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Global climate change

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ABSTRACT **Most of the last 100,000 years or longer has been characterized by large, abrupt, regional-to-global climate changes. Agriculture and industry have developed during anomalously stable climatic conditions. New, high-resolution analyses of sediment cores using multiproxy and physically based transfer functions allow increasingly confident interpretation of these past changes as having been caused by "band jumps" between modes of operation of the climate system. Recurrence of such band jumps is possible and might be affected by human activities.**

Studies of past climate changes show that the Earth system has experienced greater and more-rapid changes over larger areas than was generally believed possible, jumping between fundamentally different modes of operation in as little as a few years. Ongoing research cannot exclude the possibility that natural or human-caused changes will trigger a mode switch in the near future.

Global climate change is of interest because of the likelihood that it will affect the ease with which humans make a living, and perhaps the carrying capacity of the planet for humans and other species. Attention is especially focused on the possibility that human activities will cause global climate change because our choices can then affect outcomes.

Prediction of climate change requires observational constraints on the current climate state, knowledge of the way the coupled air-ocean-ice-earth-life system behaves, and information on changing forcings such as solar variability. Studies of past climate are also required, to focus model-building efforts on climate components that are likely to change and to allow testing of the ability of models to predict time-evolution of the system.

Short, geographically restricted records of past climates have been reconstructed from instrumental data and other historical documents. For longer perspectives, we interpret the physical, chemical, isotopic, and biological records in sediments. Most studies focus on the sediments of oceans and lakes and on ice sheets and glaciers, but tree rings, cave formations, the collections of packrats, and many other recorders provide useful information.

Several techniques are used to relate sediment characteristics to climate. Some climate information is recorded by simple physics. For example, the ice 1–2 km deep in the Greenland ice sheet was deposited at very cold temperatures during the most recent ice age and remains colder than ice above or below because it has not finished warming (1). Diffusive information loss ranges from significant to trivial. The record of old, high-frequency temperature changes is no longer preserved in the temperature of the Greenland ice sheet because of diffusion. However, when abrupt climate changes cause strong temperature gradients in near-surface, permeable layers of the ice sheet, thermal-diffusion fractionation of gases produces a clear isotopic anomaly in bubbles being formed beneath (Fig. 1), and that anomaly suffers almost no measurable diffusion over 100,000-year time scales (2).

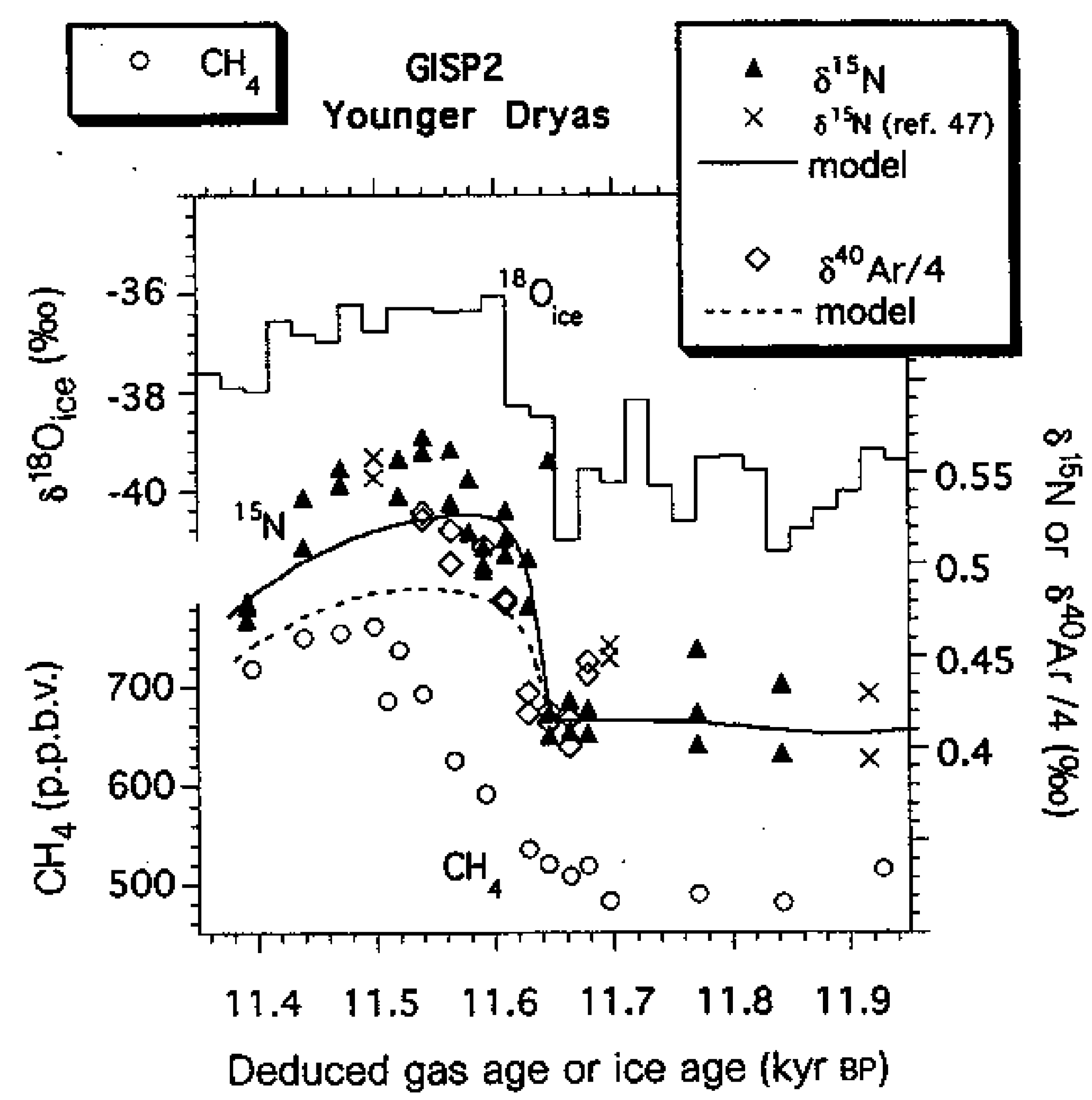

FIG. 1. Gas-isotopic data from an ice core in central Greenland covering the last deglaciation. Bubbles are formed ~70 m deep in the ice sheet, below a permeable layer of old snow called firn. Gravitational fractionation in this layer causes the gases to be isotopically slightly heavier than the free atmosphere. An abrupt warming causes the surface snow to be warmer than the firn 70 m down, and temperature gradients fractionate heavy isotopes to the cold end. The gaseous signal diffuses to the trapping depth in a few years, while heat flow reaches that depth in a century or so. The rise and fall in the isotopic ratios of nitrogen ($\delta^{15}N$) and argon ($\delta^{40}Ar/4$) record the rise and fall of the temperature gradient caused by the abrupt surface warming followed by the gradual warming at the depth of bubble trapping. The differential response of these two indicators allows separation of contributions from temperature gradients and gravitational fractionation, and indicates a warming of ~8°C in on the order of a decade. This agrees closely with temperature change inferred from the isotopic composition of the ice, shown by the upper curve. Significant rise in methane, produced in global wetlands with a dominant role for the tropics, lags the warming in Greenland by one sample (0–30 years), showing a widespread geographic impact for the abrupt-change event. [Figure and legend reproduced with permission from ref. 2 (Copyright 1998, Macmillan Publishers Ltd, http://www.nature.com/)].

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Calibration in some cases involves correlation of characteristics of recent sediments to instrumental climate records. For example, abundance of species of shells observed in marine sediments may be related statistically to site conditions. This modern calibration is then applied to past times. Close agreement between reconstructions using independent techniques is sought to improve confidence that time-variation of calibrations has not been severe.

Ages of sediments are determined by counting of annual layers (in favorable ice cores, tree rings, corals, cave formations, and ocean and lake sediments), by radiometric techniques or by correlation techniques to other well dated records. Again, close agreement among independent results provides confidence.

Long climate-change records show alternations between warm and cold conditions over hundreds of millions of years associated with drifting continents. Large glaciers and ice sheets require polar land masses, continental rearrangement and associated changes in topography affect oceanic and atmospheric circulation, and these affect global biogeochemical cycles with high atmospheric CO_2 levels associated with warm times.

The last few million years have been generally cold and icy compared with the previous hundred million years but have alternated between warmer and colder conditions. These alternations have been linked to changes over tens of thousands of years in the seasonal and latitudinal distribution of sunlight on Earth caused by features of the Earth's orbit. Globally synchronous climate change despite some hemispheric asynchrony of the forcing is explained at least in part by lowering of CO_2 during colder times in response to changes in ocean chemistry. We live in one of the warmer times of these orbital cycles; the coolest times brought glaciation to nearly one-third of the modern land area.

Recently, high-time-resolution records have shown that much of the climate variability has occurred with typical spacings of 1–2 thousand years and a few thousand years. Changes have been large (in Greenland, for example, 5–10°C, 2× in snowfall, up to order-of-magnitude in wind-blown dust), widespread (hemispheric to global, with cold, dry, and windy conditions typically observed together), and rapid (in as little as decades to possibly a single year).

The changes have been especially large in the North Atlantic basin. In the modern climate, the warm and salty surface waters of the Gulf Stream heat the overlying atmosphere during winter, becoming dense enough to sink into and flow through the deep ocean before upwelling and returning in a millennium or so. Numerical models and paleoclimatic data (e.g., ref. 3) agree that changes in this "conveyor-belt" circulation can explain at least much of the observed millennial variability, although the reconstructed changes may be more dramatic than those modeled. Sinking can be stopped by North Atlantic freshening associated with increased precipitation or with melting of ice sheets on land or after a surge into the ocean; North Atlantic sinking also might be stopped by changes in the tropical ocean or elsewhere [reviewed by Alley and Clark (4)].

Of concern is that some global-warming models project North Atlantic freshening and possible collapse of this conveyor circulation, perhaps with attendant large, rapid climate changes. At least one model (5) indicates that slowing the rate of greenhouse-gas emissions might stabilize the modern circulation.

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1. Cuffey, K. M., Clow, G. D., Alley, R. B., Stuiver, M., Waddington, E. D. & Saltus, R. W. (1995) *Science* **270,** 455–458.
2. Severinghaus, J. P., Sowers, T., Brook, E. J., Alley, R. B. & Bender, M. L. (1998) *Nature (London)* **391,** 141–146.
3. Charles, C. D., Lynch-Stieglitz, J., Ninnemann, U. S. & Fairbanks, R. G. (1995) *Earth Planet. Sci. Lett.* **142,** 19–27.
4. Alley, R. B. & Clark, P. U. (1999) *Annu. Rev. Earth Planet. Sci.*, **27,** 149–182.
5. Stocker, T. F. & Schmittner, A. (1997) *Nature (London)* **388,** 862–865.