Bipolar correlation of volcanism with millennial climate change

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Analyzing data from our optical dust logger, we find that volcanic ash layers from the Siple Dome (Antarctica) borehole are simultaneous (with >99% rejection of the null hypothesis) with the onset of millennium-timescale cooling recorded at Greenland Ice Sheet Project 2 (GISP2; Greenland). These data are the best evidence yet for a causal connection between volcanism and millennial climate change and lead to possibilities of a direct causal relationship. Evidence has been accumulating for decades that volcanic eruptions can perturb climate and possibly affect it on long timescales and that volcanism may respond to climate change. If rapid climate change can induce volcanism, this result could be further evidence of a southern-lead North–South climate asynchrony. Alternatively, a volcanic-forcing viewpoint is of particular interest because of the high correlation and relative timing of the events, and it may involve a scenario in which volcanic ash and sulfate abruptly increase the soluble iron in large surface areas of the nutrient-limited Southern Ocean, stimulate growth of phytoplankton, which enhance volcanic effects on planetary albedo and the global carbon cycle, and trigger northern millennial cooling. Large global temperature swings could be limited by feedback within the volcano–climate system.

Although the Earth maintains a remarkably constant temperature, climate fluctuations have been identified on many timescales. On the 10^3-year scale, poorly understood Dansgaard–Oeschger (DO) events (1, 2), extremely rapid coolings/warmings and subsequent cold/warm periods, are best exhibited during the last glacial period [20,000–110,000 years before the present or 20–110 thousand years ago (ka)] but may extend with reduced amplitude into the Holocene (3) (the comparatively stable, warm, last ~11 ka). Proposed causal mechanisms involve harmonics of Milankovitch (orbital) forcing, thermohaline circulation, internal ocean–atmosphere oscillations, solar forcing, and even long-period tidal resonances in the motions of the Earth and Moon. Recent work suggests that the fluctuations resemble those of a system possessing threshold instability. Rapid transitions between states are exhibited in many climate models, including those of oceanic circulation, atmospheric energy balance, and atmospheric regime change. It is becoming increasingly apparent that global climate models currently either omit or implement some natural forcings from the simulations or underestimate the size and extent of climate response to threshold crossings, e.g., by considering the North Atlantic as the amplifier for DO oscillations and only including North Atlantic triggers in the model (4). The possibilities that rapid climate change can induce volcanic activity and, conversely, that volcanic eruptions can force millennial climate have both been suggested in the past (5). Based on evidence we have found using our optical profiles of deep boreholes in the polar ice caps, we conclude that volcanism may supply a vital missing link in millennial climate change.

Methods

Dust Logger. Ice cores extracted from boreholes yield precious samples for laboratory analyses of gases, isotopes, crystal fabric, chemistry, and particulates as far back as 100–400 ka. Our complementary approach is to measure in situ features of the glacial ice by lowering an optical instrument into the boreholes, which are kept open with an insoluble antifreeze matched to the density of ice. The dust LOGGER principle is simple (6). Light-emitting diodes shine 370-nm light radially (horizontal to ±5°) into the ice surrounding the borehole in which the instrument is kept centralized. At shallow depths, the light encounters air bubbles and dust; at greater depths, where all bubbles have transformed into air hydrate crystals, the light is absorbed or scattered only by dust particles. A fraction of the light scatters back into the borehole and is detected by a phototube that is shielded from outgoing light. Depth resolution is determined by the planar collimation of the source, its separation from the phototube, and, for weak signals, the smoothness of the borehole wall. Our log of the GISP2 borehole (3,054 m) closely tracks the depth dependence of Ca^{2+} (a measure of insoluble dust; ref. 7) and δ18O of water (a proxy for temperature; ref. 8) measured in the ice cores, because colder periods are generally associated with higher winds, higher aridity, and consequently a greater amount of dust swept into the atmosphere. Among other features, our log shows abrupt DO changes in dust concentration over periods as short as a decade. Bubbles in the ice at Siple Dome (West Antarctica, 1,004 m) are present all of the way to the bedrock but contribute decreasingly to light-scattering with depth. Secular climate changes seen worldwide produce variations in background dust that negatively correlate in Fig. 1. In bubbly Siple Dome ice, absorption on dust decreases the return signal, whereas at GISP2 scattering on dust in bubble-free ice (the situation at depths >1,600 m or ages >11 ka) increases the signal.

Volcanic Ash Verification. In addition to its response to dust, our dust logger responds with a unique signature to the thin (approximately mm to several cm), opaque layers of ash deposited by volcanic eruptions, in particular, in ice in which scattering is dominated by bubbles, which do not absorb light. We have verified that the ash signals identified with our loggers at Siple Dome are caused by volcanic emissions. The distinctive response of the dust logger to thin, opaque volcanic ash layers is an asymmetric double cusp (see Fig. 1) produced as the focused-beam emitter and the receiver consecutively traverse the ash layer (6). Monte Carlo simulations confirm that the signal distinguishes ash layers from the more gradual changes in dust concentration and the quasi-periodic scarring of the borehole by the drill. Visual scans of the ice core certified the darkest of the ash deposits, except for those in badly fractured sections from depths below ~780 m (~30 ka), where visual searches for ash in the Siple Dome core have been impractical. In unfractured core sections, ash layers that at first escaped visual detection were evident in the logger data and then later confirmed visually in the core. By probing outward into the ice surrounding a borehole, the logger samples a larger cross section of ice (of the order m^2) and integrates lateral irregularities that can be misleading in...
studies of the 13-cm-diameter core. Many of the ash layers detected in our optical borehole logs were not visible in the core to the naked eye and so are likely composed of micrometer- and submicron-sized particles. To assist in confirming their volcanic origin, we sent Nelia Dunbar (New Mexico Tech, Socorro, NM) a list of depths of a sample of 24 ash layers from below 500 m (~7.8 ka) that we had located with the logger, most of which could not be seen in the core. By melting portions of the core, filtering, and microscopically examining the filtrate (9, 10), she found all but three within ~30 cm of the depth we specified and confirmed that they were indeed layers of volcanic tephra (glass shards). The remaining three (not used in the correlation calculation), despite being clear examples of ash signals in the borehole logs, were probably missed because of errors of as much as 1 m in our corrected depths, because she limited her search to depths close to the predicted locations. In some cases she recovered enough material to analyze composition, and it appeared to correlate with basaltic, basanitic, and trachyctic sources on the Antarctic continent. A few non-Antarctic compositions suggested South American provenance. We detected >60 volcanic ash layers in the Siple Dome ice but far fewer at GISP2. In addition to a higher altitude and less favorable location relative to volcanic regions, bubbly ice (where ash identification is most straightforward) makes up only 10% of the temporal ice record at GISP2.

Dating. To reduce minor errors in depth we forced our borehole profiles to agree with studies of the cores; we tied features in our dust logs at GISP2 to Ca⁴⁺ measurements by Mayewski et al. (7), and at Siple Dome we calibrated the strongest volcanic ash signal depths to those measured in visual core scanning. We then applied the best available age vs. depth conversions¹ (refs. 11 and 12 and references therein). Siple Dome ages before 11 ka were determined by matching core gases with those at GISP2, by using methane concentrations back to 19 ka with estimated relative age uncertainties of ±0.5–1 thousand years (kyr) and isotopic anomalies of trapped O₂ (which, like methane, is constant throughout the atmosphere) before 24 ka with relative age uncertainties conservatively estimated to be between −1 kyr and +1–2.5 kyr.

correlation to nearly 99.7% (>300 to 1). Alternatively, the use of methane tie points (E. Brook, J. W. C. White, A. S. M. Schilla, M. L. Bender, J. P. Severinghaus & R. B. Alley, unpublished work) back to 43 ka for relative dating preserves both the high correlation and the volcanic lead. Thus, the correlation of Antarctic volcanic activity with northern abrupt climate change is insensitive to time intervals examined and to small uncertainties in the age vs. depth relationship.

Because of their proximity, volcanoes of the Antarctic plate are likely overrepresented in the Siple Dome volcanic record, in particular, those in the Marie Byrd Land province on the north flank of the West Antarctic rift system, one of the planet's largest active continental rifts. The Siple Dome volcanic ash record may not represent episodic increases in volcanism but merely increases in deposition due to reorganizations of atmospheric circulation over Antarctica. To help resolve this uncertainty we defined a Siple Dome ash index as the 1-k yr running average of our existing volcanic ash measurements on a signal scale of 1–20 based on area under the curve (6), and we compared it to the global volcanicity estimate of Bryson and Bryson (13). The Bryson team combed the literature for all radiocarbon-dated eruptions, eliminated duplicates, and counted the number per century by using a database of nearly 3,000. After correcting for the paucity of older eruptions in the records they were able to generate an index of global activity. The agreement of our ash deposition index at Siple Dome with the Bryson activity index, when both are integrated over 1 kyr, is rather good (Fig. 4).

Studies of the Siple Dome ice core (14) indicate that Siple Dome climate may have strong ties to the Pacific region, so the submicron-sized component of ash in the clean Siple Dome ice could be a representative sample of the global atmospheric fine ash load, including very small injections that would not be detected by visual inspection of ice-core sections. If our ash record is entirely dominated by local sources, these may have served as quantitative indicators, over sufficiently long timescales, by erupting sympathetically with periodic increases in volcanism of all types worldwide. As Fig. 4 shows, the two indices are also similar to the GISP2 volcanic sulfate record of Zielinski et al. (15) in that the greatest activity occurred at ~9 or 10 ka, during the main deglaciation of the early Holocene.

The concept of a connection between volcanic eruptions and the advance of glaciers dates back to Lamb (16), and the idea has persisted (5). We found the closest association between volcanic events and the onset of millennial cold periods, and this persistent coincidence seems to point to a volcanic-forcing view of causation. The reversed-causality explanation should not be excluded on the basis of the Monte Carlo significance calculation, given the relative dating errors and previous findings that Northern Hemisphere climate is time-lagged with respect to that of the Southern Hemisphere. We will explore a number of plausible mechanisms for forcing in both directions.

**Millennial Climate Change Forcing Volcanism.** Kyle et al. (17) pointed out that abundant visible tephra layers found by Gow and Williamson (18) at Byrd Station (also near volcanic sources in West Antarctica), which were clustered during the late part of the last glacial period, might have been due to a thickening of the West Antarctic Ice Sheet that initiated the eruptions in nearby Marie Byrd Land. Zielinski et al. (15) noted that in the sulfate record at GISP2 the periods of greatest volcanic activity seemed to occur during changing climatic conditions, especially during the early Holocene. Maclellan et al. (19) found a link between deglaciation and volcanism in Iceland that they attributed to increased melt generation rates in the shallow mantle caused by unloading of the ice sheet. Numerical studies have shown that mantle stress accumulation associated with glaciation/deglaciation and meltwater change may have triggered or accelerated active Quaternary volcanism of the circum-Pacific (20). Eruptions might be induced by climatically driven atmospheric jolts to the solid Earth’s rotational angular momentum (21) or by crustal stresses resulting from ice-sheet loading/unloading effects on the planet’s distribution of mass.

The high volcanic activity during the main deglaciation of the early Holocene (Fig. 4) suggests that ice-sheet unloading and/or sea level rise increased volcanism during this period, although this response may not be fast enough to explain the volcanic variability seen during the glacial period. The volcanism we detected at Siple Dome may be further evidence of a North–South asynchrony, having been driven by southern climate changes, which typically led Greenland changes by 1–2 kyr over the last glacial period (22). Our volcanicity record at Siple Dome
correlates less with Antarctic temperature changes than with those in the Greenland record, as evidenced in the Siple Dome record itself (Fig. 2). The broad peak near 50 ka is a southern cold event, one of several seen throughout Antarctica between the Last Glacial Maximum and the stadial near 60 ka seen globally, yet we found no associated volcanic ash during this period. The episodic volcanic activity we have found may be connected to changes not readily seen in Antarctica because of the continent’s isolation by circum-Antarctic ocean circulation. The agreement between our Siple Dome ash record and global indices of volcanism is surprising if the ash reflects only local effects. Perhaps sea level or some other global climate variable with wide-ranging influence were able to affect volcanic rates uniformly over much of the globe.

**Volcanism Forcing Millennial Climate Change.** Ice-rafted debris sediments found in the North Atlantic correlate with DO events, and these surges of fresh water are thought to have disrupted or even largely halted ocean thermohaline circulation (23, 24). Amplified by gradients in salinity but driven primarily by high-latitude cooling, the thermohaline circulation is believed to have alternated between a glacial state and an interglacial state on the millennial scale. This finding has prompted searches for an external, possibly atmospheric cooling mechanism, which does not involve thermohaline circulation or orbital parameters, to trigger episodic ice-sheet discharges.

From his studies of global volcanism in compiling his Dust Veil Index, Lamb found that eruption patterns seemed to indicate that stresses building up within the Earth’s crust led to widespread simultaneous fractures, and the resulting volcanism was sufficient to explain climate changes on a variety of timescales. Gow and Williamson (18) originally suggested that the tephra layers they found at Byrd during the last glacial period may have been an indication that eruptions of volcanic ash in Antarctica triggered or intensified worldwide cooling. Bray (25), an early proponent of a connection between glaciation and volcanism, found that of 18 phases of glacial advance and volcanic activity, all but four showed a lag in ice advance of 100–300 years after the initial volcanic eruption. Because of poor statistics his conclusions were not regarded as convincing at the time. Bryson (26) suggested a link between long-timescale volcanic variations and climate fluctuations in the Holocene. Some have suggested that the Toba mega-eruption (~71,000 years ago) could have initiated the glacial period (27) or enhanced the kiloyear stadial event that followed (28).

The large-particle ash component of a volcanic eruption settles out quickly from the atmosphere, presumably limiting its influence in both space and time. If volcanic ash covered a substantial area of snow or ice, this could significantly reduce the surface albedo of that region for a short time and possibly cause melting, in particular, if the eruption occurred in the summer. The aerosol component of an eruption, resulting mainly from the emission of SO2 and H2S, can remain aloft and potentially force melting, in particular, if the eruption occurred in the summer. The agreement between our Siple Dome ash record and global indices of volcanism is surprising if the ash reflects only local effects. Perhaps sea level or some other global climate variable with wide-ranging influence were able to affect volcanic rates uniformly over much of the globe.
and a 10^14 mol pulse of O₂ emanating from the oceans in the Southern Hemisphere during austral summer 1991–1992 (50). Ash injection 100 times that of Pinatubo, including individual eruption volumes 10–50 times greater, can be expected on a timescale of 1 ky. Whereas Watson (34) assumed 1% by weight iron concentration for the ash deposited by Pinatubo, the ash samples from Siple Dome were found to contain iron on the order of 1% by weight, unusually high for explosive volcanism. A fertilization 20 times as effective as the Pinatubo eruption could serve as a sink, at least temporarily, for an amount of carbon greater than annual anthropogenic CO₂ emissions (7 billion metric tons). Alternative explanations for Pinatubo’s effect on CO₂ have also been suggested, such as increased terrestrial photosynthesis or a reduction in terrestrial soil and plant respiration (51).

The overall maximum in volcanic activity occurred in the Holocene between 9 and 9.5 ka. No glacial transition was associated with this volcanism, except perhaps for the relatively short-lived and weak 8.2-ka cold event (3) of the order of −5°C seen at all northern latitudes. If the Holocene differs substantially from the glacial regime, as is widely believed, then when the ice volume was larger, temperatures were colder and sea level was lower; this could help explain a muted effect.

**Implications**

Volcanism may be critical to our understanding of climate threshold instabilities and in developing a consistent picture of climatic teleconnections between hemispheres. Volcanism represents the most violent of potential reactions to or causes of abrupt climate change, and the possibility of increases in volcanic activity further underscores the need for a more comprehensive understanding of the earth system. It has often been proposed that iron fertilization of the ocean could be used as a sort of bioremediation to compensate for global warming. Although our results suggest that such action has the potential for dramatic consequences, it would likely be difficult to engineer effective fertilization of a large enough area of ocean to have substantial climatic impact. If warming and deglaciation induce volcanism, and if increasing volcanic activity can promote glaciation, this system represents a volatile although ultimately stable feedback for atmospheric temperature regulation. Large global temperature swings could be limited by a mechanism in which volcanism causes cooling, whereas warming factors trigger ice-sheet unloading and/or sea-level rise, leading to increased volcanic activity.

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