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A one-dimensional temperature and age modeling study for selecting the drill site of the oldest ice core around Dome Fuji, Antarctica

Takashi Obase[1], Ayako Abe-Ouchi[12], Fuyuki Saito[3], Shun Tsutaki[24], Shuji Fujita[24], Kenji Kawamura[234] and Hideaki Motoyama[24]

[1] Atmosphere and Ocean Research Institute, The University of Tokyo, Kashiwa, Japan
[2] National Institute of Polar Research, Research Organization of Information and Systems, Tachikawa, Japan
[3] Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokosuka, Japan
[4] The Graduate University for Advanced Studies, SOKENDAI, Tachikawa, Japan

Correspondence to: Takashi Obase (obase@aori.u-tokyo.ac.jp)

Abstract. The recovery of a new Antarctic ice core spanning the last ~1.5 million years will advance our understanding of climate system dynamics during the Quaternary. Recent glaciological field surveys have been conducted to select the most suitable core location near Dome Fuji (DF), Antarctica. Specifically, ground-based radar-echo soundings have been used to acquire highly detailed images of bedrock topography and internal ice layers. In this study, we use a one-dimensional (1-D) ice flow model to compute the temporal evolutions of age and temperature, in which the ice flow is linked with not only transient climate forcing associated with past glacial–interglacial cycles, but also transient basal melting diagnosed along the evolving temperature profile. We investigated the influence of ice thickness, accumulation rate, and geothermal heat flux on the age and temperature profiles. The model was constrained by the observed temperature and age profiles reconstructed from DF ice-core analysis. The results of sensitivity experiments indicate that ice thickness is the most crucial parameter influencing the computed age of the ice because it is critical to the history of basal temperature and basal melting, which can eliminate old ice. The 1-D model was applied to a 54 km long transect in the vicinity of DF and compared with radargram data. We found that the basal age of the ice is mostly controlled by the local ice thickness, demonstrating the importance of high spatial resolution surveys of bedrock topography for selecting ice-core drilling sites.

1. Introduction

Earth's climate system experienced glacial–interglacial cycles during the Quaternary, associated with the waxing and waning of continental ice sheets and climate system feedbacks. Ice cores from the Antarctic ice sheet have provided fruitful information on climate system changes in the past because they can provide continuous reconstructions of past atmospheric compositions and temperature up to ~800 thousand years before the present (ka BP) (Jouzel et al., 2007; Kawamura et al., 2017). Such reconstructions have contributed to our understanding of the climate system dynamics of glacial–interglacial cycles (e.g., Abe-Ouchi et al. 2013; Obase et al. 2021). Meanwhile, a stacked sequence of marine sediments (Lisiecki and Raymo 2005) indicates that the periodicity of glacial–interglacial cycles changed from 40 to 100 ka at the middle Pleistocene transition (MPT, approximately 800–1250 ka BP, Paillard, 2001; Clark et al., 2006). However, continuous ice core records that cover the MPT are still lacking, leading to a limited understanding of the mechanisms of this climate event. To help remedy this issue, the International Partnership for Ice Core Sciences (IPICS) has identified the quest for an "oldest ice core" as a critically scientific challenges. In this article, we define the term "old ice" as a continuous ice core with a basal age reaching 1.5 million years (Ma) BP, as defined in a IPICS community paper (Fischer et al., 2013).

In recent years, international efforts have been made to find plausible sites to obtain old ice in several locations in the interior of the Antarctic continent. In particular, in EPICA (European Project for Ice Coring in Antarctica) Dome C (EDC), glaciological surveys and ice-flow modeling studies have been used to select the location of the suitable sites (Parrenin et al., 2017; Young et al., 2017;

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Passalacqua et al., 2018; Lilien et al., 2021). The present article focuses on Dome Fuji (DF), Antarctica, which is located at 77.31° S, 39.70° E, with a surface elevation of 3810 m above sea level, and ice thickness of 3028 m. The most recent ice core at DF was obtained between 2003 and 2006 (Motoyama et al., 2021). The ice age at the bottom of this core was approximately 720 ka BP based on Antarctic ice core chronology 2012 (AICC2012) (Kawamura et al., 2017; Uemura et al., 2018). The temperature of the ice was at the pressure-melting point near the bedrock (Motoyama et al., 2021). Recently, field surveys have been conducted to collect bedrock elevation data near DF using ground and airborne radar surveys. On the basis of surveys performed by Japanese Antarctic Research Expeditions (JARE) since the late 1980s until 2008, the results of which are included in BEDMAP2 datasets (Fretwell et al., 2013), the typical ice thickness around DF is approximately 2000–3200 m (Fig. 1). Later, the 54th JARE (2012–2013 Antarctic summer) conducted ground-based radar surveys in areas where subglacial mountains were detected in the south of DF (data compiled in Tsutaki et al., 2022). More recently, Alfred Wegener Institute (AWI) in Germany conducted airborne radar surveys covering the DF area (Karlsson et al., 2018). Based on these data, the 59th and 60th JARE (2017–2018 and 2018–2019 Antarctic summers) conducted ground radar surveys to investigate the internal layers of ice sheets over an areal extent of ~ 50 km, covering DF and NDF sites (77.8° S, 39.05° E) (Rodrigez-Morales et al., 2020).

To select suitable ice-core drilling sites, it is essential to investigate the conditions required to preserve old ice using constraints from glaciological and climatological data. Previous ice-flow modeling studies have examined the requirements to preserve old ice using both three-dimensional (3-D) and one-dimensional (1-D) models. Pattyn (2010) used a 3-D ice sheet model under present-day constant climate forcing, and suggested the importance of minimal horizontal flow and low geothermal heat flux (GHF) to preserve old ice near the base of ice sheets. Other studies have used 3-D models to represent 3-D ice-flow fields and ice age for the relatively small area near Antarctic Domes (Huybrechts et al., 2007; Seddik et al., 2011; Sun et al., 2014; Passalacqua et al., 2018; Zhao et al., 2018). These studies estimated the age distribution of the ice expected from 3-D ice flow fields under a constant present-day climate. More recent studies used glacial–interglacial cycle forcing (Sutter et al., 2019, 2021) and discussed how the past variation of the Antarctic ice sheet affects ice age distributions.

One-dimensional vertical ice-flow models have been used as the vertical profiles of age and temperature near Antarctic Domes, where horizontal flow is relatively minor. Horizontal velocity in the vicinity of DF and NDF is < 2 m a^{-1}, evidenced by satellite-based measurements (Rignot et al., 2011, 2017; Mouginot et al., 2012). Such 1-D models perform well in long-term forward simulations over glacial cycles and are able to conduct many experiments with different parameters. In particular, Fischer et al. (2013) investigated the influence of a wide range of parameters, including ice thickness, accumulation, and GHF on the basal age of ice. The key finding was that melting at the base reduces the likelihood of old ice; hence, a lower accumulation rate and ice thickness compared with previous ice core sites are required conditions to avoid basal melting and preserve old ice. Other studies used an equivalent 1-D ice-flow model, investigated the necessary conditions to keep the ice base frozen (Van Liefferinge and Pattyn, 2013; Van Liefferinge et al., 2018), and examined the observed basal conditions of the ice (Passalacqua et al., 2017). Parrenin et al. (2017) estimated ice-flow parameters and basal melting rate using internal layers of the ice near EDC and proposed candidate sites for old ice. Saito et al. (2020) presented a numerical scheme of ice advection calculation and conducted numerical simulations using idealized glacial cycle forcings. This contributed to a good representation of annual layer thickness, which is critical to the occurrence of old ice near the base of the ice column.

Simplified factors in previous modeling studies were the time-dependent climate forcing and temperature profile, which are critical to basal ice melting. In particular, the basal temperature of the ice sheet shows a minimum during interglacials because it takes a long time to convey the information of surface temperature changes to the base of the ice sheet (Saito and Abe-Ouchi 2004; Van Liefferinge et al., 2018). In this context, the model used in Parrenin et al. (2007, 2017) assumed that basal melting

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rates were constant over time, and Fischer et al. (2013) used a constant climate forcing. Some studies (Van Liefferinge and Pattyn 2013; Passalacqua 2017; Van Liefferinge et al., 2018) have investigated ice temperature using realistic climate forcing, but did not investigate the resultant impact on the age of the ice. Similarly, Hondoh et al. (2002) and Talalay et al. (2021) estimated GHF at DF and other Antarctic domes based on observed vertical temperature profiles, but the observed age–depth profiles were not used as constraints.

Despite the close link between the temperature and age of ice owing to basal melting, the thermodynamics of ice and time-dependent basal melting were not represented in previous modeling studies of old ice. In this study, we use a 1-D ice-flow model, which simultaneously computes the evolution of ice temperature and age, and the model is forced by past climate history. The remainder of the article is organized as follows: Section 2 describes the 1-D model used in this study. In Sect. 3, we apply this model to DF and conduct systematic sensitivity experiments to calibrate GHF and a tuning parameter of the vertical profile of ice velocity by comparing simulated age and temperature profiles with observations. We also use parameters at EDC to examine whether the model can simulate temperature and age profiles under different glaciological conditions. In Sect. 4, using the results of the tuned vertical velocity parameters, we investigate the influences of ice thickness, surface mass balance (SMB), and GHF on the basal temperature and age. In Sect. 5, we apply the 1-D model to the DF–NDF transect and compare the results with the internal layers of the ice.

2. Method

2.1. Model description

We used a 1-D ice-flow model, IcIES-2 (Saito et al., 2020). This model computes the temporal evolutions of the age and temperature profiles of ice columns.

The evolution of the age of the ice is computed using the vertical advection equation,

$$\frac{\partial A}{\partial t} = -w\frac{\partial A}{\partial z} + 1\,. \quad (1)$$

where A is the age of the ice, defined as the duration since deposition, and w is the vertical velocity of the ice (a positive value indicates upward velocity). Here, ζ is a normalized coordinate defined as $\zeta = \frac{s}{H}$, where s is the surface elevation, z is the height above bedrock, and H is the ice thickness (thus $\zeta =$ 1 and 0 correspond to the ice surface and base, respectively). The first and second terms on the right-hand side of Equation (1) represent the vertical advection and aging owing to time-lapse, respectively.

The vertical velocity of the ice can be represented as:

$$w(\zeta) = -\left[\left(M_s + M_b - \frac{\partial H}{\partial t}\right)\omega(\zeta) - M_b\right]. \quad (2)$$

The terms M_s and M_b represent surface (positive indicates ice gain) and basal (positive indicates ice melt) mass balance caused by accumulation and ablation, respectively, and $\frac{\partial H}{\partial t}$ is the change in ice thickness over time. The normalized vertical velocity profile, ω, is given as a function of the normalized coordinate following previous studies (Van Liefferinge and Pattyn, 2013; Passalacqua et al., 2017; Van Liefferinge et al., 2018), and derived from Llibtoury (1979):

$$\omega(\zeta) = 1 - \frac{p+2}{p+1}(1-\zeta) + \frac{1}{p+1}(1-\zeta)^{p+2}. \quad (3)$$

where ω is 1 at the surface and 0 at the base. Hence, if we assume steady state, $\frac{\partial H}{\partial t} = 0$, the vertical velocity of the ice at the surface and base equates to $-M_s$ and M_b, respectively. The shape of ω with different p parameters is shown in Fig. 2, indicating that a larger p-value tends to induce a larger downward ice velocity. Compared with Fischer et al. (2013), in the case of $m = 0.5$ in their study (Fig. 2 dashed lines), $p = 3$ from Equation (3) gives a different vertical temperature profile, with a smaller vertical velocity, particularly near the base of the ice.

The temperature of the ice is computed using the following vertical advection and diffusion equation:

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$$\frac{\partial T}{\partial t} = -w\frac{\partial T}{\partial z} + \frac{1}{\rho_I c_P}\frac{\partial}{\partial z}\left(\kappa\frac{\partial T}{\partial z}\right). \quad (4)$$

where κ is the thermal conductivity, ρ_I is the ice density, and c_p is the heat capacity of the ice. The strain heating term is neglected in the present study. The thermal conductivity and specific heat capacity of the ice are functions of temperature (Greve and Blatter 2009, following Ritz, 1987). The density of ice is set as a constant (910 kg m^{-2}), i.e. we ignore effects of lower density in the firn column.

Boundary conditions at the surface and base of the ice are required to close the equations. At the ice surface, the age is set as 0, assuming no surface melt, and the temperature is set to the surface temperature at the given time. The basal boundary conditions for temperature depend on the basal condition:

$$\frac{\partial T}{\partial z}|_b = -\frac{G}{\kappa} \text{ if no melting}, \quad (5)$$

$$T_b = T_{pm} \text{ if melting}, \quad (6)$$

where G is the GHF at the ice–bedrock boundary, and T_{pm} is the pressure-melting point of the ice, which is given as a function of depth using a Clausius–Clapeyron gradient (8.7 x 10^{-4} K m^{-1}). The basal melting rate at the ice–bedrock interface is determined by the conservation of heat:

$$M_b \rho_I L = G - \kappa\frac{\partial T}{\partial z}, \quad (7)$$

where L is the latent heat of the ice (335,000 J kg^{-1}), and $\frac{\partial T}{\partial z}|_b$ is the temperature gradient at the ice–bedrock interface. This model assumes basal melting only occurs at ice–bedrock interfaces, and the temperature gradient at the ice–bedrock interface is calculated using a central difference discretization. The calculated basal melting rate M_b influences the velocity field according to Equation (2). Basal melting can occur in the interior of the ice as represented by polythermal ice sheet models, but we ignore such effects in this study for simplicity. For this reason, we set the vertical resolution of the model for thermodynamics as relatively coarse (~30 m) to prevent representing layers of basal melting, which can have significant errors in the diagnosis of basal melting rates.

We adopted different vertical resolution setups in computations of the temperature and age of the ice. The ice profile was discretized with 101 even vertical layers for thermodynamics; it was discretized with 2661 unevenly spaced vertical layers (finer near the base to resolve the thin layers of old ice) for age calculations, which was optimized following Saito et al. (2020). In the typical ice column thickness of 3000 m near DF, the vertical resolution was set to approximately 20 m near the surface and 20 cm near the bedrock, which is sufficient to resolve paleoclimate information (glacial–interglacial annual layer variations) of ~1 ka. We used the rational function-based constrained interpolation profile (RCIP) scheme in the advection equation for the numerical scheme, as in Saito et al. (2020). One significant advantage of this scheme is the avoidance of numerical diffusion and ability to reasonably preserve the time derivative of age, which is critical to the resolution of old ice. The time step was set to 5 years, and the basal melting rates were updated every 500 years to reduce the effect of temporal oscillations in basal melting and freezing.

3. Model calibration using DF age and temperature profiles

3.1. Experimental design

This section applies the 1-D model to DF under a realistic climate history for model calibration and parameter constraints. Parrenin et al. (2007) determined the *p*-value as ~3.7 for DF, but the chronology of ice older than 335 ka BP was not established at that time; therefore, we revisited DF to determine the *p*-value covering the entire DF ice core age–depth dataset. The glaciological boundary conditions at DF are summarized in Table 1: we used an ice thickness of 3028 m, a present-day SMB of 30 ice equivalent mm a^{-1} (equivalent to 27.3 freshwater mm a^{-1}, based on Kameda et al., 2008 and Fujita et al., 2011) and −55.5 °C for the mean ice surface temperature at present. We determined the boundary condition of ice surface temperature by calibrating the temperature profile to be consistent with measured temperature profiles of the top 500 m within uncertainty ranges of the observations.

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The observed present-day 10-m-depth annual mean snow temperature is −57.3 °C (Kameda et al., 1997), which was also used in Parrenin et al. (2007). We note that the annual mean surface air temperature based on meteorological observation was −54.4 °C (during the period 1995−1997, Yamanouchi et al., 2003).

The model was forced by a realistic history of SAT (surface air temperature) and SMB. We used local SAT anomalies at DF for the past 715 ka BP (Uemura et al., 2018) and the benthic record of marine oxygen isotope data (Lisiecki and Raymo, 2005) to construct a continuous time series of SAT anomalies during the last 2 Ma. We applied a simple translation of δ^{18}O to scale the temperature change at DF by the amplitude of glacial−interglacial cycles:

$$\Delta Ts = \alpha(\beta - \delta^{18}\mathrm{O}) \qquad (8)$$

where δ^{18}O is the benthic marine oxygen isotope value [‰]; we set $\alpha = 4.5$, and $\beta = 3.23$ to scale the amplitude of the glacial cycles, which generated a time series of temperature change over the last 2 Ma, as shown in Fig. 3a. We used past SMB as a function of temperature anomaly compared with the present day following Huybrechts and Oerlemans (1990), as used in paleoclimate 3-D Antarctic ice sheet modeling (Saito and Abe-Ouchi 2010). From this function, an increase in surface air temperature of 1 °C increases SMB by approximately 7%. At the Last Glacial Maximum (LGM, approximately 20 ka BP), when SAT was 8 °C cooler, the SMB was approximately 60% of the present day (Fig. 3b), which is consistent with reconstructions based on the isotopic content of the ice (Parrenin et al., 2016). This relationship between SAT and precipitation changes used in this study was within uncertainties estimated from observations and climate model simulations, following a summary by IPCC AR6 in Chapter 9.4.2.3 (Fox-Kemper et al. 2021), which used the studies of Bracegirdle et al. (2020) and Frieler et al. (2015). Although this relationship is not based on SMB, but rather on precipitation, herein we assume the precipitation change ratio is the same as that of the SMB. The other boundary conditions (ice thickness and GHF) were set as constants in the present study. Some modeling studies have considered ice thickness changes over glacial cycles because it can change by approximately 200 m (Parrenin et al., 2007), but herein, the ice thickness is fixed, and the ice thickness tendency is assumed to be 0. One recent study (Buizert et al., 2021) proposed that the temperature change at the LGM in interior regions of the East Antarctic ice sheet was less than previously estimated. Therefore, we conducted one set of experiments where SAT anomalies were set to 0%, 25%, 50%, and 75% of the standard experiments, while keeping changes in SMB the same. Furthermore, we also applied this model to the conditions at EDC to check whether the model could simulate observed temperature and age profiles (Table 1).

Using this set of boundary conditions, we conducted simulations with different *p*-values (1–5) and GHFs (50–60 mW m^{-2}) to calibrate the model with observed values at the DF ice core. We used the depth–age profile of the DF ice core, which was constructed by orbital tuning of a gas record above ~2500 m, and by matching to the AICC2012 chronology below that depth (Kawamura et al., 2017). We also used the measured depth–temperature profiles from the JARE54 surveys during the 2012–2013 Antarctic summer (Buizert et al. 2021). The model was initialized with the conditions of 2 Ma BP, where the initial age and temperature were set to 0 years and –10 °C for the entire ice column, respectively. All experiments were integrated for 2 Ma to reach the present day; therefore, the age of any ice older than 2 Ma did not appear in the experiments. These simplified initial conditions generated unrealistic temperature fields in the early stage of the simulation, but realistic glacial cycle forcing prevailed over the entire ice column within approximately 100 ka. Therefore, we mainly analyzed the results of the last 1.5 Ma, which is sufficient to discuss old ice in this study.

Parameters	DF	EDC
Ice thickness [m]	3028	3233
Surface mass balance [ice equivalent mm a^{-1}]	30.0	28.4
Surface temperature [°C]	−55.5	−54.65

Table 1: List of parameters used in Sect. 3. Ice thickness (DF and EDC), surface mass balance, and

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surface temperature at EDC come from Parrenin et al. (2007); surface mass balance at DF comes from Kameda et al. (2008) and Fujita et al. (2011); surface temperature at DF is calibrated in this study but is within previously observed ranges (Kameda et al., 1997; Yamanouchi et al., 2003).

3.2. Results for DF

In Fig. 4, the simulated temperature profiles at 0 ka (end of the simulations) with different GHFs under the same *p*-value ($p = 3$) are compared with observations (Fig. 4a). The close-up of the bottom 120 m of the ice column is shown in Fig. 4b; the basal temperature is well below melting point with a GHF of 52 mW m^{-2}, and at the melting point with a GHF > 56 mW m^{-2}. Compared with the observed temperature profile (Fig. 4 black lines), the simulated temperature near the ice base was colder by approximately 1 °C. In all simulations, the simulated temperature profiles were generally colder than observed temperature profiles especially in the middle of the ice columns (Fig. 4a).

The time series of simulated basal ice melting rates over the last 500 ka show that there have been significant temporal changes in these rates over time (Fig. 5). With a GHF of 52 mW m^{-2}, the temperature at the ice base has been below the melting point through the last 500 ka. In contrast, in the case of a GHF of 55 mW m^{-2}, the basal melting rate is zero at 0 ka, while the maximum basal melting rate of 1 mm a^{-1} occurs at the end of interglacial periods (e.g., 100 ka BP). This variability in basal melting rate is caused by glacial–cycle forcing in SAT and SMB, and minimum basal melting tends to occur in the interglacial periods. This result is broadly consistent with previous studies (Saito and Abe-Ouchi, 2004; Van Liefferinge et al., 2018), in that colder ice, which accumulated during glacial maximums, increased advection towards the ice base owing to an increased SMB during interglacials. A larger GHFs (58 or 60 mW m^{-2}) results in basal melting occurring most of the time, with a rate of approximately 3 mm a^{-1}. A downward flow of ice caused by basal melting (as in Equation 2) compensates for the basal melting owing to the increased downward advection.

The simulated age profiles at the present day are compared with the reconstructed profiles in Fig. 6a. With a small GHF (52 mW m^{-2}) where basal melting does not occur, the ice age at the ice–bedrock interface is > 1.5 Ma. In contrast, if basal melting occurs, the ice age at the ice–bedrock interface can be much younger; for example, it is 980 or 650 ka for a GHF of 55 or 56 mW m^{-2}, respectively. The result obtained with a GHF of 55 mW m^{-2} exhibits the closest fit to the data at least 250 m above the bedrock. A larger GHF tends to decrease the ice age, owing to a higher basal melting rate. In this article, we define the "resolution of age" (ka m^{-1}) as the inverse of annual layer thickness as an indicator of old ice (Lilien et al., 2021). In Fig. 6b, the resolution of old ice is compared with the actual DF ice core. The model results largely reproduced the glacial–interglacial contrasts in annual layer thickness caused by the temporal variations of SMB at the site. The observed resolution of age is approximately 0.5–1 ka m^{-1} near the base, and the results using a GHF of 55 mW m^{-2} reproduced similar values. Furthermore, on the basis of Fig. 6b, the annual layer thickness of 1.5 Ma BP ice is approximately 0.1 mm if the ice base temperature is well below the melting point (dark blue lines).

In accordance with the results described above, a larger GHF tends to result in a higher basal melting rate and younger age of ice at the base of the column. One critical point is that an excessive GHF (i.e., an increase of the order of 2 mW m^{-2}) can have a considerable effect on the age of the ice and the likelihood of old ice. Next, we evaluate the effects of different vertical velocity profiles. In Figs 7 and 8, results with GHF of 55 mW m^{-2} and different *p*-values are compared. Generally, a larger *p*-value induces a colder temperature (Fig. 7a) and a lower basal melting rate (Fig. 7b). The simulated age profiles indicate that a larger *p*-value induces a younger age of ice in the mid-depths of the ice column (Fig. 8). Both of these results can be explained by differences in advection, in that a larger *p*-value induces larger advection of the temperature and age. Near the ice surface, the influence of basal melting is relatively small; therefore, a larger vertical velocity tends to result in a younger ice age. In contrast, near the base, a larger *p*-value results in a colder basal temperature owing to greater advection of cold ice, which leads to less basal melting and an older ice age.

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3.3. Results for EDC

We also applied this model to the EDC conditions to enable performance checks with one different location. We used the parameters listed in Table 2 and conducted sensitivity experiments with different GHFs. For the vertical velocity profile, we used p = 2.3 following Parrenin et al. (2007). The model generally results in colder temperatures compared with observations, similar to DF (Fig. 9). The results using a GHF of 51 mW m^{-2} give a basal ice age of approximately 900 ka (Fig. 10a), which is close to the value (802 ka) presented in Veres et al. (2013), and the resolution of age closely fits the chronology estimated from ice-core analysis (Fig. 10b). One important result is that the threshold of GHF that allows basal melting is 5 mW m^{-2} lower at EDC than at DF. This result is generally consistent with previous studies (Parrenin et al., 2007; Van Liefferinge et al., 2018). This lower threshold of GHF can be attributed to the combination of larger ice thickness, smaller SMB, and higher SAT at the present day. The results from the application to EDC show that our model produces results which are consistent with observations for slightly different glaciological parameters.

3.4. Sensitivity of temperature amplitudes over glacial cycles

The results using DF conditions with different amplitude of temperature changes but the same GHF and p parameters (same as Sect. 3.2) are summarized in Fig. 11, in terms of temperature and basal melting rates. The control experiments exhibit colder ice temperatures near the middle of the ice column than observations, and this cold bias can be reduced if a smaller temperature amplitude over the glacial cycles is used (Fig. 11a), broadly consistent with Buizert et al. (2021). Temperature amplitude also changes basal melting rates; a smaller amplitude of the glacial cycle contributes to larger basal melting rates (Fig. 11b), because mean temperature over the glacial cycles increases if we reduce a smaller temperature amplitude of glacial–interglacial cycles. The results using a fixed surface temperature (dTs = 0.0) correspond to the same present-day SAT for the last 2 Ma, which induces basal melting of ~3 mm a^{-1} most of the time. A slight fluctuation in basal melting still occurs owing to time-dependent SMB. It is possible to tune the GHF as in Sect. 3.2, assuming different temperature changes over the glacial cycle. We regard this as an uncertainty in the forcing, and we note that it can change basal melting rates.

3.5. Summary of Sect. 3

On the basis of the results described in this section, we conclude that using a combination of p = 3 and GHF = 55 mW m^{-2} gives reasonable temperature and age profiles; therefore, we decided to use these values as calibrated parameters for the DF region. We use these parameters as a calibrated values for the DF region for the following reasons. Later in the article, we investigate the possibility of old ice in the DF region using different parameters (i.e., spatially variable ice thickness and GHF). Hence, obtaining precise tuning at one specific DF location is unnecessary. We do not state that the GHF of 55 mW m^{-2} is a single best estimate for the DF location compared to the previous estimates (Burton-Johnson et al., 2020; Talalay et al., 2021), because there were assumptions in the vertical velocity profiles and experimental design of this study. Also, the calibrated GHF depends on chosen SAT scenario over the glacial cycles.

4. Sensitivity studies using various parameters around DF

4.1. Experimental design

This section investigates the impact of the other three parameters, ice thickness, SMB, and GHF, which may have spatial variations in the DF region. We investigated a range of ice thicknesses between 2000 and 3200 m, based on an ice thickness map of the area around DF (Fig. 1). We used present-day SMB ranges of 25–35 ice mm a^{-1}. There is large uncertainty in GHF; we adopted a range of 50–70 mW m^{-2}. The list of experiments is given in Table 2. Other aspects of the experimental design are the same as in Sect. 3.

Variable	Parameter range
Ice thickness [m]	2000–3200, every 100
Present-day SMB [ice equivalent mm a^{-1}]	25–35, every 1
GHF [mW m^{-2}]	50–70, every 2

Table 2: List of experiments in Sect. 4.

4.2. Results

In Fig. 12a, the relative effects of ice thickness and GHF on basal temperature are compared, using the same SMB (30 mm a^{-1}). As in Sect. 3, we used an ice thickness of 3028 m, which is comparable to that at DF, and a threshold of GHF for basal melting of 55 mW m^{-2}. On the basis of the gradient of contours in Fig. 12a, an increase in ice thickness by 100 m has a comparable impact on the basal temperature as does an increase in GHF by 2 mW m^{-2}. In Fig. 12b, the relative effects of ice thickness and SMB are compared using the same GHF (55 mW m^{-2}). A larger SMB results in a colder temperature; a 10% change in GHF leads to a ~4 ℃ change in the basal temperature, while a 10% change in SMB leads to a ~1 ℃ change. These results are generally consistent with those by Fischer et al. (2013). We note that the spatial distribution of SMB has a minor impact on the basal temperature compared with that of the ice thickness.

We further investigated the impact of different ice thicknesses on age profiles using climatic conditions at DF (SMB = 30 ice mm a^{-1}) and a calibrated GHF (55 mW m^{-2}). Figure 13a shows the simulated age of the ice at 50 and 100 m above the ice–bedrock interface, which were used as indicator depths for potential sites by Fischer et al. (2013). The results indicate that the rate of aging of ice rapidly decreases with depth between 2900 and 3100 m owing to the occurrence of basal melting. Note that the age of 2 Ma BP is the limit of the experiments, and the results indicate that the old ice exists 50 m above the bedrock if the ice thickness is thicker than ~2100 m. Figure 13b shows the age resolution of the 1.5 Ma BP ice, indicating that a larger ice thickness tends to show a finer age resolution. The vertical age profiles and resolution of ice ages at three selected ice thicknesses (2200, 2600, and 3000 m) with the same GHG are shown in Fig. 14. The expected age resolution is approximately 10–20 ka m^{-1}.

5. Application to the DF–NDF transects

5.1. Experimental design

In this section, we apply the 1-D model to interpret the internal layers of the ice near DF, the structure of which was obtained by ground surveys during JARE59 (2017–2018). Here, we use the dataset from 17th December, 2017, which comprises a 54 km long transect from DF to NDF (Fig. 1). The horizontal axis of Fig. 15 indicates the distance from DF, and the vertical axis indicates the depth from the surface. The gray shading indicates the reflectivity, which is an indicator of contours representing ice of the same age. The bedrock elevation, shown by brown lines, was detected based on the maximum reflectivity from the base (Tsutaki et al., 2022). The bedrock elevation was calibrated to match the observed bedrock elevation at DF. We calculated the 1-D age and temperature profiles of the ice at approximately 400 m intervals along the transect. We assumed that the vertical profile of vertical velocity could be determined locally using Equation 1, and that there were no horizontal interactions in temperature and age in this simulation. The present-day SMB was linearly interpolated between DF (30 ice equivalent mm a^{-1}) and NDF (25.5 ice equivalent mm a^{-1}). As there was very limited information regarding the spatial distribution of GHF, we set a uniform value of 55 mW m^{-2} following the discussion in Sect. 3. As described in Sect. 3, the initial age of the ice was set to 0, the temperature set to −10 ℃, and the model was integrated over the last 2 Ma of forcing until it reached the present day (Fig. 3).

5.2. Results

In Fig. 15, the computed vertical profiles of the age are overlaid on a radargram using seven

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colored lines, and the simulated basal temperature is indicated by shading in the bottom panel. The colored bar below the radargram indicates the simulated present-day basal temperature. The simulated distribution of ice age captured large-scale features in the black–white contour lines derived from the radargram signal (grayscale color in Fig. 15). The simulated age contours of 21 ka BP (approximately 500 m depth) and 128 ka BP (approximately 1500 m depth) can be traced from DF, although the deepest layer corresponding to an age older than 300 ka BP is hard to see in this image. Where ice is relatively thick (e.g., 20–25 km from DF), the simulated age of the ice at the ice–bedrock interface is younger than 700 ka BP, while ice older than 1.5 Ma BP occurs where the ice is relatively thin. A comparison of the simulated ice age and the radargram signal gives an opportunity to examine the validity of the model results. For example, between 5 and 35 km from DF, the computed 128 ka BP contour deviates to shallower levels by 150 m from the tracked layer for the age from the radar measurements, suggesting that the model overestimates the age of the ice near the bedrock in such locations.

6. Discussion

In this study, we used a 1-D ice-flow model, which computes the temporal evolution of age and temperature profiles. We used glaciological conditions at DF to tune some unknown parameters according to the observed temperature and age profiles. The results showed that the age profile is sensitive to the choice of GHF, but one experiment using a specific combination of GHF and vertical velocity profile exhibited reasonable temperature and age profiles (Figs 4 and 6). One important result is that the melting rate at the base of ice exhibits temporal changes associated with glacial–interglacial forcing. This is caused by relatively cold ice deposited during glacial periods being pushed towards the bottom of the ice column by increased SMB and downward advection during interglacial periods, as shown in previous studies (e.g., Van Liefferinge et al., 2018). This point is critical for preserving old ice, in that the temperature should be well below the melting point of the ice at the present day because basal melting rates during glacial periods can be much higher than that of present day (Fig. 5, blue lines). Our sensitivity experiments highlighted the relative effects of ice thickness and GHF, whereby a small GHF excess above the condition that induces basal melting can result in a considerable reduction in the age of ice at the ice–bedrock interface (Fig. 6a). Below, we discuss the limitation of the interpretations of our results, their relevance to previous ice-flow modeling studies, and uncertainty factors.

On the basis of data presented in Fig. 6, the GHF of 55 mW m^{-2} sufficiently explains the observed temperature and age–depth profiles of the DF ice core. However, there is considerable uncertainty in the estimation of the actual GHF value at DF because of some simplifications in the model experiments and limited representations in physics. One point of difference is that the model tends to give a generally colder temperature profile compared with the observations (Fig. 4), which suggests that the model overestimates the GHF threshold of basal freezing. One possible reason for this difference is that the basal melting of ice can occur within a certain ice thickness; the extrapolation of observed temperature profiles at DF and EDC (Figs 4 and 9, black lines) shows that the ice reaches the pressure-melting point approximately 30 m above the bedrock. This feature cannot be simulated in the model of the present study, which assumes that basal melting can only occur at the ice–bedrock interface. These representations in the physics of basal melting can be improved by using enthalpy as a state variable and adopting polythermal ice sheet models (e.g., Aschwanden et al., 2012). Another important factor in the temperature profiles is the temperature anomaly over glacial cycles, as a smaller glacial–interglacial temperature change tends to result in a warmer, more linear temperature profile compared with the control experiment (Fig. 11a). The temperature change over the last glacial cycle used in this study is based on deuterium and oxygen isotopes (Uemura et al., 2018), which exhibit an LGM temperature anomaly of approximately 8 °C (Fig. 3a). A recent study proposed that the temperature anomaly at the LGM at DF and EDC was about a half of the previous estimates based on the observed temperature profiles and other independent methods (Buizert et al., 2021). This study is

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in agreement with Buizert et al. (2021) in that our control experiment exhibits colder ice temperatures, especially at mid-depth within the ice column, and a smaller temperature difference between glacial and interglacial periods improves the modeled temperature profiles (Fig. 11a). If this is indeed the case, the actual threshold of GHF value for the basal freezing should be lower than that used in the control experiment.

We note that the simulated age of the ice depends on the shape of the vertical velocity profile of the ice. The formulation of the present study has a smaller vertical velocity of the ice, especially near the base, compared with that used in Fischer et al. (2013). Because the age of the ice is related to the inverse of the vertical velocity, a different vertical velocity profile or a p parameter can lead to a quantitatively different result. Moreover, vertical velocity profiles represented by a single p-value are merely one assumption; this formulation is derived from a solution of an idealized ice-sheet configuration (Lliboutry, 1979), which may not be the case for realistic ice-sheet. For example, the observed magnitude of layer thinning of the DF ice core exhibits a decreasing trend over the bottom 500 m (Fig. 6). According to analyses of the DF ice core (Azuma et al., 1999; Saruya et al., 2022) or 3-D ice sheet modeling (Seddik et al., 2011), deformation of the ice or flow regime towards the ice bottom is complex. Thus we suggest that both horizontal and vertical ice flow should be complex as well, which may be difficult to represent by using the current formulation of vertical velocity profiles.

We also note that the resolution of 1.5 Ma ice, one indicator of old ice, depends on ice thickness. In particular, Lilien et al. (2021) presented similar 1-D ice-flow model results from BELDC (Beyond EPICA Little Dome C, ice thickness of ~2750 m) constrained by radar internal layers and estimated the resolution of 1.5 Ma ice as $19 \pm 2\ \mathrm{ka\,m^{-1}}$. In contrast, our results for EDC conditions have a resolution of the ice (with a small enough GHF to keep the base of the ice frozen) have an ice age resolution of approximately 10 $\mathrm{ka\,m^{-1}}$ (Fig. 10, dark blue lines), which is approximately half of that in Lilien et al. (2021). This difference can be attributed to the combination of the model parameters, such as ice thickness, p of the vertical velocity profile, or SMB history (3233 m and p = 2.3 in this study), because the two studies adopted the same formulation of the vertical velocity profile. According to Figs 13 and 14, a larger ice thickness leads to a better resolution of the ice age if the base of the ice is frozen throughout time. Therefore, we speculate that the different ice thickness, p-value, or SMB history in the Lilien et al. (2021) study (whose value ranges were not explicitly presented) may have caused the difference in the age resolution of 1.5 Ma BP ice.

Application of the 1-D model to the transect between DF and NDF provides an opportunity to examine the influence of spatially varying glaciological conditions (e.g., ice thickness and GHF) on the age of the ice. The simulated age–depth distributions with constant GHF but different ice thickness and SMB exhibit general agreement with observed internal layers (Fig. 15). One noticeable model–data discrepancy occurs at 14–18 km from DF, where the simulated age contours of 128 ka BP are ~150 m above the observed internal layers traced from DF. This model–data discrepancy indicates that the effects of vertical or horizontal advection (Huybrechts et al., 2007; Sutter et al., 2021) or ice thickness changes over glacial cycles (Saito et al., 2020) may have contributed to this difference. Although the relative importance of the spatial distributions of GHF, SMB, and horizontal flow is difficult to assess in the present study, we expect that future glaciological data constraints and model developments will better constrain these uncertain parameters and the spatial distribution of old ice. One recently published present-day SMB from the vicinity of the DF region exhibits spatial variabilities reflecting surface topographical features (Van Liefferinge et al., 2021). On the basis of systematic sensitivity experiments (Sect. 4), we have shown that the impact of SMB on the age of the ice is relatively minor compared with that of ice thickness, but the small-scale features present in internal layers of the ice can be improved by using the spatial distribution of present-day SMB, and this will contribute to the selection of the most suitable drilling site.

7. Conclusions

We draw the following conclusions from this study.

1. In experiments using the configurations of DF, the model largely reproduced the observed age and temperature profiles under a calibrated GHF. If the GHF is small enough to keep the basal temperature below the melting point, it is expected that ~1.5 Ma could be present. If such old ice exists, the simulated annual layer thickness of ~1.5 Ma BP ice is approximately ~0.1 mm, which corresponds to 10 ka m^{-1}. According to IPICS, this is a feasible resolution for analysis with minimized effects of diffusion. This is also true for EDC, but the threshold of GHF for basal melting is different because of a different ice thickness and SMB.
2. Under the configuration and range of parameters of the present study, the ice thickness has a larger impact on basal melting than does the present-day SMB; an ice thickness difference of ~100 m corresponds to a SMB difference of 5 ice equivalent mm a^{-1} (Fig. 12). Near the DF region, the ice thickness has larger spatial variability above these ranges, while SMB does not. Though there is considerable uncertainty in the spatial distribution of GHF, ice thickness is suggested to be one of the most critical factors for the preservation of old ice.
3. The climate forcing of the past influences the temperature and age profiles, and induces a substantial change in basal melting rates. The calibrated age profile at DF resulted from temporally evolving basal melting rates, which mostly occurred after interglacial periods. This temporally changing basal melting can eliminate the old ice of ~1.5 Ma BP.
4. From the simulation of the DF–NDF transect, a small ice thickness and colder basal temperature are the necessary conditions for the presence of the old ice of ~1.5 Ma. However, a small ice thickness contributes to a coarser resolution of the old ice (small annual layer thickness), which may make it difficult to extract paleoclimate information. As discussed in Pattyn (2010), ice thickness is found to be a compromising factor in the selection of a drilling site.
5. The simulation along the DF–NDF transect does not reproduce the depth of the internal layers of the ice corresponding to 128 ka BP at some locations (e.g., at distances 5–35 km from DF), suggesting possible error in the simulated age of ice near the bottom of the ice column. The simulated age of ice in this area, especially where there is a large discrepancy between the simulation and radar images, could be caused by uncertainties derived from several assumptions or uncertainty in the model or methods, including spatial distributions of GHF, representation in vertical temperature profile that depends only on normalized altitude (DF ice core suggests complex ice-flow near its base), representation in thermodynamics associated with basal melting, or history of surface temperature changes. Therefore, future improvements in numerical models and methods would contribute to better constraining the age of the ice.

A recent compilation of ice thickness data around DF indicates the presence of complex and steep terrain in the area, with uncertainty in bedrock elevation of > 60 m (Tsutaki et al., 2022), highlighting the necessity of a high spatial resolution survey of bedrock topography. The results from this study help to support the interpretation of observational data and the selection of a suitable drilling site.

Code availability:
The numerical model is available from Github. https://github.com/saitofuyuki/icies2.git

Data availability:
The scripts and data for conducting experiments and analyzing results are available at AORI-CESD (https://cesd.aori.u-tokyo.ac.jp/cesddb/publication/index.html). All figures were generated using GMT version 4.5.9. The ice core chronology and temperature at DF are available from previously published articles (Veres et al., 2013; Kawamura et al., 2017; Buizert et al., 2021).

Author contribution
T. O., A. A-O, and F. S. conceived the study, developed the numerical model, designed and carried out experiments, and analyzed the results. T. S., S. F., K. K., and H. M. provided glaciological data

from JARE surveys and contributed to the experimental design. T. O. prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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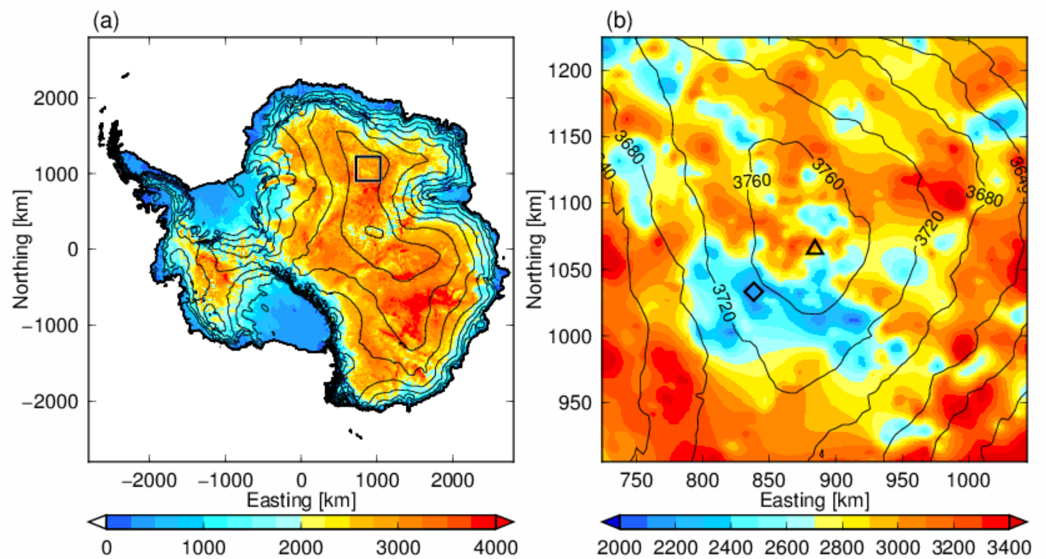

Fig. 1: (a) Map of Antarctica. The contours (every 500 m) indicate the surface elevation, and colors indicate ice thickness, using BEDMAP2 (Fretwell et al., 2013). The square indicates the location of the inset shown in (b). (b) Enlarged view near DF (Dome Fuji). The triangle indicates the location of the DF ice core site, and the diamond indicates the NDF site.

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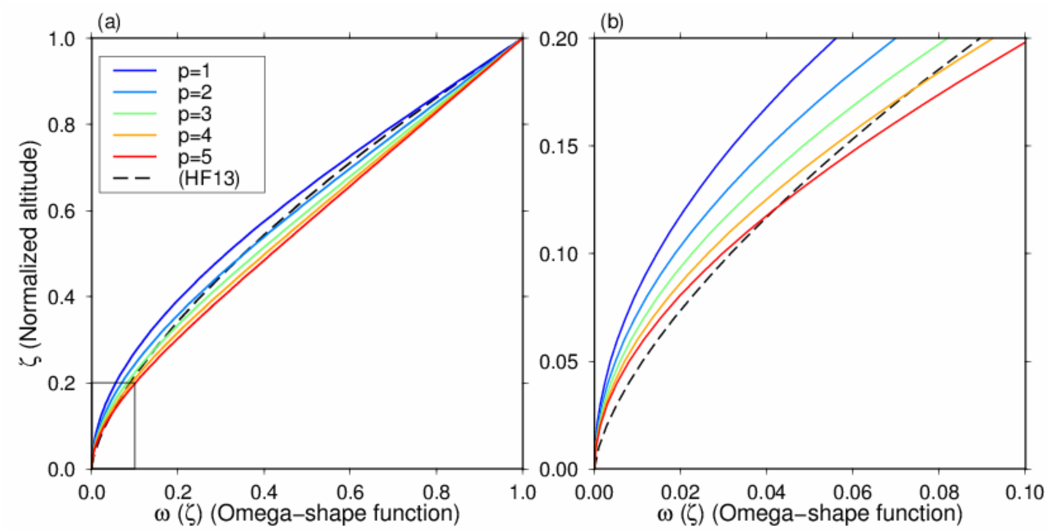

Fig. 2: (a) Normalized vertical velocity profiles adopted from Equation [1] with different *p* parameters. The dashed black line (HF13) indicates the vertical velocity profile used in Fischer et al. (2013) with *m* = 0.5. (b) Enlarged view near the bottom of the ice column (see black rectangle in (a)).

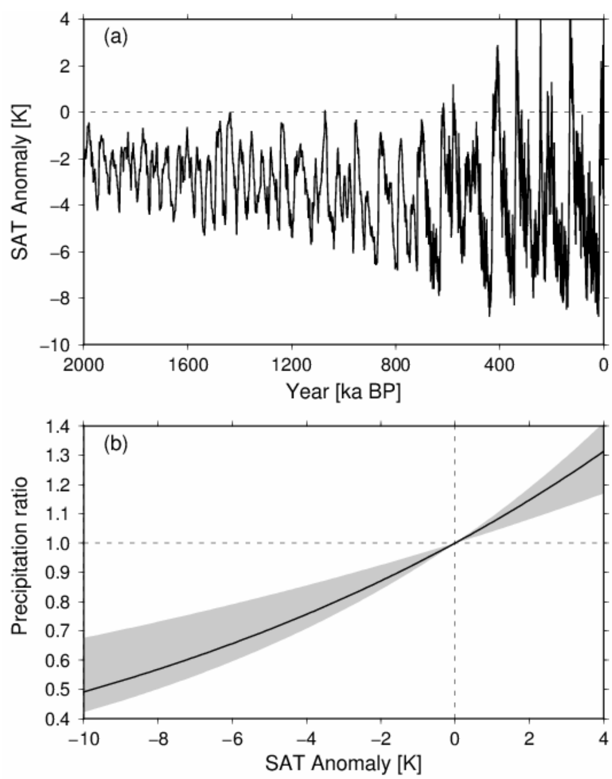

Fig. 3: Glacial cycle forcing used in the present study. (a) Surface air temperature (SAT) anomaly from

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the present day for the last 2 Ma. (b) Relationship between SAT anomaly and precipitation ratio. The black line corresponds to the one used in the present study; the gray shading indicates a 4%–9% increase per degree, summarized in Fox-Kemper et al. (2021).

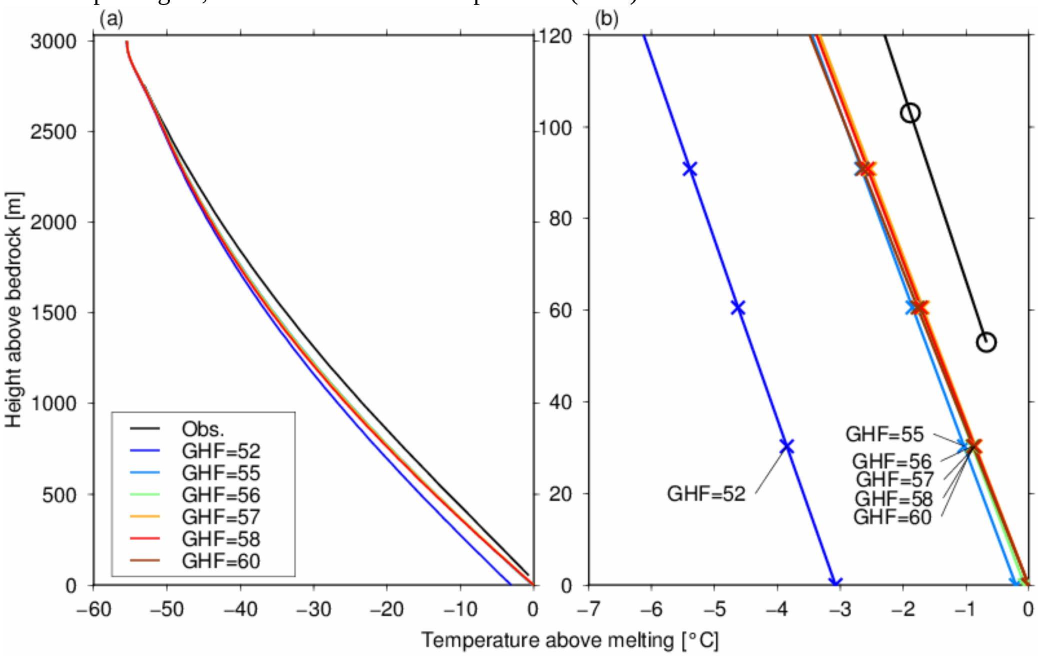

Fig. 4: Simulated vertical temperature profiles under the DF configuration (Table 1) with different geothermal heat fluxes (GHF; units are mW m^{-2}). (a) Simulated temperature profiles at 0 ka (end of the simulation) from the surface to the base. (b) Close-up of (a) for the bottom 120 m of the ice column. The black lines represent the measured temperature profiles and the black circles in (b) indicate the location of data points, while the colored crosses in (b) represent the model grid points.

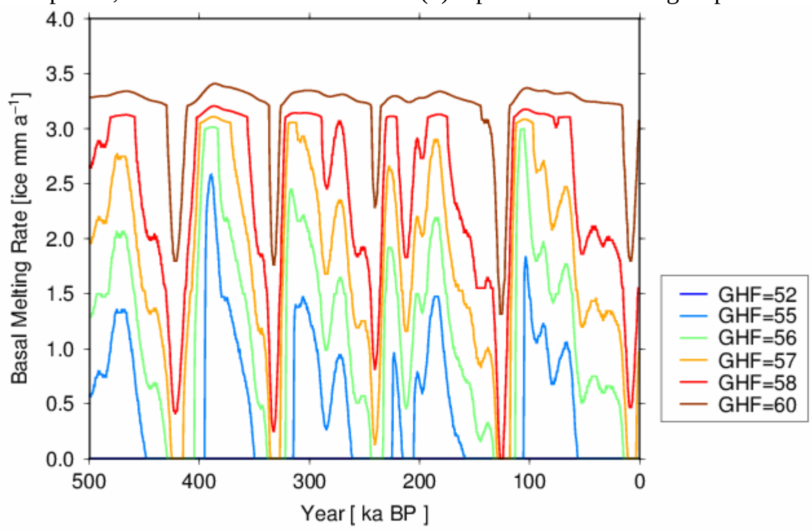

Fig. 5: Time series of the simulated basal melting rates of the last 500 ka under the DF configuration (Table 1) with different geothermal heat fluxes (GHF; units are mW m^{-2}).

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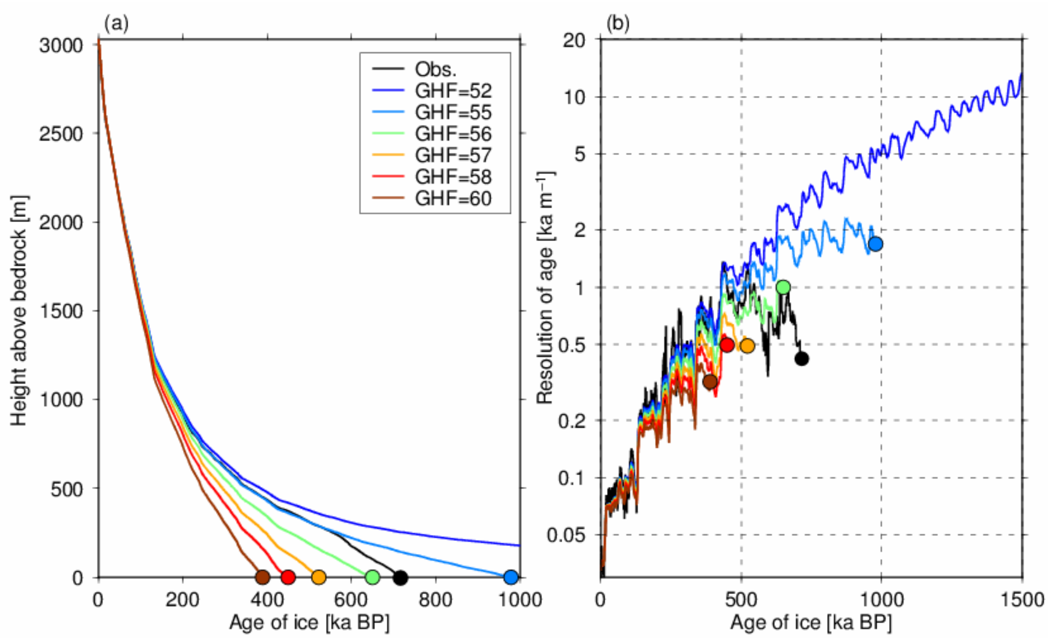

Fig. 6: Simulated vertical ice age profiles under the DF configuration (Table 1) with different geothermal heat fluxes (GHF; units are mW m^{-2}). (a) Vertical age profiles at present (0 ka). The black line represents the reconstructed depth–age profile based on the AICC2012 chronology (Kawamura et al., 2017). The circles indicate the bottom of the ice. (b) Vertical resolution of ice age, calculated by the central difference using the simulated vertical age profiles of (a).

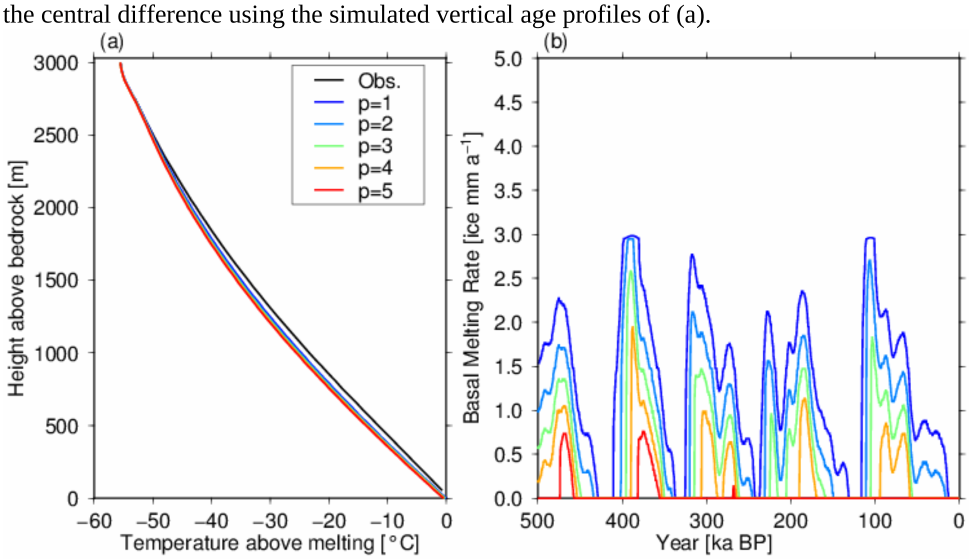

Fig. 7: Simulated vertical temperature profiles and basal melting rates under the DF configuration (Table 1) with different *p* parameters. (a) Simulated temperature profiles at present (0 ka) from the surface to the base. (b) Time series of basal melting rates over the last 500 ka. A geothermal heat flux of 55 mW m^{-2} is adopted in these experiments.

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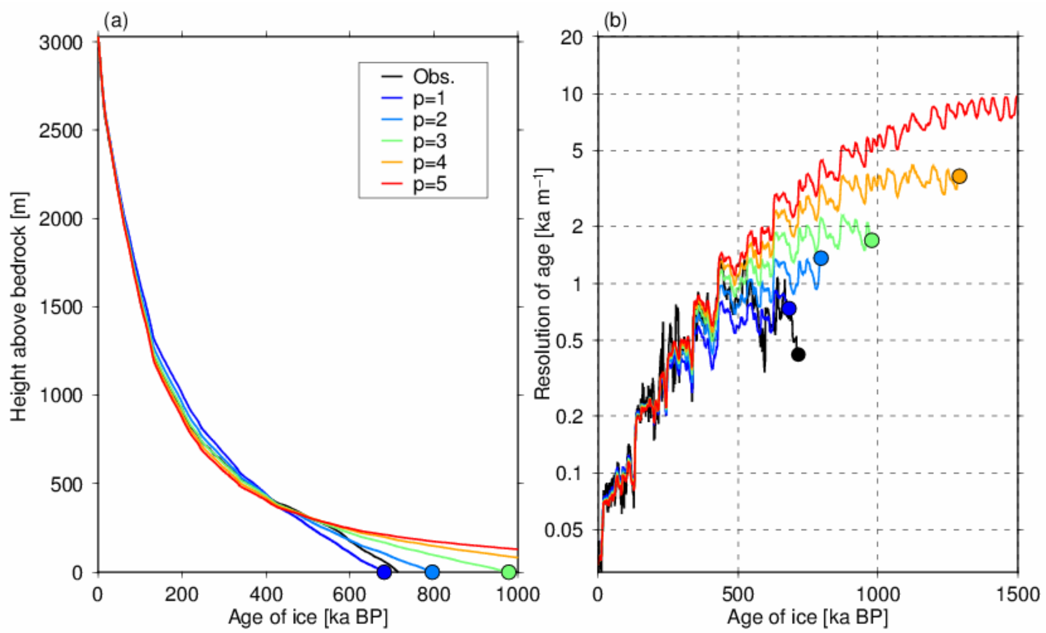

Fig. 8: Same as Fig. 6, with different *p* parameters. (a) Simulated age profiles at present (0 ka) from the surface to the base. (b) Vertical resolution of ice age. The circles indicate the bottom of the ice. A geothermal heat flux of 55 mW m^{-2} is adopted in these experiments.

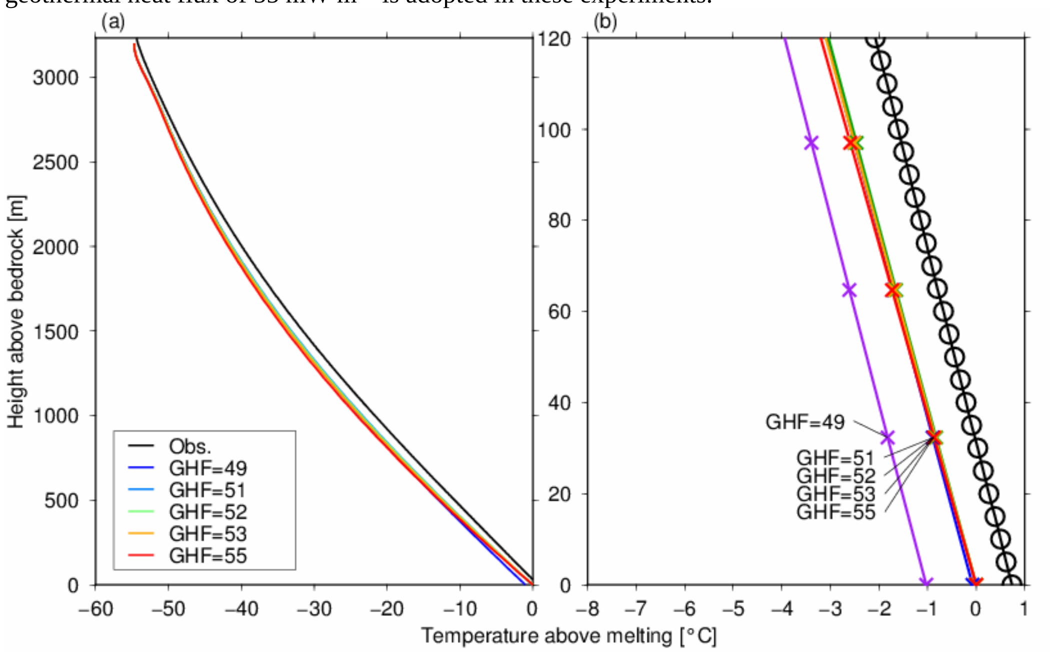

Fig. 9: Same as Fig. 4, but under the EDC configuration (Table 1) with different geothermal heat fluxes (GHF; units are mW m^{-2}). The black lines represent the measured temperature profiles and the black circles in (b) indicate the location of data points, while the colored crosses in (b) represent the model grid points.

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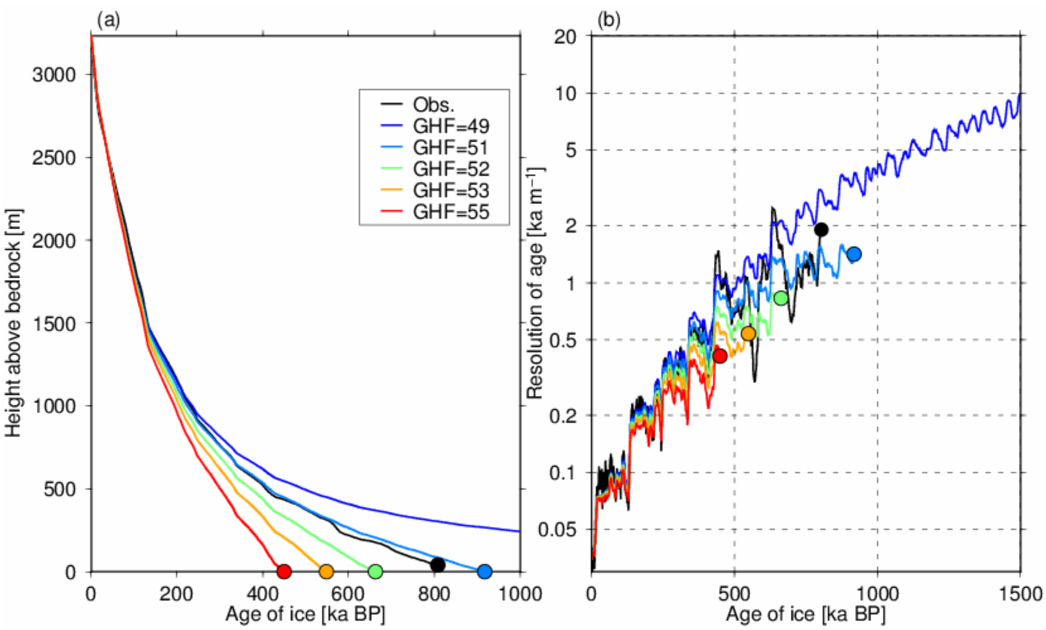

Fig. 10: Same as Fig. 6, but results under the EDC configuration (Table 1). The AICC2012 chronology (Veres et al., 2013) is used in this figure for the observed depth–age profile.

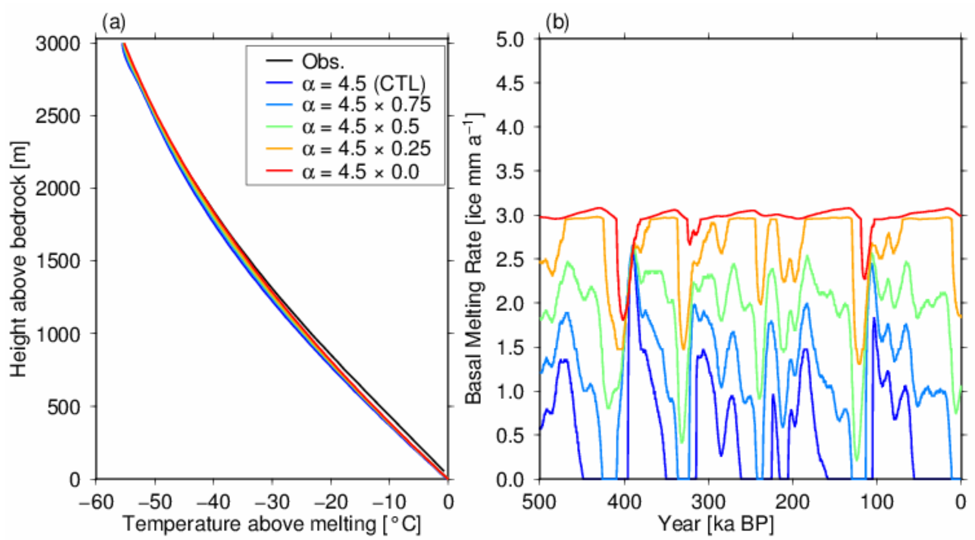

Fig. 11: Simulated vertical temperature profiles and basal melting rates under the DF configuration (Table 1), using different temperature amplitudes over glacial cycles in Equation 8. A combination of p = 3 and GHF = 55 mW m^{-2} is adopted in these experiments. (a) Simulated temperature profiles at present (0 ka) from the surface to the base. (b) Basal melting rates of the last 500 ka. The dark blue lines are the same as the green line of Fig. 4.

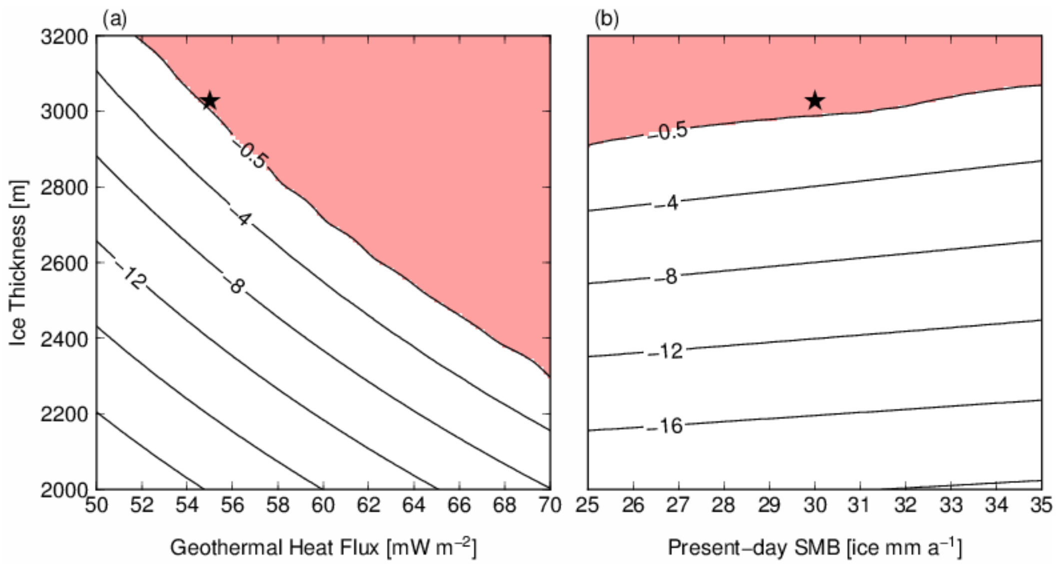

Fig. 12: Simulated basal temperature at the present day with combinations of ice thickness, geothermal heat flux, and present-day SMB. (a) Red shading indicates a basal temperature −0.5 °C below the pressure-melting point. (b) Basal temperature at the present day with GHF = 55 mW m^{-2}. The black star represents the condition at the DF ice core (H = 3028 m, SMB = 30 ice mm a^{-1}), with a calibrated geothermal heat flux (55 mW m^{-2}).

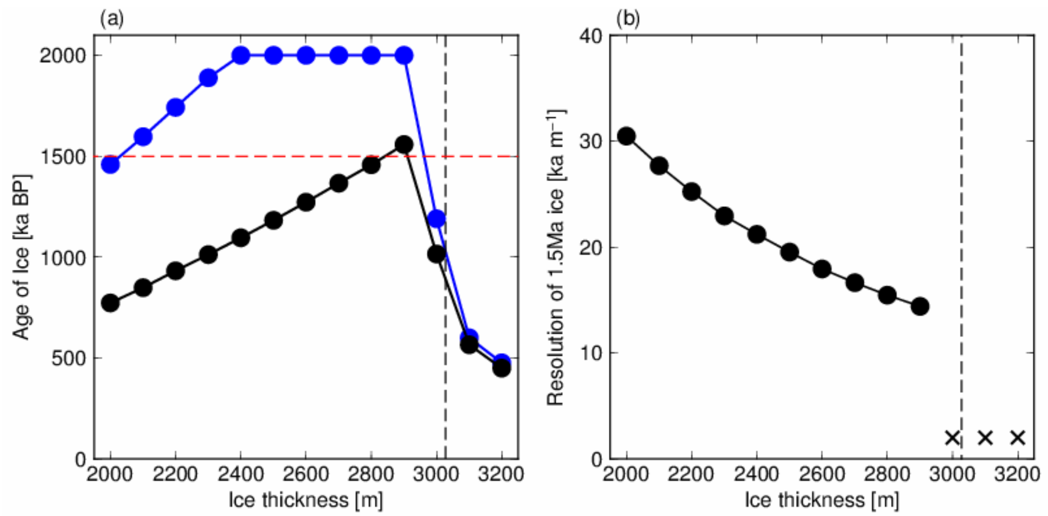

Fig. 13: Results with different ice thicknesses. (a) The black and blue lines indicate the simulated age of the ice at 100 and 50 m above the bedrock, respectively. The vertical dashed line (H = 3028 m) indicates the condition at DF, and the horizontal red dashed line indicates the age of 1.5 Ma. Note that an age of 2 Ma is the limit of the experiments. (b) The vertical axis indicates the resolution of the ice age (ka m^{-1}) at 1.5 Ma BP. The crosses indicate that the 1.5 Ma age of ice does not exist under these conditions.

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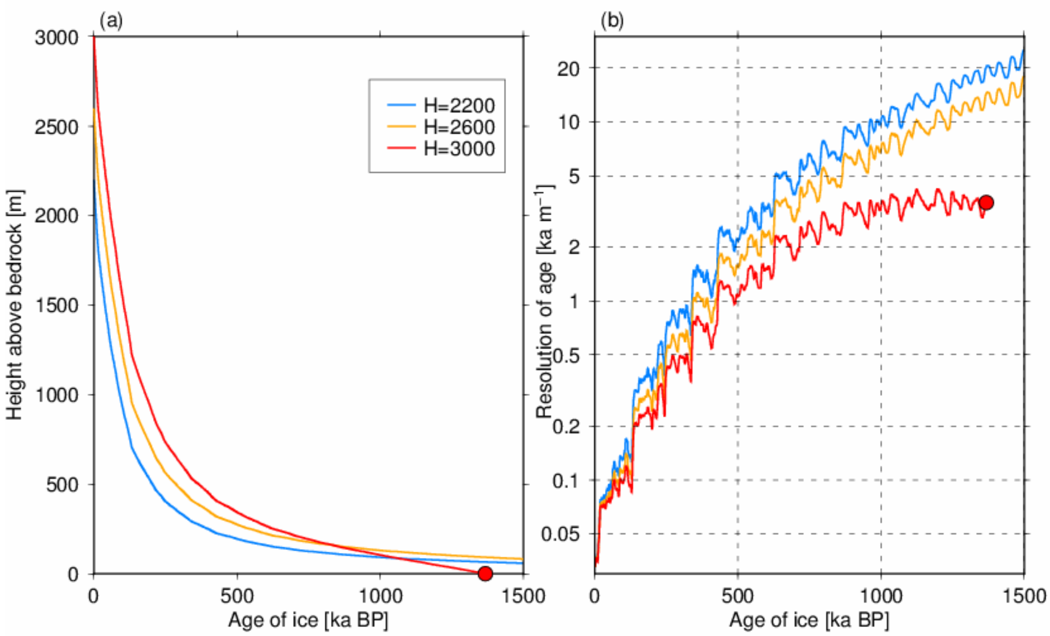

Fig. 14: Results with different ice thicknesses (2200, 2600, and 3000 m) with calibrated geothermal heat flux and SMB (55 mW m^{-2}, 30 ice mm a^{-1}) at DF. (a) Vertical age profiles (the circle on the H = 3000 m case indicates the bottom of the ice) at present (0 ka). (b) Vertical resolution of the ice age.

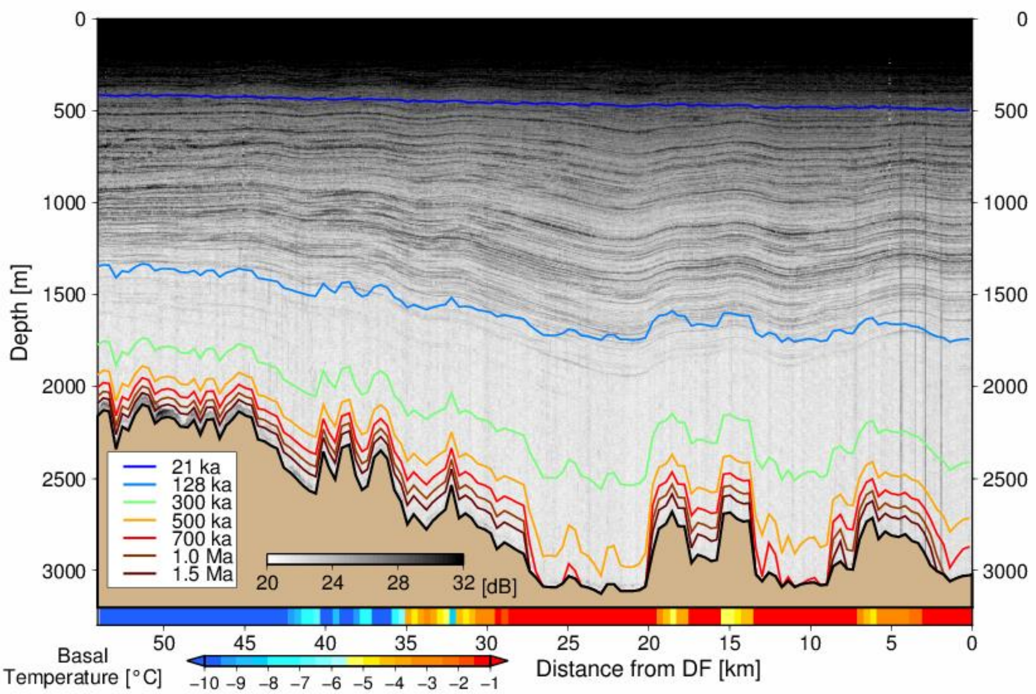

Fig. 15: Results of the experiments overlaid with the observed radargram for the DF–NDF transect.

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The horizontal axis indicates the distance from DF (km), and the vertical axis indicates the depth from the surface (m). The gray coloring indicates the reflection intensity from the ground radar surveys, and the color contours indicate the simulated age of the ice using the 1-D model. The bottom color bar indicates the simulated basal temperature (relative to the melting point) at the present-day.