Sciencexpress Perspective

"C"ing Arctic Climate with Black Ice

Richard B. Alley

The author is in the Department of Geosciences, Pennsylvania State University, University Park, PA 16802, USA. E-mail: rba6@psu.edu

New ice-core measurements suggest that soot influenced recent Arctic climate change.

Humans have put our sooty foot in a lot of places, leaving visible tracks with consequences. In this week's *Science* Express, McConnell *et al*. report a new way to see those tracks, finding them bigger, blacker, and more influential than we thought (*1*).

Climate scientists are now confident that business-as-usual fossil-fuel burning for another century or two would lead to substantial global warming in response to increased atmospheric carbon dioxide (CO_2) concentrations. However, it is more difficult to project the climate of the next decade, and it has only recently become possible to confidently attribute most of the changes over the past century to specific causes. This is because the CO_2 forcing of the past century, and the additional forcing of the next decade, are of the same order of magnitude as many other natural and human effects (*2*).

In particular, the effects of airborne particles (aerosols) introduce large uncertainties into climate-change attributions (*2*). Most aerosols cause net cooling, partially offsetting greenhouse-gas warming, but black carbon (or soot) tends to warm the atmosphere, especially by lowering the very high reflectivity of snow. The short-term reduction in warming achievable by reducing soot emissions may help to avoid dangerous human influence on the climate (*3*).

Has soot contributed to past climate change? In the early 20th century, the Arctic warmed more strongly than anywhere else on Earth (*4*); was this natural climate variability, or might human soot have contributed? Unfortunately, modern instruments did not sample black carbon until recently. Investigators have relied on models and estimates of various combustion sources and efficiencies to constrain the effects of soot. McConnell *et al*. now report a detailed history of black carbon and its sources, extracted from a Greenland ice core, that goes a long way toward answering these questions.

A quiet revolution over the past decade has transformed many ice-core analyses. Once, trace chemicals in ice were determined by laboriously cutting, cleaning, and analyzing individual ice samples; now, clean melters feed streams of ice-core–derived water to a suite of instruments for continuous analyses. McConnell *et al*. used such an automated process (see the figure) to analyze a recently recovered core from a central-Greenland site where large amounts of snow accumulate every year. They obtained highly accurate, well-dated chemical histories—including black carbon concentrations—from 1788 to 2002, with a time resolution of less than a year.

For the first 60 years of the record, black carbon concentrations remained relatively stable, but the period from 1850 to 1951 showed highly elevated soot concentrations, especially during winter, when peak values were 10 times higher than the baseline. Lower values (although still higher than before 1850) mark the last 50 years of the record. Comparison to selected sections of a second core, collected 350 km to the south, shows close agreement, demonstrating the regional coherence of the signal.

Thus, black carbon concentration rose greatly to a peak in Greenland and still remains somewhat elevated. What was responsible? McConnell *et al.* were also able to detect low concentrations of organic molecules. They focused on vanillic acid, which originates largely from the burning of coniferous trees. Before 1850, soot and vanillic acid were highly correlated, especially during the summer fire season. Around 1850, when soot levels rose, correlation to the forest-fire indicator was lost, especially during winter. Instead, the higher soot values correlated closely with an acid-rain indicator (non–sea-salt sulfate, after exclusion of the well-known sulfate spikes from large volcanic eruptions). The human fingerprint is clear.

McConnell *et al.* even traced the soot to its source. Using the instrumental weather record for 1958 to 2002, they identified the main snowfall events for their site. Adopting a typical residence time for atmospheric particles, they then looked back along the trajectories of the precipitating air masses, finding the primary source region in eastern North America. They infer a similar source for older samples by analogy, although circumstantial evidence points to increasing importance of an Asian source as North American emissions decreased after 1951.

Thus, a natural biomass-burning source of soot, primarily in summer, was overwhelmed by a fossil-fuel–burning source, primarily in winter, for a carbon-blacked century

beginning about 1850. Since 1951, a weakening human signature may reflect technological advancement leading to cleaner combustion in eastern North America.

Do these observations help us understand climate history? Recent attempts to assess the climatic effects of black carbon, especially in the Arctic, have been largely restricted to the short interval of reliable instrumental records. McConnell *et al.* calculated the effect of their measured soot on absorbed solar radiation at their Greenland site. Based on comparison to an analysis for 1998 and 2001 for the whole Arctic (*5*), they then estimate the whole-Arctic effect of soot since 1788.

Changes in absorbed solar radiation are unimportant in the dark Arctic winter, and peak during early summer, before seasonal snow melts away to reveal darker surfaces less affected by soot. Focusing on that most sensitive season, McConnell *et al*. estimate an average Arctic warming effect from soot of more than 1 W/m^2 between 1850 and 1951, peaking in 1906 to 1910 at more than 3 W/m^2—eight times the natural forcing. For comparison, the globally and annually averaged forcing from the total anthropogenic CO_2 increase in the year 2006 was ~1.7 W/m^2 (*2*). For regional and seasonal changes, the soot effects must be important.

20th-century Arctic warming arrived in two sharp ramps (*6*): a late-century rise that paralleled the global response to greenhouse-gas increase, and a similarly strong early-century rise of more obscure origin. Processes in the Arctic, such as the ice-albedo feedback, tend to amplify natural variability (*7*) and the response to some forcing. The broad correspondence between the soot peak and the observed warming suggests that the Arctic changes in this case may also be amplified, because the forcing was stronger in the Arctic than elsewhere.

Greenland is not the whole world, and more records (*8*) and modeling will be needed to establish whether soot was important in the early–20th century Arctic warming. But the results of McConnell *et al.* place much tighter constraints on the history of soot forcing of Arctic climate and should reduce uncertainties in climate-change attribution. The rise and fall of soot in Greenland illustrate the human ability both to alter our environment and to limit those alterations.

The instrumental virtuosity and the richness of the ice-core record promise additional discoveries: today black carbon and vanillic acid, but what about tomorrow? At a recent meeting, I was asked whether big questions still remained to be solved in ice-core science. As shown by McConnell *et al*., the answer is an unequivocal yes.

References and Notes

1. J. R. McConnell *et al*., *Science* 9 August 2007 (10.1126/science.1144856).
2. Intergovernmental Panel on Climate Change, *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon *et al*., Eds. (Cambridge Univ. Press, Cambridge, UK, and New York, USA, 2007).
3. J. Hansen, L. Nazarenko, *Proc. Natl. Acad. Sci. U.S.A.* **101**, 423 (2004).
4. T. Delworth, T. R. Knutson, *Science* **287**, 2246 (2000).
5. M. G. Flanner, C. S. Zender, J. T. Randerson, P. J. Rasch, *J. Geophys. Res*. **112**, D11202 (2007).
6. P. D. Jones, M. New, D. E. Parker, S. Martin, I. G. Rigor, *Rev. Geophys.* **37**, 173 (1999).
7. L. Bengtsson, V. A. Semenov, O. M. Johannessen, *J. Clim.* **17**, 4045 (2004).
8. T. M. Jenk *et al.*, *Atmos. Chem. Phys.* **6**, 5381 (2006).

9. This work was funded in part by the U.S. National Science Foundation through grants 0531211, 0538578, and 0424589.

Published online 9 August 2007; 10.1126/science.1147470
Include this information when citing this paper.

History in the making. A section of an ice core is melted in the clean laboratory for the report by McConnell *et al.;* meltwater from only the central part of the sample is diverted to the analytical line.

Credit: J. R. McConnell/Desert Research Institute, Reno, Nevada.