E. Smerdon, Lamont-Doherty Earth Observatory, Earth Institute at Columbia University, 61 Rte. 9W, Palisades, NY 10694, USA. (rdd@ldeo.columbia.edu)

A. N. LeGrande, NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, USA.