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Twin Ice Cores from Greenland Reveal History of Climate Change, More

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PAGES 209–210

Two projects conducted from 1989 to 1993 collected parallel ice cores—just 30 km apart— from the central part of the Greenland ice sheet. Each core is more than 3 km deep and extends back 110,000 years. In short, the ice cores tell a clear story: humans came of age agriculturally and industrially during the most stable climatic regime recorded in the cores. Change—large, rapid, and global—is more characteristic of the Earth's climate than is stasis.

The unprecedented swings in Earth's climate recorded in these ice cores were the center of discussion as members of the two groups, the U.S. Greenland Ice Sheet Project 2 (GISP2) and the European Greenland Icecore Project (GRIP), met at a September meeting in Wolfeboro, New Hampshire. More than 100 scientists exchanged data and ideas, finalized arrangements for a special joint issue of *JGR Oceans* and *JGR Atmospheres* (due out in about a year), and planned future analyses and ice-coring projects. Research findings made with these ice cores have been detailed in roughly 200 refereed publications so far. A brief synopsis of some of the more recent major results of the projects discussed at the meeting is presented here. For further details, interested readers are referred to the primary literature and to the forthcoming *JGR* issue.

Recent Climate Change Is Rapid

Workshop participants agreed that the Earth has experienced large, rapid, regional-to-global climate oscillations through most of the last 110,000 years, of a scale that agricultural and industrial humans did not face. Though a few of these stadial/interstadial oscillations such as the Younger Dryas event were known for decades, many more were found in the first Greenland deep ice cores, but most of the oscillations occurred in ice from close to the bed where flow may have disturbed the climatic record. In the new cores, these events are recorded far enough above the bed that ice flow is unlikely to have altered the early section of the 110,000-year climatic record. The almost perfect match back to this date between records from the two cores should dispel any lingering doubt about the climatic origin of the events.

These millennial-scale events represent large climate deviations that probably include change in temperature of many degrees Celsius, twofold changes in snow accumulation, order-of-magnitude changes in wind-blown dust and sea-salt loading, and large changes in methane concentration, etc., with cold, dry, dusty, and low-methane conditions correlated. Changes during these events commonly occur over decades or less. Shifts in the patterns of atmospheric circulation could explain the rapidity and magnitude of these events. Most recently subtle versions of these rapid climate change events have been identified through the reconstruction of atmospheric circulation patterns in the Holocene portion of the GISP2 record. Major climatic change events also are also recorded in the isotopic temperature record of the Vostok core from central East Antarctica, although with smaller amplitude and a more ramped appearance than in Greenland.

Greenland Is Warmer Today

Ice-age temperatures in central Greenland were roughly 20°C colder than today. The stable isotope composition of accumulated snow responds primarily to depositional temperature, but it is sensitive to many other factors. Borehole temperatures can be used to calibrate the isotopic thermometer. Two such isotopic calibrations yield larger glacial-interglacial temperature changes than previously suspected. These calibrations, plus instrumental, model, and other studies, demonstrate that the isotopic ratio of accumulated snow is an excellent thermometer, although it seems that the calibration may be nonlinear in Greenland over glacial to interglacial timescales. Lively discussion centered on several possible causes of these results, and improved explanations should be forthcoming. Calibrations for the rapid glacial-age oscillations are not complete, although large changes are indicated compared with previous estimates.

Factors Affecting Local and Regional Climate

Comparison of sunspot cycles to oxygen-isotopic ratios (temperature) reveals clear solar-modulated climatic response. Similarly, the ice-core volcanic record leads to estimates both of volcano size and atmospheric response. Time-series analyses of chemical and other data reveal significant periodicities, some related to cyclical changes in Earth's orbit. The detailed ammonium record gives some evidence for a fast buildup of the biosphere on the North American continent after the retreat of the ice sheet. Methane measurements show large variations during the Holocene, indicating large changes in the global extent of wetlands.

Rethinking Rapid Changes in Glacial-Age CO_2

Initial interpretation of the GRIP ice-core data indicated that the large, rapid climate oscillations that dominate the record of the last 110,000 years also persisted through the previous warm period, the Eemian, which took place ~120–130 thousand years ago. The GISP2 core also shows rapid oscillations during that time period, but with different timing and character. In both cores, physical examination shows significant structural disturbances from ice flow beginning at or slightly above the depth at which difference in their climate records appear—roughly 2800 m, or approximately 110,000 years ago. New results presented at the meeting show that globally mixed gases in both cores differ from those of the Vostok, Antarctica core, where Eemian ice is far above the bed and therefore undisturbed by ice flow.

Much remains to be learned about Eemian climate from these cores. Just as they were needed to validate the rapid oscillations observed in older cores, a core from a site where the Eemian is farther above the bed and thus is less subject to flow disturbance will provide the best information. Planning and selection of a site capable of delivering records with comparable time resolution are already underway in North Greenland and Antarctica.

Measurements of gas-bubble compositions from Antarctic cores provide the best paleorecords of CO_2 concentrations. Greenlandic records indicate some unexplained "noise" possibly related to chemical reactions with the more abundant carbonate dust in Greenland ice. Further, high-resolution ice records reported on at the meeting support the view that interpreting the Greenland CO_2 record is more complex than interpreting the Antarctic record. However, the results do not question earlier findings about the increase of the atmospheric CO_2 concentration at the end of the last glaciation and a steady increase since the beginning of the industrial epoch.

Ice Cores Lead to Progress in Related Research

Meeting participants also agreed that great progress is being made on "fundamentals" research, more basic science. The ability to count annual layers in the cores well into the glacial period and probably through 110,000 years will help to answer questions about deglacial chronology, radiocarbon calibrations, etc. The use of volcanic markers and atmospheric-oxygen isotope ratios to determine the ages of ice cores and ocean records greatly extends our ability to map climate changes and understand their causes.

Reconstruction of atmospheric circulation patterns and their changes over time from chemical indicators and dust sources provides new insight into the large, rapid changes documented in the cores. Vigorous work on the air-snow transfer function for chemicals and particulates is clarifying the significance of the paleoclimatic records. Glacier geophysics and flow modeling, coupled with physical and electrical studies of ice cores, are leading to better understanding of the ice cores and ice-sheet behavior, and possible contributions to sea-level change.

Other topics discussed at the meeting included basal conditions of the ice sheet, changes in atmospheric acids, evidence of extraterrestrial impacts, the influence of anthropogenic activity on the chemistry of the atmosphere, reconstruction of forest-fire frequencies upwind of the site from analysis of their fallout on the ice, and details of Holocene climate variability. Many studies are underway to help understand the Greenland record in more detail.

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Chart Links Solar, Geophysical Events With Impacts on Space Technologies

PAGE 211

While developing a Space Weather Training Program for Air Force Space Command and the 50th Weather Squadron, both based in Colorado, ARINC Incorporated produced a flowchart that correlates solar and geophysical events with their impacts on Air Force systems.

Personnel from both organizations collaborated in the development of the flowchart and provided many comments and suggestions. The model became the centerpiece of the Space Environment Impacts Reference Pamphlet, as well as the formal Space Weather Training Program. Although it is not a numerical or computer model, the flowchart became known as the "Space Environmental Impacts Model."

Figure 1 is a small excerpt extracted from the more comprehensive and complex model. The complete flowchart addresses many other solar-geophysical events and their impacts on a variety of space-based and ground-based systems. A printed copy of the entire Space Environmental Impacts Model is available from the author upon request.

Since developing this flowchart for the Air Force, ARINC has used it many times to help identify the sources of impacts on operational systems and to relate observable phenomena to their likely impacts. This may be the first time so many of the interrelated linkages that characterize the space environment have been assembled on a single flowchart.

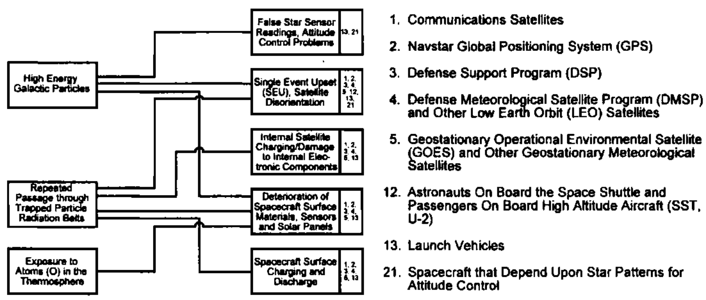

Fig. 1. An excerpted flowchart from the full Space Environmental Impact Model shows some of the complex relationships described in the model.

The model identifies solar-geophysical events such as energetic solar flares, coronal mass ejections, coronal holes, and objects that can affect systems, including natural and man-made debris. It then maps the events to their impacts upon space-based and ground-based systems. Finally, it identifies systems that are likely to experience the impacts. Observable space environmental phenomena are identified within the boxes on the left side of the flowchart, and resulting impacts are shown on the right. Each impact box identifies one or more operational system that can be degraded by the impact. Linkages enter the various boxes from the left or at the top, and they leave the boxes to the right or at the bottom.

For example, on a portion of the flowchart not included in the accompanying figure, the model indicates that a solar radio burst is likely to accompany an energetic solar flare event. The solar radio burst maps to radio frequency interference that can impact geostationary and low-Earth orbit satellites, various detection and tracking radars, passive spacecraft tracking systems, and communications systems operating over a range of radio frequencies.

The information to assemble the Space Environmental Impacts Model was gathered during interviews with spacecraft and ground system operators and by researching the technical literature. The linkages cull, summarize, and organize the work of many researchers into a concise and consistent flowchart that presents a great deal of information in one place. Scientists and engineers have spent years, in some cases entire careers, establishing and explaining the relationships and linkages that are represented by the lines that connect the boxes of the flowchart. The flowchart confirms the relevance of their work. For more information contact the author by e-mail at gdavenpo@arinc.com.—*George R. Davenport, ARINC Incorporated, Colorado Springs, Colo.*

An electronic supplement to this article may be obtained on the World Wide Web at http://www.agu.org/eos_elec as 95183e.html by George R. Davenport.