ods of, for example, Dust Bowl level aridity, lasted for 20-40 years. Graham et al. (submitted) have used proxies to estimate medieval SSTs and demonstrated that when they are used to force an atmospheric GCM, drought results over North America. The altered mean state of the medieval period, not only in North America but also in other ENSO sensitive regions (e.g., East Africa, northern South America, South Africa, the Sahel and the Indian ocean; Herweijer et al., submitted), is consistent with a solar-induced La Niña-like state in the tropical Pacific. The tree ring data also show that the Little Ice Age was a relatively wet period in the central U.S. compared with the earlier medieval period (Fig. 1c), consistent with a shift towards a reduced east-west gradient, as shown in Figure 1b.

Final points

Of course, a number of caveats apply here. First, model studies have shown that Atlantic SSTs exert an influence on central U.S. precipitation (Schubert et al., 2004; Seager et al., submitted; Sutton and Hodson, 2005), so there is no reason to believe that conditions in the tropical Pacific are a perfect predictor of central U.S. rainfall. It should also be noted that the observations of tropical Pacific SSTs are quite sparse prior to the 20th century, and coral data for the last 1000 years are critical to filling in these gaps. Finally, there is the issue of the magnitude of solar irradiance changes. While the ZC model is fairly sensitive to even small solar forcing (Emile-Geay et al., accepted), if the mid-range value of 0.5 Wm^{-2} is accepted, the model response is quite small (~0.15°C). Thus, while the linkages explored here might have qualitative support from models and paleoclimate observations, it is difficult to argue for such large quantitative changes in the climate system from solar forcing alone. Thus remains the centuries-old problem of why the climate response to solar forcing appears to be so large. Perhaps the tropical Pacific is part of the answer but it may not be the whole story.

Note

Data used in the study can be found in the 'data' section of the authors research page at http://www.ldeo.columbia.edu/~julieneg/research.html.

References

Clement, A.C., Seager, R., Cane, M.A., and Zebiak, S.E., 1996: An ocean dynamical thermostat. *J. Climate*, **9**: 2190-2196.

Emile-Geay, J., Cane, M., Seager, R., Kaplan, A., and Almasi, P., accepted: ENSO as a mediator of the solar influence on climate, *Paleoceanography*.

Evans, M.N., Kaplan, A. and Cane, M.A., 2002: Pacific sea surface temperature field reconstruction from coral delta O-18 data using reduced space objective analysis. *Paleoceanography*, **17**, Art. No. 1007.

Herweijer, C., Seager, R. and Cook, E.R., 2006a: North American droughts of the mid to late nineteenth century: a history, simulation and implication for Mediaeval drought, *The Holocene*, **16**(2): 159-171.

Seager, R., submitted: The turn of the century drought across North America: Dynamics, global context and prior analogs. *J. Climate*.

For full references please consult: www.pages-igbp.org/products/newsletters/ref2006_2.html

The mystery interval 17.5 to 14.5 kyrs ago

George H. Denton[1], Wallace S. Broecker[2] and Richard B. Alley[3]

[1]Department of Earth Sciences and Climate Change Institute, University of Maine, Orono, USA; gdenton@maine.edu
[2]Lamont-Doherty Earth Observatory, Columbia University, Palisades, USA
[3]Pennsylvania State University, University Park, USA

The time period between the beginning of Heinrich event #1 (H-1) and the onset of the Bølling/Allerød rivals the Younger Dryas in importance to our understanding of how the planet responds to abrupt mode switches. This interval also constitutes the onset of the most recent termination, arguably the most fundamental climate shift of the last 100-kyr glacial cycle. As some of the responses during this time appear to be mutually contradictory, we term it the "Mystery Interval".

Key observations

Notable events during the 3000-year-long Mystery Interval are as follows (Fig. 1).

- The H-1 iceberg armada was discharged into the North Atlantic Ocean (Bond et al., 1992; Hemming, 2004).
- Export of ^{231}Pa from the Atlantic to the Southern Ocean appears to have come to a halt, signaling a shutdown of North Atlantic meridional overturning circulation (McManus et al., 2004).
- The northern Atlantic Ocean and the Mediterranean Sea became unusually cold (Bard et al., 2000; Cacho et al., 2001).
- Conditions in Greenland were heavily weighted toward hypercold winters (stadial GS-2a; Denton et al., 2005).
- Northwestern Europe was similarly dominated by hypercold winters (Late-Pleniglacial; Renssen and Isarin, 2001).
- The Asian monsoons were notably weakened (Wang et al., 2001).
- The Atlantic Intertropical Convergence Zone (ITCZ) was locked into a southerly position (Peterson et al., 2000; Lea et al., 2003).
- Temperate mountain glaciers in both hemispheres underwent major recession that began about 17.5 kyr (Denton et al., 1999; Schaefer et al., 2006). By 14.5 kyr at the end of the Mystery Interval, Swiss mountain glaciers had withdrawn to the inner Alps (Schlüchter, 1988).
- Closed-basin lakes in North America's Great Basin reached their greatest size (Benson, 1993; Garcia and Stokes, 2000).

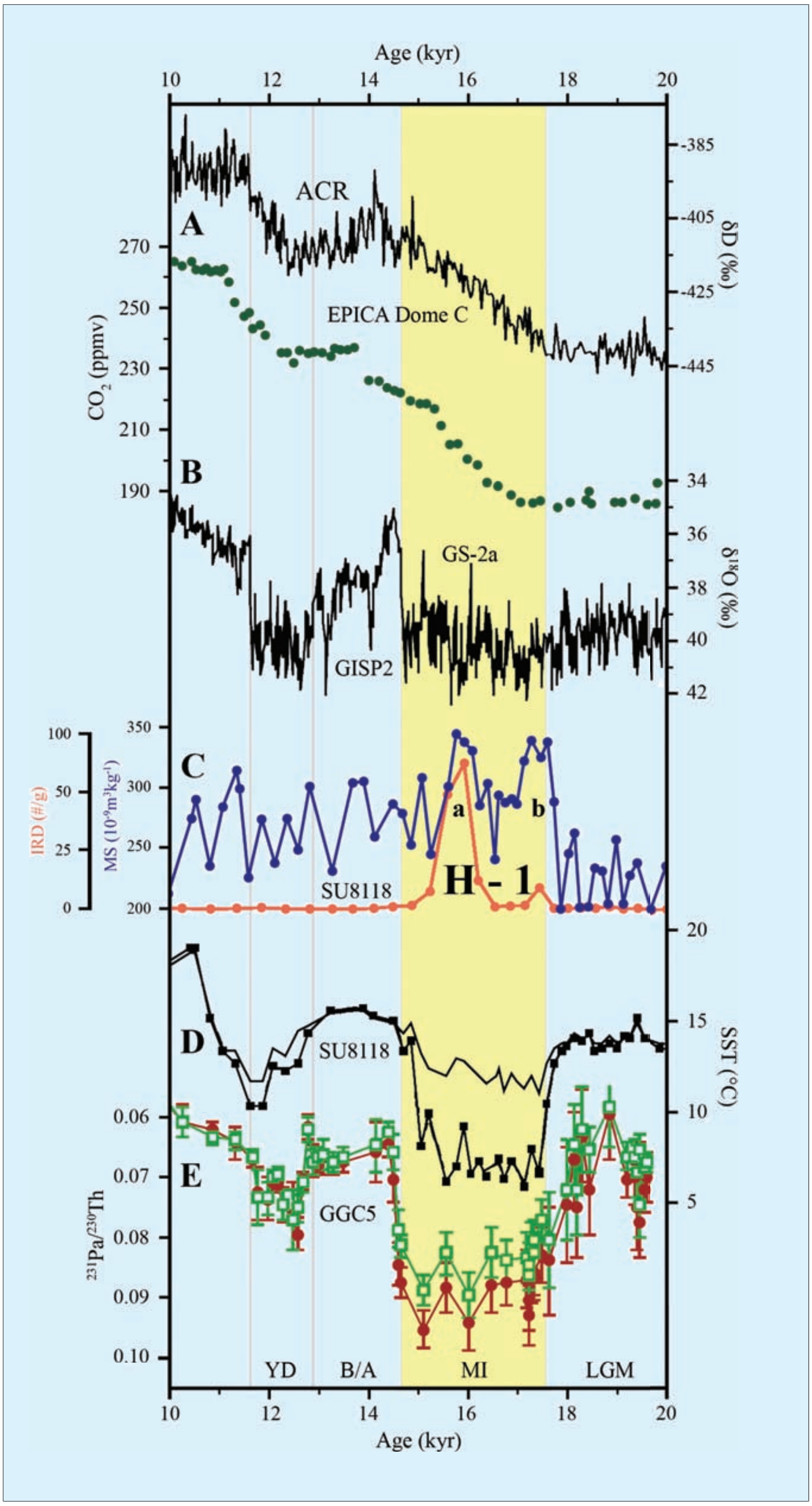

Figure 1: The Mystery Interval is marked by yellow background. ***A*** *shows deuterium and CO_2 records from the EPICA Dome C ice core on the East Antarctic plateau (Monnin et al., 2001). Chronology is based on Schwander et al. (2001).* ***B*** *gives the GISP2 isotope record (Stuiver and Grootes, 2000).* ***C*** *illustrates ice-rafted grains and magnetic susceptibility in core SU-8118 off Portugal (Bard et al., 2000). IRD is expressed as the number of grains per gram for the size fraction greater than 150 µm. The H-1a IRD peak features quartz and feldspars, with minor hematite-coated grains, glauconite, and volcanic shards. The H-1b IRD peak is largely detrital carbonate, with minor amounts of quartz and feldspar (Bard et al., 2000).* ***D*** *is SST from two calibrations for alkenone unsaturation ratios from core SU-8118 (Bard et al., 2000).* ***E*** *is a $^{231}Pa/^{230}Th$ profile from core GGC5 from the Bermuda Rise (McManus et al., 2004). YD: Younger Dryas, B/A: Bølling/Allerød, MI: Mystery Interval, LGM: Last Glacial Maximum. Figure adapted in part from McManus et al. (2004).*

- The African rift valley suffered maximum aridity (Johnson et al., 1996).
- The ^{14}C to C ratio in the atmosphere dropped by 190 per mil (Broecker and Barker, in press).
- Deglacial warming of Antarctica and the rise of atmospheric CO_2 content became pronounced (Monnin et al., 2001).

Possible explanation

How these events fit together is a major puzzle. One seeming contradiction may afford an important clue; namely, extensive deglaciation of the European Alps occurred during a time of maximum cold in the adjacent Atlantic Ocean and Mediterranean Sea, along with some indications of continued cold conditions, at least during winter, on the continent itself. This conclusion comes from oxygen-isotope curves of carbonate from lakes and mires that allow European climate oscillations to be tied directly to the Greenland template (e.g., von Grafenstein et al., 1999). Such records from the Swiss Alps show that extensive glacier recession had already occurred prior to the distinctive earliest Bølling isotope switch, which was accompanied by a "juniper jump" in pollen profiles (Eicher and Siegenthaler, 1976). It is important to note from isotope chronologies that both Andean and New Zealand mountain glaciers abandoned their innermost Last Glacial Maximum (LGM) positions and also suffered extensive retreat during the Mystery Interval (Denton et al., 1999; Strelin and Denton, 2005; Schaefer et al., 2006).

Assuming that our read of the evidence is correct, we can think of only one explanation for this contradiction; namely, that the cold oceanic and terrestrial conditions reflect extensive winter sea-ice cover in the northern Atlantic and that the retreat of temperate mountain glaciers reflects warming summer conditions brought on by rising atmospheric CO_2. If this is indeed the explanation, then we suggest the following scenario: The Mystery Interval was initiated by the melting of the H-1 iceberg armada. This melting reduced the salinity of the northern Atlantic to the point where deep water could no longer form. The resulting shutdown of meridional overturning circulation was so severe that the export of ^{231}Pa from the North Atlantic was reduced by an even larger extent during the Mystery Interval than during either the LGM or the Younger Dryas (McManus et al., 2004). As a consequence of this shutdown, the northern North Atlantic cooled, allowing the spread of winter sea ice. Such expansion of sea ice, perhaps as far south as 48°N, is required for the severe winter cooling that produced widespread periglacial features in northwestern Europe (Renssen and Isarin, 2001). In addition, winter sea ice is almost certainly the primary cause of depressed mean annual temperatures in Greenland, which are highly skewed toward winter (Denton et al., 2005). As shown by Chiang and Bitz (2005), widespread winter sea ice in the northern Atlantic not only cools the northern high-latitude region, but pushes southward the Atlantic sector of the ITCZ. Furthermore, according to Barnett et al. (1988), the consequent increase in the duration of Asian snow cover lessens the effectiveness of the summer warm season in heating the continent, hence weakening summer monsoons. It thus appears likely that severe winter conditions in the northern latitudes during the Mystery Interval, originating from the shutdown of North Atlantic overturning and spread of winter sea ice, afforded the physical linkage between millennial-scale Greenland, European, and North Atlantic temperature fluctuations; the ITCZ; and Asian monsoons (Denton et al., 2005).

The relative timing of northern and southern events shown in Figure 1 suggests that the shutdown of meridional overturning in the North Atlantic during the Mystery Interval may have been the major factor in driving the last termination, which in panel A of Figure 1 is marked by the rise of Antarctic temperature and of atmospheric CO_2. A consequence of this shutdown of northern overturning appears to have been an overall reorganization of ocean circulation, probably through the operation of a bipolar thermohaline seesaw (Broecker, 1988), that led to shrinkage of the sea-ice fringe around Antarctica. As a result, Antarctica warmed while atmospheric CO_2 slowly increased, perhaps due to more efficient degassing from the Southern Ocean (Stephens and Keeling, 2000). These events were curtailed when northern overturning resumed during the Bølling/Allerød. They were then renewed during the Younger Dryas, which in many ways was a shorter repetition of the Mystery Interval.

It is far from clear why the shutdown from the H-1 iceberg armada could have had a greater impact than those associated with the five earlier Heinrich armadas. A possible clue is that terminations begin at what would intuitively seem to be unlikely times; namely, just as ice sheets achieve maximum volumes at the culmination of the long buildup leg of an asymmetric 100-kyr cycle. In fact, Raymo (1997) suggested from marine benthic oxygen-isotope records that the prerequisite for a sharp and complete termination was "excess" ice stored in northern ice sheets. Once excess ice volume is achieved, major deglaciation awaits only the next rise of northern summer insolation. Does this suggest that the collapse of such excess ice into the North Atlantic is what caused the H-1 ice armada to be so effective in triggering the last termination?

Princeton GFDL's Isaac Held (2006) makes the case that the warmer climate to be generated by the ongoing buildup of greenhouse gases will lead to even wetter conditions in the tropics and even drier conditions in the deserts of the extra tropics. The converse of this is that in the colder glacial world, the opposite should have been true. If so, then the cold ocean conditions and the enhanced sea ice cover of the Mystery Interval might account for the unusually large extent of the closed-basin lakes in the Great Basin and the dessication of equatorial Africa's Lake Victoria. Hostetler et al. (1999) found such a signature for modeled water-balance anomalies in response to specified changes in North Atlantic sea-surface temperatures at the time of Heinrich event #2 (H-2).

One last occurrence merits mention. As shown by Adkins and Schrag (2003), during peak glacial time, an abyssal ocean reservoir with one gram per liter higher salt content than the rest of the deep ocean appears to have existed. Their idea is that the reservoir owed its existence to the input of dollops of brine released from Antarctica's greatly expanded glacial sea-ice apron. If, as the result of its isolation from the rest of the ocean, this reservoir were greatly depleted in radiocarbon, it could help to explain why the ^{14}C to C ratio of the glacial atmosphere was so much higher than that for the late Holocene. Even more importantly, the demise of this reservoir caused by the reduction in brine supply related to the retreat of the ice margin could explain the large drop in the atmosphere's ^{14}C to C ratio during the course of the Mystery Interval (Broecker and Barker, in press).

References

Bard, E., Rostek, F., Turon, J.-L., and Gendreau, S., 2000: Hydrological impact of Heinrich events in the northeast Atlantic. *Science*, **289**: 1321-1323.

Denton, G.H., Alley, R.B., Comer, G.C., and Broecker, W.S., 2005: The role of seasonality in abrupt climate change. *Quaternary Science Reviews*, **24**: 1159-1182.

McManus, J.F., Franciois, R., Gherardi, J.-M., Keigwin, L.D., and Brown-Ledger, S., 2004: Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate change. *Nature*, **428**: 834-837.

Monnin, E., Indermühle, A., Dällenbach, A., Flückiger, J., Stauffer, B., Stocker, T.F., Raynaud, D., and Barnola, J.-M., 2001: Atmospheric CO_2 concentrations over the last glacial termination. *Science*, **297**: 112-114.

Stuiver, M., and Grootes, P., 2000: GISP2 oxygen-isotope ratios. *Quaternary Research*, **53**: 277-284.

For full references please consult:
www.pages-igbp.org/products/newsletters/ref2006_2.html