bonding in FeO becomes more important at high pressure. The shorter Fe–Fe distance across shared FeO_6 octahedral faces in the NiAs structure could lead to metallic conductivity in FeO by electron delocalization. The metallization will also be enhanced by the loss of local Fe moments (*13*).

Earth's core is about 10% less dense than pure iron at core pressures and temperatures (*14*). This density deficit implies that a substantial amount of light elements, such as H, O, S, C, Si, or Mg, is incorporated into the core. Although there is no simple answer to what light elements may be present in the core, recent experimental results on the solubility of FeO in molten iron (*15–18*) and the metallization of FeO (*19–20*) at high pressure and temperature imply that oxygen is the alloying element. The covalently and metallically bonded NiAs-type structure of FeO at high pressure would allow some solubility of oxygen (in the form of FeO) in molten iron.

FeO is the only monoxide that has been found to have covalently and metallically bonded NiAs structure at high pressure and temperature, contrary to CaO, SrO, and BaO, which transform from rock salt (B1) to CsCl (B2) structures. The changes in the structure and the nature of chemical bonding in FeO would allow FeO to form solid solutions with compounds of similar structure and bonding, such as FeS and Fe (hexagonal closest packing), at high pressure and temperature. This opens the possibility of incorporating both oxygen and sulfur in the Earth's core.

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23. We thank C. M. Bertka, R. E. Cohen, L. W. Finger, R. J. Hemley, R. Jeanloz, A. Navrotsky, and C. T. Prewitt for discussions and comments. Supported by the NSF Center for High-Pressure Research and the Carnegie Institution of Washington.

7 September 1994; accepted 1 November 1994

The Accumulation Record from the GISP2 Core as an Indicator of Climate Change Throughout the Holocene

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A depth-age scale and an accumulation history for the Holocene have been established on the Greenland Ice Sheet Project 2 (GISP2) deep core, providing the most continuously dated record of annual layer accumulation currently available. The depth-age scale was obtained with the use of various independent techniques to count annual layers in the core. An annual record of surface accumulation during the Holocene was obtained by correcting the observed layer thicknesses for flow-thinning. Fluctuations in accumulation provide a continuous and detailed record of climate variability over central Greenland during the Holocene. Climate events, including "Little Ice Age" type events, are examined.

The GISP2 ice core was drilled from surface to bedrock to obtain a paleoclimatic history spanning the last 200,000 years. The summit drilling site is located at 72.6°N, 38.5°W, at an elevation of 3200 m. A European companion study, the Greenland Ice Core Project, has obtained a parallel ice core at a site approximately 30 km east of the GISP2 site. The Holocene accumulation record (*1*) from the GISP2 core provides a continuous, detailed history of climate fluctuations over central Greenland. In this report we describe the accumulation record spanning the last 11,000 years (Holocene) and its relation to climate change (*2*) but we make no comparison with other records, which tend to vary.

Although the degree of climate change during the Holocene has been small in comparison to events such as the Younger Dryas, the events that have taken place are important to our understanding of future changes and the effect they may have on our society. Although the accumulation record cannot necessarily answer these questions, it can provide initial detailed information on when climate changes have occurred. In addition, layer thickness (accumulation) as determined in the field also provides investigators with immediate information on where to sample the core in detail.

We dated the ice core throughout the top 1640 m by identifying and counting annual layers using a number of physical and chemical parameters, including measurements of visual stratigraphy (*3*), electrical conductivity (ECM) (*4*), laser light scattering (from dust) (*5, 6*), oxygen isotopes, and chemistry. Each of these parameters exhibits a distinct seasonal signal. The definitive summer stratigraphic signal at the GISP2 site throughout the Holocene is coarse-grained depth hoar (*3*). These layers are easily recognized in a core examined in transmitted light. Annual stratigraphic layers are visible to a minimum of 55,000 cal B.P. (equivalent to calendar years before the present).

A relation between $\delta^{18}O$ and surface

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temperature has been established for ice cores (*7*), where more negative $\delta^{18}O$ values correspond to lower temperatures. Many factors affect the isotopic ratio; therefore, $\delta^{18}O$ values should be used to predict not actual surface temperature but rather relative changes (*8*). Accumulation rate is associated with oxygen isotopes in the GISP2 core, where increasing $\delta^{18}O$ values (indicating warming climate) correspond to increasing accumulation and conversely decreasing $\delta^{18}O$ values (indicating cooling climate) correspond to decreasing accumulation. Using radiosonde data, Bromwich and Robasky (*9*) found a correspondence between temperature and precipitation. Additional correlations between accumulation and oxygen isotopes have been noted for Greenland and Antarctica (*10–13*). These results suggest that, like $\delta^{18}O$, accumulation may also be used as a proxy for temperature.

Accumulation and oxygen isotopes correlate significantly at GISP2. Correlations for the last 11,500 years show that dramatic excursions in climate, such as the Younger Dryas Holocene transition, relate very well, whereas smaller changes do not relate as well (Fig. 1). This is not surprising, as the more detailed accumulation record is an annual signal, whereas the sampling for isotopes cannot be done on such a fine scale and one measurement represents several years. Moreover, both accumulation and isotopes may be affected by external factors. Because of the relation that exists, accumulation can be used in conjunction with isotopes and also as an excellent first indicator of climate change during core processing. The relation between accumulation and oxygen isotopes at GISP2 can be defined by

$$a = 0.234 \exp [0.077 (\delta^{18}O + 35.01)] \quad (1)$$

where a is accumulation. The 7.7% change in accumulation for a 1 per mil change in $\delta^{18}O$ from Eq. 1 corresponds very well to the 7 to 9% change predicted from work done on other cores in Greenland (*10–12*). Johnson *et al.* (*11*) also predicted a 7.9% per mil change in accumulation in Greenland. In addition to these relations over extended periods, comparisons of the $\delta^{18}O$, accumulation, and ECM records (*14*, *15*) show these same relations during much more dramatic but shorter periods of change in climate, such as the Younger Dryas.

The Holocene is considered a relatively stable period. Although there have been climate fluctuations [for example, the Altithermal, Medieval Warm Period (MWP), and the Little Ice Age (LIA)], these have not been of the same magnitude as, for example, the Younger Dryas. It is well recognized that the timing and duration of Holocene climate events can be quite variable. This variability can be attributed to often spotty records and to the limited accuracy of different dating techniques or the nonsynchroneity of the events. Because the GISP2 record combines local influenees on Greenland with the effects of global climate fluctuations, caution is required in correlating records from elsewhere on the globe with the GISP2 data set (this, of course, is true of all records; local influences have an effect on the timing and duration of specific events). Generally, specific events that have been identified in the GISP2 core correlate well with other records. As the GISP2 depth-age scale for the Holocene is continuous and extremely accurate (>95%), the timing of events from this core (central Greenland) can be dated and constrained to an accuracy comparable to the sampling frequency or interval.

The GISP2 Holocene record shows that accumulation increased rapidly in a series of steps from the Younger Dryas to Preboreal times, indicative of a rapid warming (Fig. 1). After this period a gradual increase continued to about 9000 cal B.P. For the remainder of the Holocene the long-term average accumulation fluctuates around a mean of 0.24 ± 0.05 m of ice per year (which also corresponds to the mean for the last 100 years for the summit).

Steps in early Holocene accumulation at the summit indicate periods of at least a stable, if not indeed a cooling, climate. These plateaus are centered at 11,195, 10,650, 9950, and 9250 cal B.P. In this sequence of early Holocene plateaus there is a significant intervening decrease in accumulation, attaining a minimum at 10,150 cal B.P., followed by a high at 9100 cal B.P. After 9300 cal B.P., there is a significant increase in accumulation rate, which is punctuated by larger magnitude but shorter term fluctuations. The overall trend is one of elevated accumulation between 9200 and 7300 cal B.P. with a cooling at approximately 8200 cal B.P. Starkel (*16*) described the period between 10,300 and 8000 years B.P. as a phase of continuous warming with rising summer radiation and divided the early Holocene into three phases (10,300 to 9500 years B.P., rapid warming; 10,000 to 8500 years B.P., Preboreal-Boreal continuous transformation; and 8700 to 7700 years B.P., change to oceanic climate). These results correspond more closely with the accumulation record at the summit than other previously published reports of 9000 to 5000 years B.P. (*17–19*) for the Altithermal.

From 8200 years B.P. to the present, accumulation has fluctuated (Fig. 1). A major warming was inferred after A.D. 575, where the summit accumulation rates increased significantly (Fig. 2), and the average accumulation from A.D. 620 to 1150 was 0.26 m of ice per year, 8% higher than the average Holocene accumulation rate and the highest rate recorded in the last 10,000 years, with the exception of the Altithermal. The warm conditions implied by the accumulation-temperature relation are corroborated by the presence of several thin melt layers in the core (Fig. 2), indicating that summer temperatures

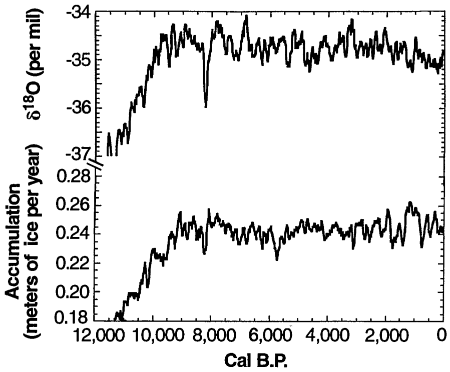

Fig. 1. Record of 100-year smoothed accumulation and oxygen isotope profiles from the GISP2 core from 12,000 years B.P. to the present.

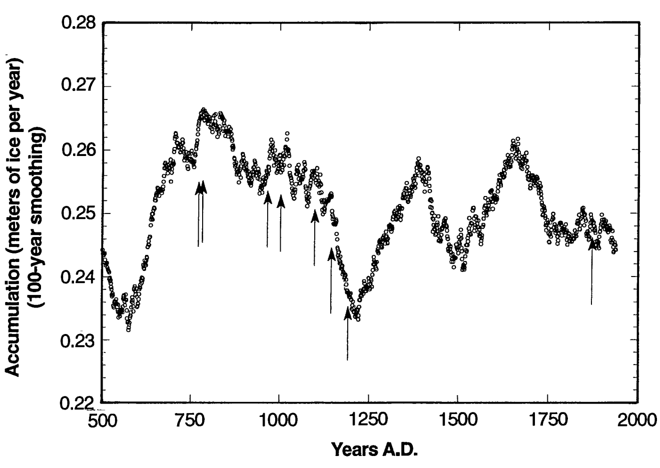

Fig. 2. The 100-year smoothed accumulation record from the GISP2 core for the period A.D. 500 to the present. The arrows show locations of visually identified melt layers in the ice core.

at the summit exceeded the freezing point. These melt layers are extremely thin and affect the signal of only one summer.

The historical records, mainly from northwestern Europe, describe an MWP occurring anywhere between A.D. 800 and A.D. 1300 (*17*, *20*, *21*) with dates varying by as much as 200 years. These dates for the MWP are approximately 200 years later than indicated by the GISP2 record. As geographical lags or leads are typically seen in these shorter climatic events, this is not surprising. For instance, the MWP in coastal Greenland began as early as A.D. 800 (*20*), which is approximately 100 years earlier than in Europe. Therefore, indications of warming taking place earlier in northern Greenland would follow.

The LIA is not as well defined as the MWP, both in the literature and in the GISP2 record. In the past, the LIA was viewed as being one long, sustained cold period with dates ranging from A.D. 1200 to 1800 to A.D. 1350 to 1900 (*16–20*, *22*). However, more recently this period has been characterized by major and very sudden fluctuations in climate often lasting only decades (*18*, *23*). Also, recent publications (*22*) have questioned the actual existence of the LIA. In the GISP2 record, the mean accumulation over the last 800 years was slightly higher than normal (approximately 3%), but there was significant variability on a decadal to century time scale (Fig. 3). Periods with average lower accumulation (or lower temperatures) center around A.D. 1200, 1500, and 1800, whereas accumulation was slightly above average (higher temperatures) around A.D. 1400 and 1700. At approximately A.D. 1750 the temperature decreased at the summit and has remained relatively constant to the present with only short periods of mildly fluctuating climate (Fig. 3). This period (from A.D. 1400 to the present) corresponds to what is typically referred to as the LIA, where there were glacial advances and cold phases in Greenland and elsewhere (*19*). The perception of the LIA as a period of sustained cold is not supported by the GISP2 record. The various time periods reported for the LIA (*17–20*, *22*, *23*) may be attributable to real geographical variations or to punctuated events that were interpreted as the beginning or the end of the LIA. This finding underscores the importance of independent, accurate time control when making climate correlations.

During the last 75 years, average accumulation rates have decreased from 0.24 to 0.21 m of ice per year. Although fluctuations exist, this result indicates a cooling trend at the summit, whereas slight warming has been identified elsewhere. Perhaps the warming has not yet reached central Greenland or is more geographically localized and not yet a global event. Chapman and Walsh (*24*) identified a cooling of 1°C in central Greenland during 1961 through 1990, substantiating the GISP2 accumulation record.

Variations in accumulation rate, which occur rapidly within a short period between A.D. 1500 and the present, also occurred earlier in the Holocene, in some cases being more severe. Data for successive 500-year periods, based on a 10-year running average (*2*), show that significant changes took place during the periods 8800 to 8000 cal B.P. (very dramatic isotope low), 7750 to 6450 cal B.P. (this section includes some breaks in the pattern), and 4350 to 3950, 3750 to 3550, and 2450 to 1950 cal B.P. These periods may be considered additional LIA type events and may indicate that such events were common throughout the Holocene. In detail, the GISP2 accumulation record shows that short-term fluctuations in temperature characterize the Holocene and that this period is not as stable as commonly thought. The GISP2 record thus has provided much detail on the extent and duration of Holocene climate change and may fill in some of the many gaps that exist in other, less highly resolved Holocene records.

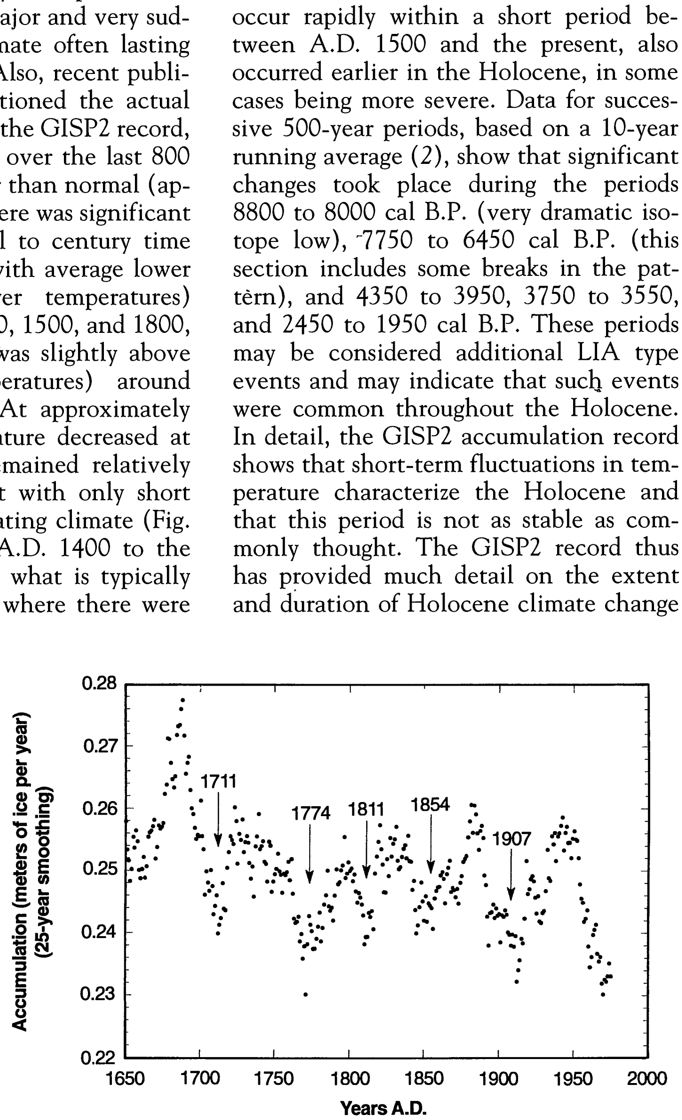

Fig. 3. The 25-year smoothed accumulation record from the GISP2 core from A.D. 1650 to the present. The dates above the arrows correspond to years of decreased accumulation that correlate with dated glacial advances or cold periods in Greenland and elsewhere (*18*).

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25. This research was funded by the National Science Foundation. We thank the Science Management Office, the 109th Air National Guard, and the Polar Ice Coring Office for logistical and field support and also all the graduate students and technicians who assisted in data procurement. Special thanks go to M. Morrison for assistance in gathering data and to D. Lawson and J. Cragin for insightful discussions.

24 May 1994; accepted 17 October 1994