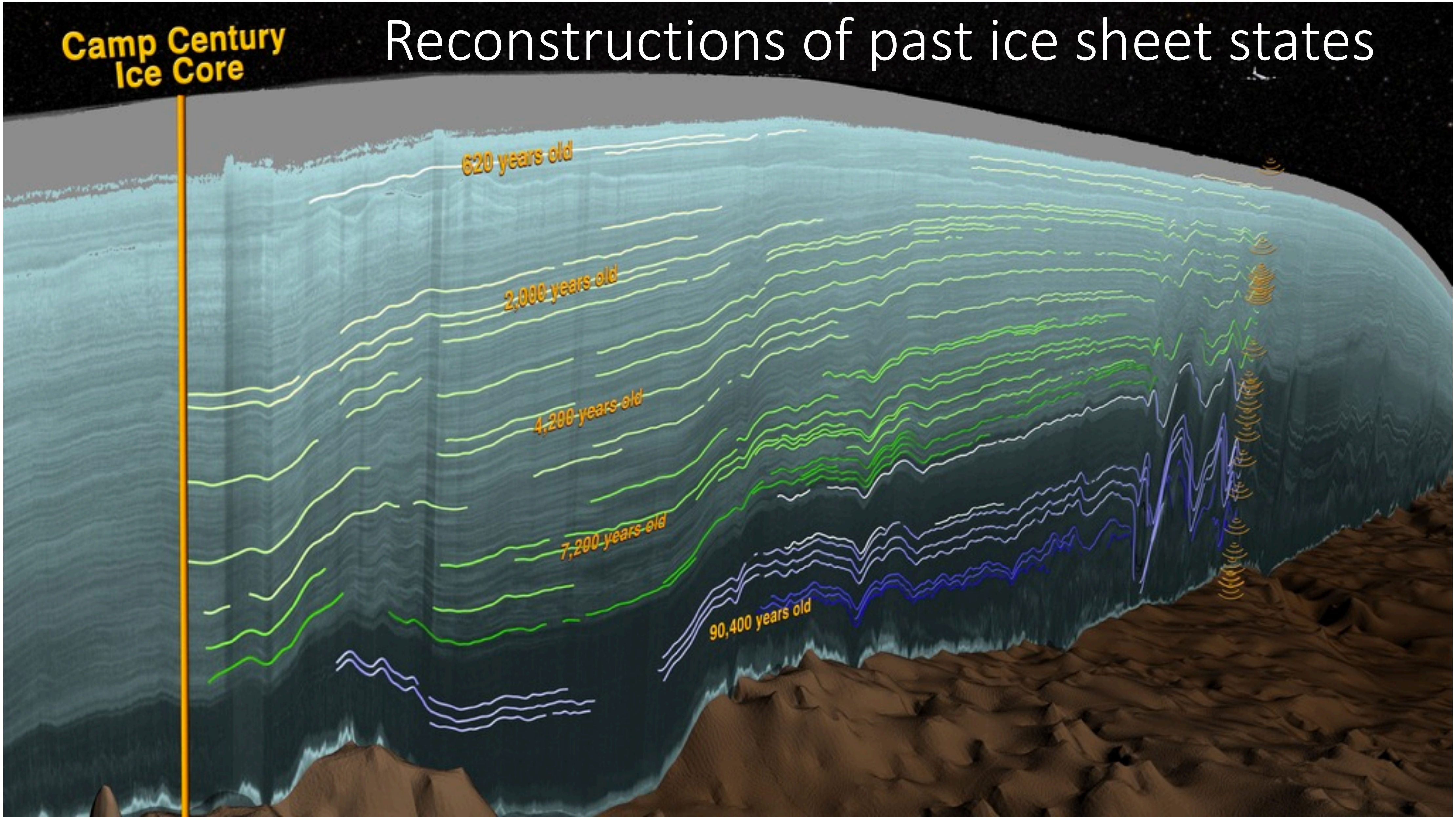
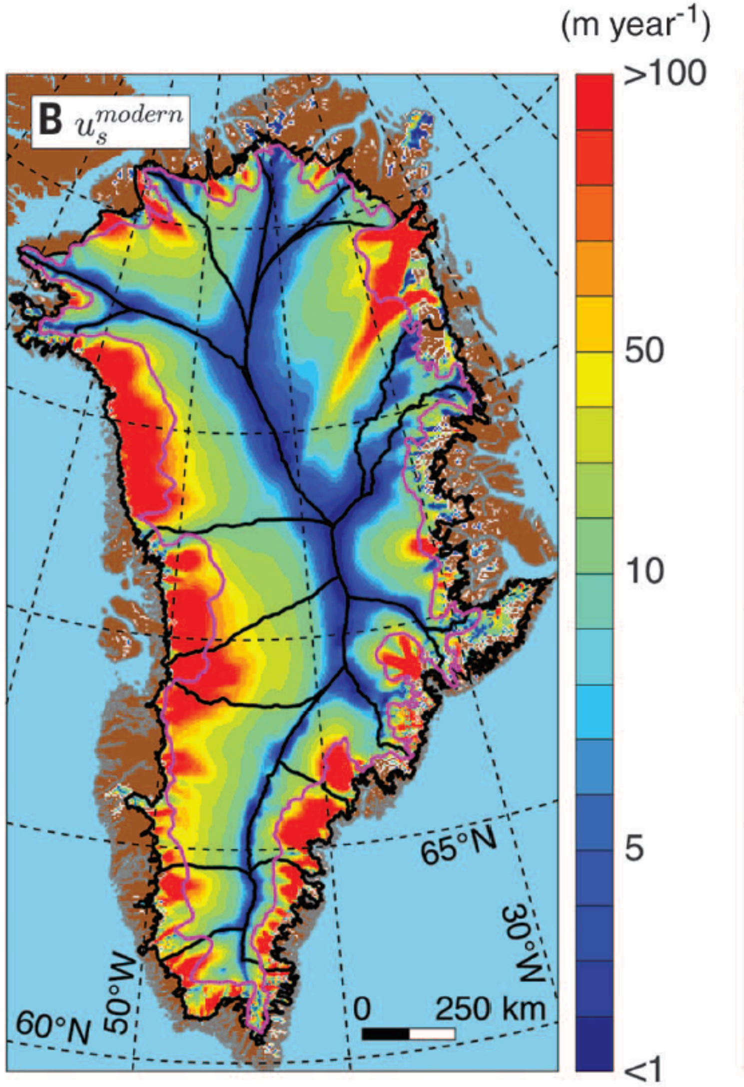
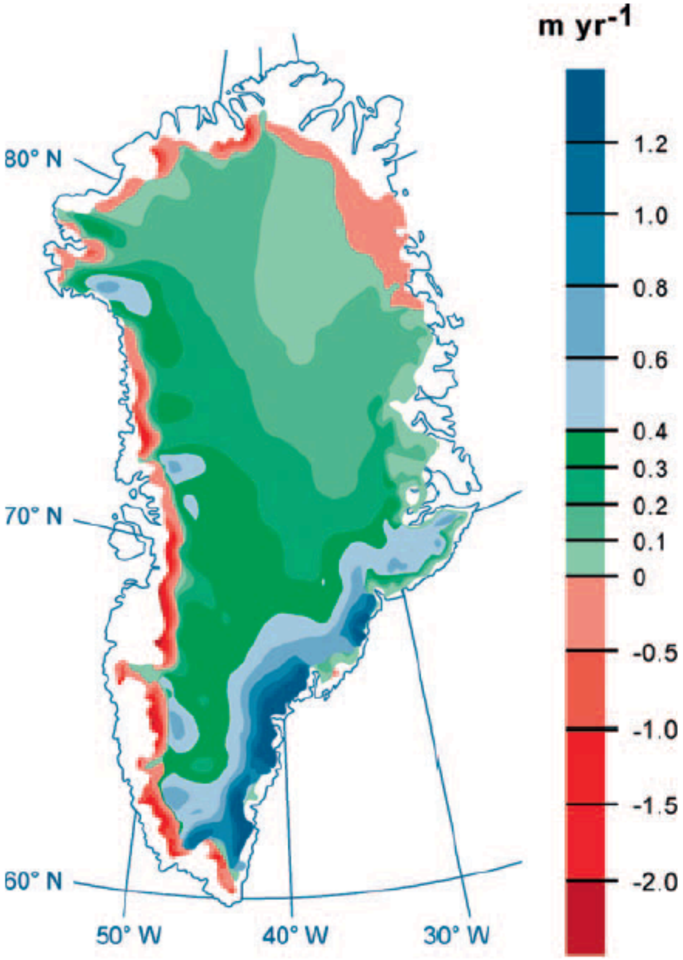
Reconstructions of past ice sheet states



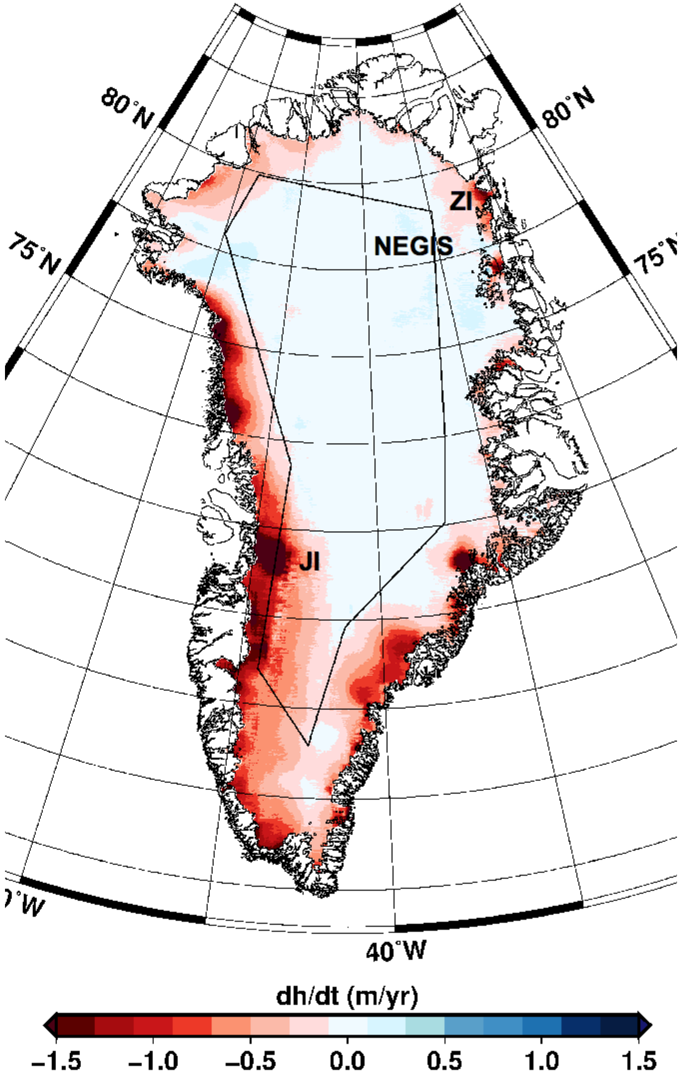
Ice Velocities



Surface Mass Balance



Surface Height Changes



Age-depth relationship

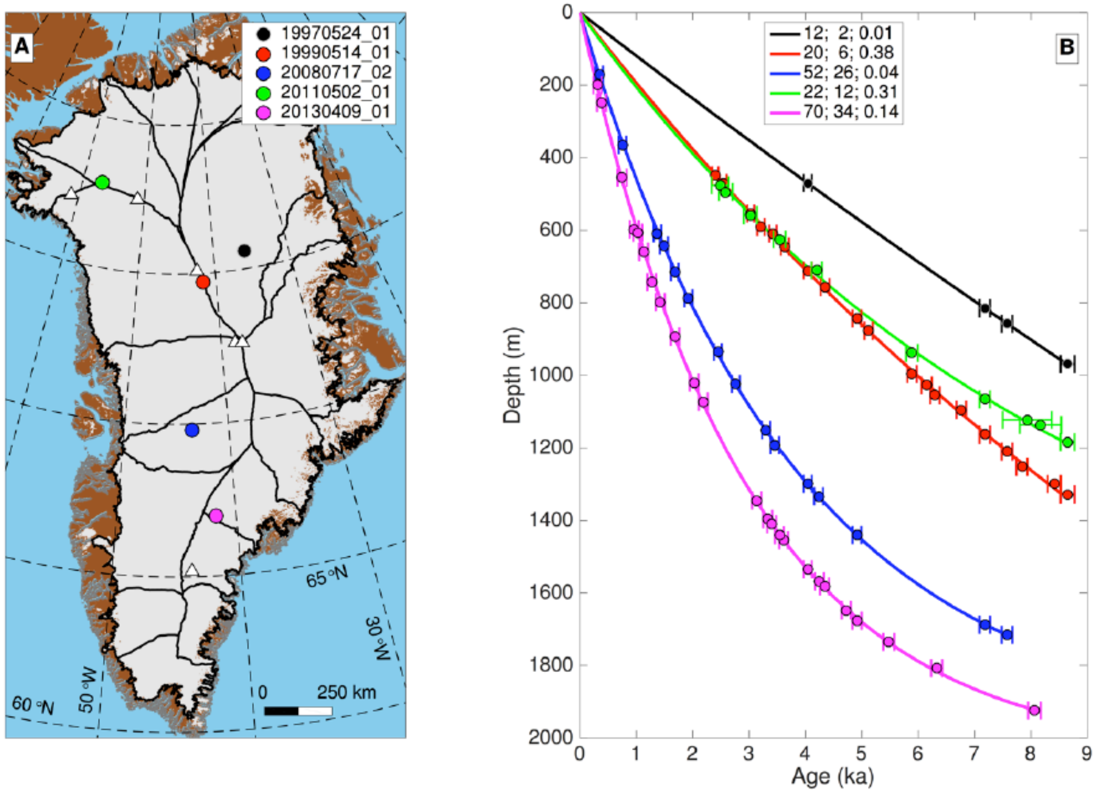


Fig. S2. Example fits of 1-D shallow ice-flow model to observed depth–age relationships. (**A**) Map locating sites shown in (**B**). Colors are the same. Airborne radar transect identifier given in legend. Existing deep ice cores shown as white triangles. (**B**) Observed (symbols and error bars) and modeled (lines) depth–age relationships at five locations across the GrIS interior. $\dot{b}_{9ka}$ (units: cm a^{-1}), $\dot{\varepsilon}_{9ka}$ (10^{-5} a^{-1}) and χ^2 / N values given in legend.

Balance velocities

full-thickness balance flux

$$Q^H_{out} = Q^H_{in} + \dot{b}_{modern} l^2$$

$$u^H_b = Q^H_{out} / Hl$$

age-constrained balance flux

$$Q^\alpha_{out} = Q^\alpha_{in} + (\dot{b}_\alpha - w_\alpha) l^2$$

$$u^\alpha_b = Q^\alpha_{out} / z_\alpha l$$

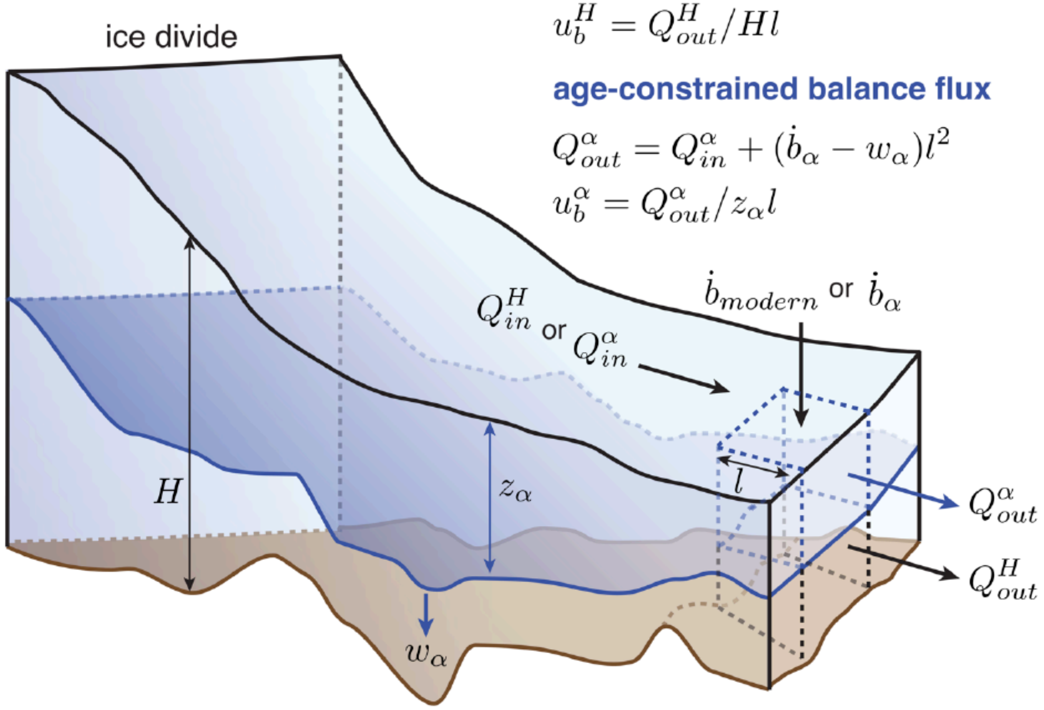
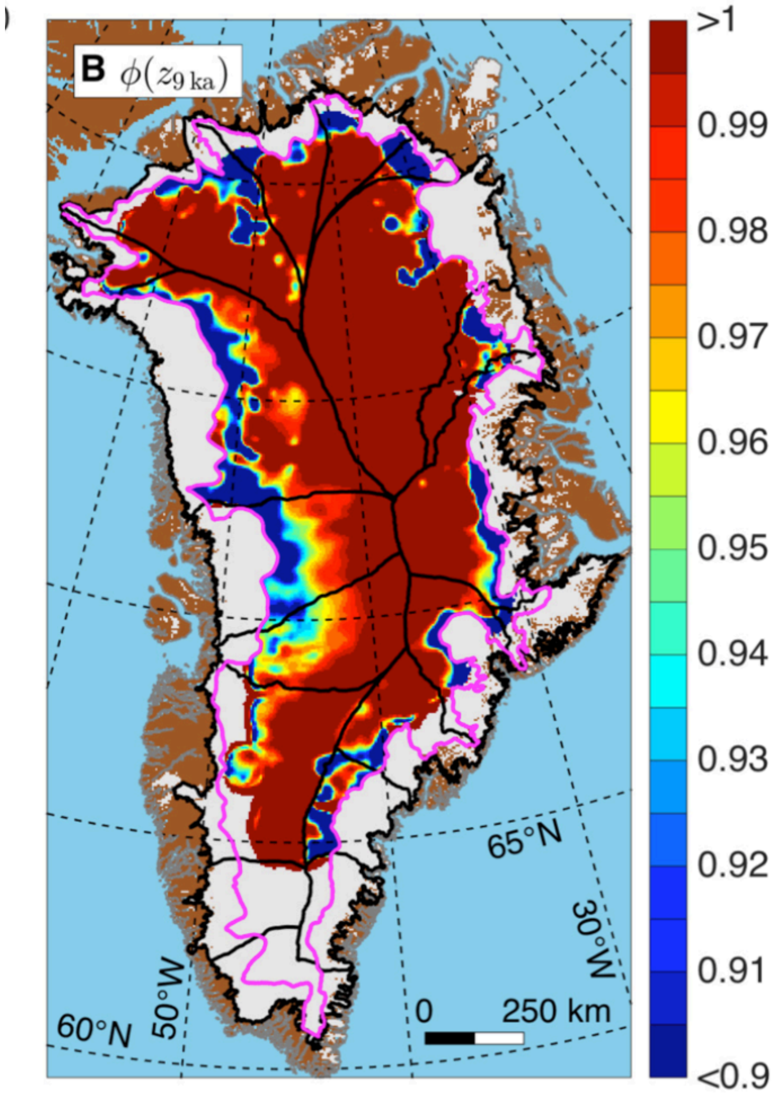


Fig. S1. Schematic illustrating conventional (full-thickness) and Holocene-averaged balance-flux methods. The Holocene-averaged balance velocity is calculated by balancing the input and output ice fluxes, averaged over the period between age α and the present, through a horizontally square column of ice bounded vertically by the subaerial ice surface and the depth of the isochrone of age α. Both balance methods assume implicitly that the ice sheet is in steady state during the period represented by the portion of the ice column considered. Schematic is not to scale.

Relationship between surface and balance velocities



Results from analysis of radar data

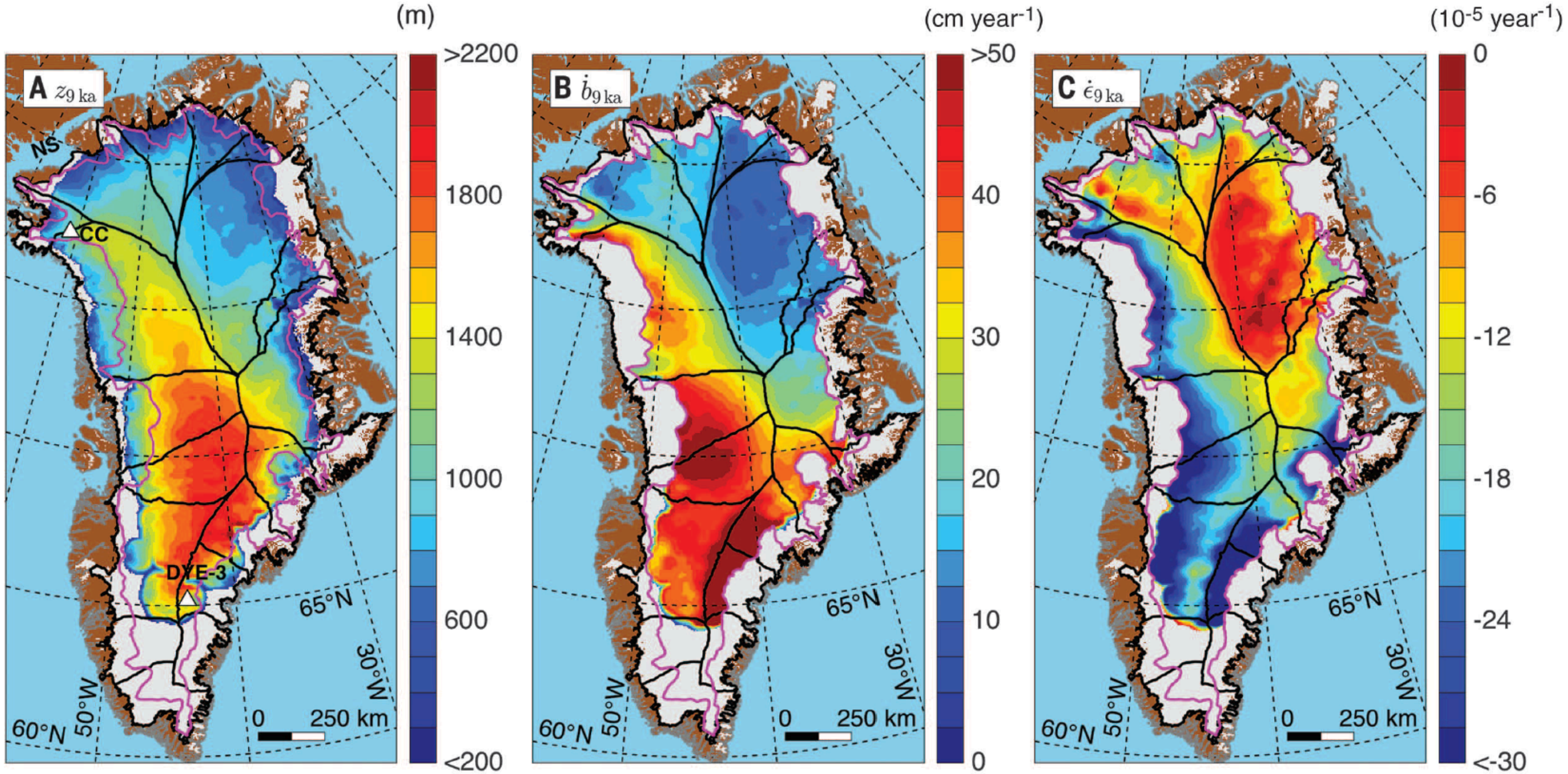


Fig. 1. Constraints on the Holocene-averaged balance ice flux across the GrIS from dated radiostratigraphy. (**A**) Ice-equivalent depth of the 9-ka isochrone (z_{9ka}) [determined as in (*21*)]. Black lines denote major ice-drainage basins (*36*). NS, Nares Strait. White triangles denote Camp Century (CC) and DYE-3 ice core sites. The magenta line represents the outer limit of reliable 1D modeling of depth-age relations to 9 ka (fig. S4). (**B**) Mean ice-equivalent accumulation rate over the past 9000 years ($\dot{b}_{9ka}$). (**C**) Mean vertical strain rate within the 9- to 0-ka portion of the ice column ($\dot{\epsilon}_{9ka}$).

Conclusion: Greenland has decelerated since 9ka

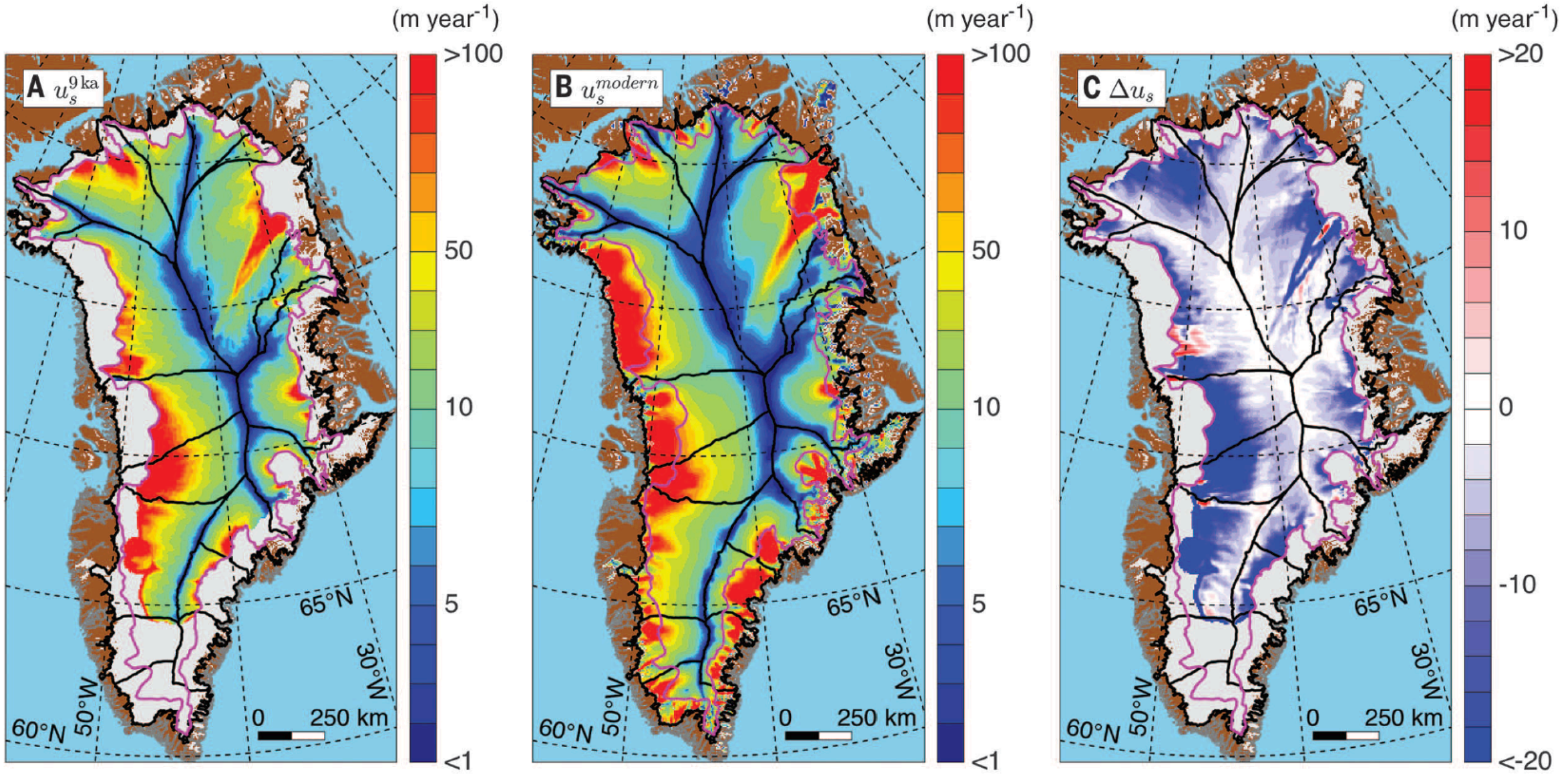


Fig. 2. Holocene-averaged and modern surface speed across the GrIS. (**A**) Holocene-averaged surface speed u_s^{9ka} (i.e., Holocene balance speed divided by shape factor) (fig. S5B). (**B**) Composite surface speed, u_s^{modern}, from 1995–2013 (*37*). (**C**) Change in surface speed between the present and the Holocene average ($\Delta u_s = u_s^{modern} - u_s^{9ka}$).

Deceleration is not due to less accumulation

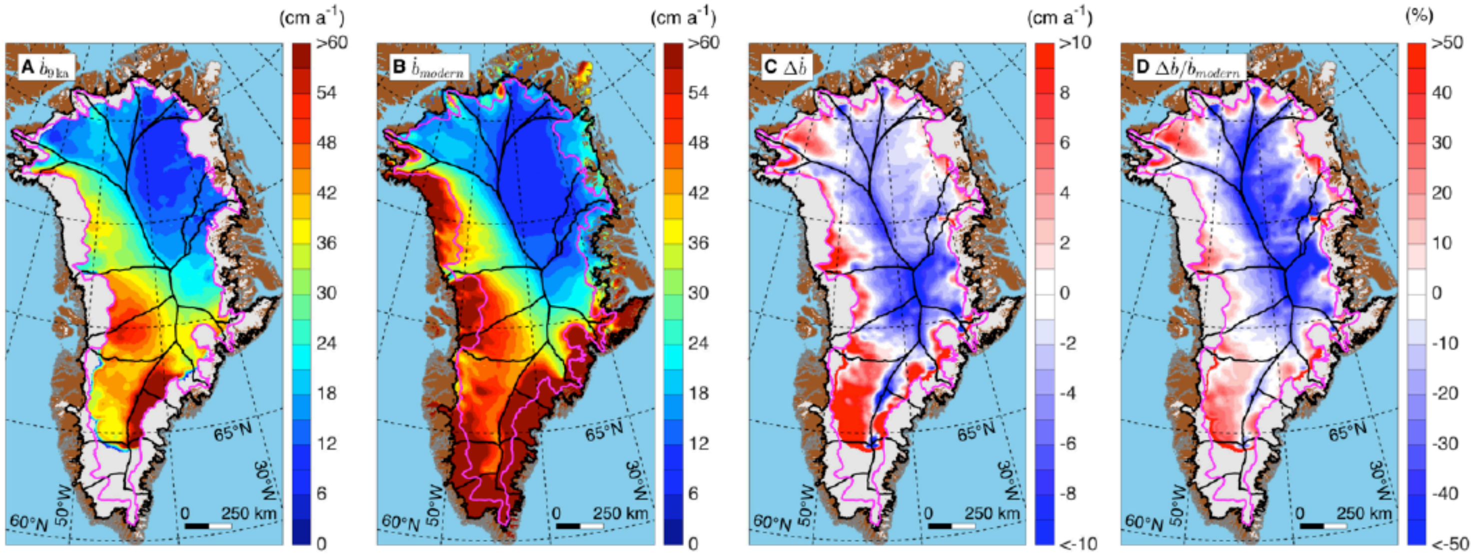
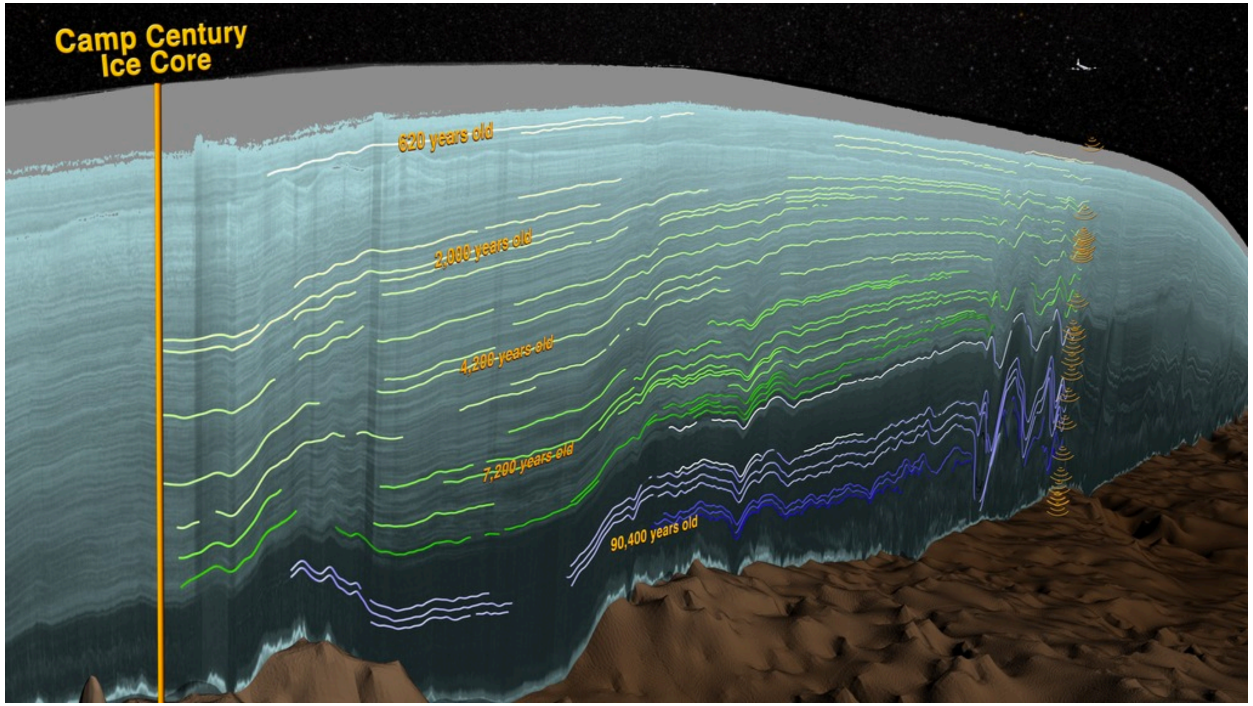


Fig. S8. Comparison of modeled Holocene-averaged (9–0 ka) and modern accumulation rates across the Greenland Ice Sheet. (**A**) Mean Holocene (9–0 ka) accumulation rate of ice $\dot{b}_{9ka}$ inferred from Holocene-dated reflections (same as Fig. 1B but different color scale). (**B**) Modeled modern accumulation rate $\dot{b}_{modern}$ (same as used to calculate $L_{\dot{b}}$ in Fig. S4B; *31*). (**C**) Difference between Holocene-averaged and modern accumulation rate $\Delta\dot{b} = \dot{b}_{modern} - \dot{b}_{9ka}$. (**D**) Relative change in accumulation rate ($\Delta\dot{b} / \dot{b}_{modern}$).

Context



nature
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Letter | Published: 31 October 1985

Was the Greenland ice sheet thinner in the late Wisconsinan than now?

Niels Reeh

Nature **317**, 797–799 (31 October 1985) | Download Citation

Abstract

Ice of Wisconsinan origin which constitutes the basal layers of the ice caps in arctic Canada and Greenland flows three to four times more readily than the Holocene ice above. A model based on simple ice sheet profile theory is set up for the thickness response of the interior ice sheet regions to the progressive thinning of this soft layer. The model is applied to calculate the thickness response of the Greenland ice sheet at the locations Dye 3 and Crête, and of the Devon Island ice cap in arctic Canada. It is concluded that the mechanism contributes significantly to the thickness change of the Greenland ice sheet, presently at a rate of about 1 cm yr^{-1} and that this rate of change will persist potentially over thousands of years to come. As regards the Devon Island ice cap, most of the estimated 15% thickness increase has already been accomplished. A further consequence is that in the late Wisconsinan, ice thicknesses of the interior regions of the Greenland ice sheet were likely to have been no greater and possibly even less than at present, in spite of the larger geographical extent of the ice sheet. It is argued that the glacial-interglacial cycles of accumulation rate and ice temperature are likely to enhance this ice thickness variation.

Context

Why ice-age ice is sometimes "soft"

W.S.B. Paterson
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(Received August 20, 1990; accepted after revision February 21, 1991)

ABSTRACT

Paterson, W.S.B., 1991. Why ice-age ice is sometimes "soft". *Cold Reg. Sci. Technol.*, 20: 75–98.

Data on the mechanical properties, texture, fabric, and impurity content of ice deposited during the last glaciation are reviewed. The conclusions are: (1) Chloride and possibly sulphate ions, in concentrations high relative to those in Holocene ice, impede grain-boundary migration and grain growth so that the crystals remain small. (2) Such ice, in shear parallel to the ice-sheet bed, develops a strong, near-vertical, single-maximum fabric. (3) This fabric favours further deformation and this, in turn, further strengthens the fabric and keeps the crystals small. (4) This is why the strain rate in ice-age ice, in simple shear, is some 2.5 times that in Holocene ice at the same stress and temperature. (5) Ice-age ice under other stress systems, such as ice in roughly the upper 60% of the ice thickness, in bedrock hollows, at a stationary ice divide, in ice streams and in ice shelves, will not have enhanced flow. (6) An anisotropic flow relation must be used for detailed modelling of polar ice sheets.

"Impurities—like patriotism—are sometimes the last refuge of scoundrels." Craig F. Bohren (1983).

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Part 2. Inference of past surface temperatures

Past Temperatures Directly from the Greenland Ice Sheet

D. Dahl-Jensen,* K. Mosegaard, N. Gundestrup, G. D. Clow, S. J. Johnsen, A. W. Hansen, N. Balling

A Monte Carlo inverse method has been used on the temperature profiles measured down through the Greenland Ice Core Project (GRIP) borehole, at the summit of the Greenland Ice Sheet, and the Dye 3 borehole 865 kilometers farther south. The result is a 50,000-year-long temperature history at GRIP and a 7000-year history at Dye 3. The Last Glacial Maximum, the Climatic Optimum, the Medieval Warmth, the Little Ice Age, and a warm period at 1930 A.D. are resolved from the GRIP reconstruction with the amplitudes –23 kelvin, +2.5 kelvin, +1 kelvin, –1 kelvin, and +0.5 kelvin, respectively. The Dye 3 temperature is similar to the GRIP history but has an amplitude 1.5 times larger, indicating higher climatic variability there. The calculated terrestrial heat flow density from the GRIP inversion is 51.3 milliwatts per square meter.

Inference of past surface temperatures

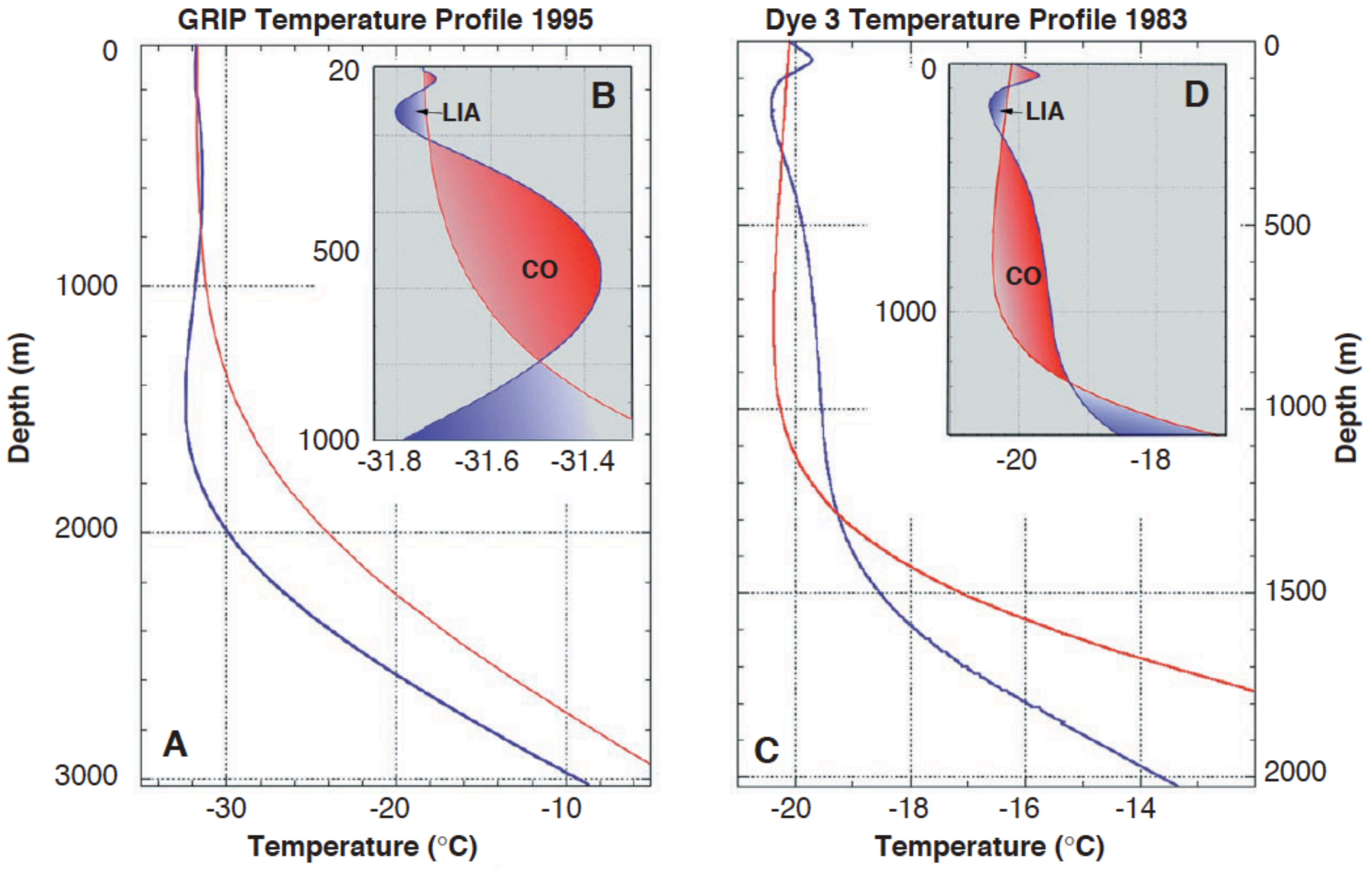

Fig. 1. The GRIP and Dye 3 temperature profiles [blue trace in (A) and (C)] are compared to temperature profiles [red trace in (A) and (C)] calculated under the condition that the present surface temperatures and accumulation rates have been unchanged back in time. (**A**) The GRIP temperature profile measured in 1995. The cold temperatures from the Glacial Period (115 to 11 ka) are seen as cold temperatures between 1200- to 2000-m depth. (**B**) The top 1000 m of the GRIP temperature profiles are enlarged so the Climatic Optimum (CO, 8 to 5 ka), the Little Ice Age (LIA, 1550 to 1850 A.D.), and the warmth around 1930 A.D. are indicated at the depths around 600, 140, and 60 m, respectively. (**C**) The Dye 3 temperature profile measured in 1983. Note the different shape of the temperature profiles when compared to GRIP and the different depth locations of the climate events. (**D**) The top 1500 m of the Dye 3 temperature profiles are enlarged so the CO, the LIA, and the warmth around 1930 A.D. are indicated at the depths around 800, 200, and 70 m, respectively.

Inference of past surface temperatures

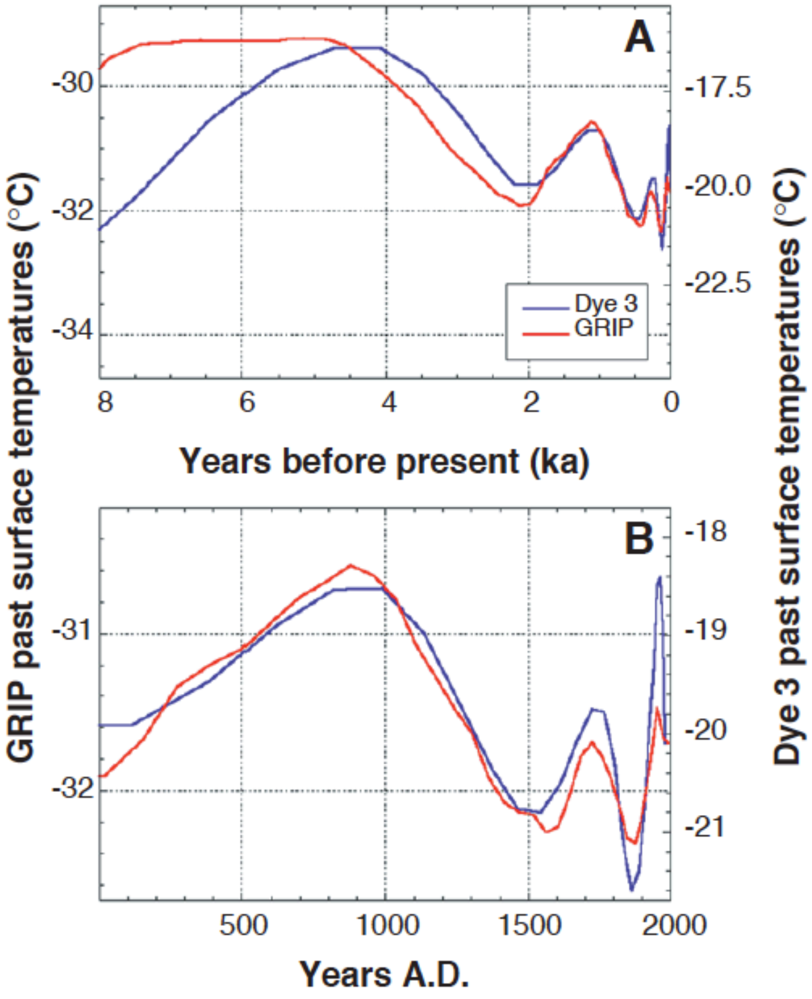

Fig. 4. The reconstructed temperature histories for GRIP (red curves) and Dye 3 (blue curves) are shown for the last 8 ky BP (**A**) and the last 2 ky BP (**B**). The two histories are nearly identical, with 50% larger amplitudes at Dye 3 than found at GRIP. The reconstructed climate must represent events that occur over Greenland, probably the high-latitude North Atlantic region.