

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

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Abstract. The recovery of a new Antarctic ice core spanning the past ~1.5 million years will advance our understanding of climate system dynamics during the Quaternary. Recently, 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 (e.g., Shakun et al., 2015). Ice cores from the Antarctic ice sheet have provided fruitful information on past climate system changes because they can provide continuous reconstructions of 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 critical scientific challenge. 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

48 studies have been used to select the location of suitable sites (Parrenin et al., 2017; Young et al.,
49 2017; Passalacqua et al., 2018; Lilien et al., 2021). The present article focuses on Dome Fuji (DF),
50 Antarctica, which is located at 77.31° S, 39.70° E, with a surface elevation of 3810 m above sea level,
51 and ice thickness of 3028 m. The most recent ice core at DF was obtained between 2003 and 2006
52 (Motoyama et al., 2021). The ice age at the bottom of this core was approximately 720 ka BP based
53 on Antarctic ice core chronology 2012 (AICC2012) (Kawamura et al., 2017; Uemura et al., 2018).
54 The temperature of the ice was at the pressure-melting point near the bedrock (Motoyama et al.,
55 2021). Recently, field surveys have been conducted to collect bedrock elevation data near DF using
56 ground and airborne radar surveys. On the basis of surveys performed by Japanese Antarctic
57 Research Expeditions (JARE) between the late 1980s and 2008, the results of which are included in
58 BEDMAP 2 and 3 datasets (Fretwell et al., 2013; Frémand et al., 2022), the typical ice thickness
59 around DF is approximately 2000–3200 m (Fig. 1). Subsequently, the 54th JARE (2012–2013
60 Antarctic summer) conducted ground-based radar surveys in areas where subglacial mountains were
61 detected in the area south of DF (data compiled in Tsutaki et al., 2022). More recently, the Alfred
62 Wegener Institute (AWI) in Germany conducted airborne radar surveys covering the DF area
63 (Karlsson et al., 2018). On the basis of these data, the 59th and 60th JARE (2017–2018 and
64 2018–2019 Antarctic summers) conducted ground-based radar surveys to investigate the internal
65 reflection horizons (internal layers) of ice sheets over a distance of ~ 5650 km (Tsutaki et al. 2022),
66 covering the DF and NDF sites (the latter located at 77.8° S, 39.05° E, south of DF) (Rodríguez-
67 Morales et al., 2020).

68 To select suitable ice-core drilling sites, the conditions that are required to preserve old ice
69 using constraints from glaciological and climatological data should be investigated. Previous ice-
70 flow modeling studies have examined the requirements to preserve old ice using both three-
71 dimensional (3-D) and one-dimensional (1-D) models. Pattyn (2010) used a 3-D ice sheet model
72 under present-day constant climate forcing, and suggested the importance of minimal horizontal flow
73 and low geothermal heat flux (GHF) to preserve old ice near the base of ice sheets. Other studies
74 have used 3-D models to represent 3-D ice-flow fields and ice age for the relatively small area near
75 Antarctic Domes (Huybrechts et al., 2007; Seddik et al., 2011; Sun et al., 2014; Passalacqua et al.,
76 2018; Zhao et al., 2018). These studies estimated the age distribution of the ice expected from 3-D
77 ice flow fields under a constant present-day climate. More recent studies used glacial–interglacial
78 cycle forcing (Sutter et al., 2019, 2021) and discussed how the past variation of the Antarctic ice
79 sheet affects age distributions of ice.

80 One-dimensional vertical ice-flow models have been used to estimate the vertical profiles of
81 age and temperature near Antarctic domes, where horizontal flow is relatively minor. Horizontal
82 surface velocity in the vicinity of DF and NDF is $< 2 \text{ m a}^{-1}$, and it has minor spatial variations,
83 evidenced by satellite-based measurements (Rignot et al., 2011, 2017; Mougnot et al., 2012). Such
84 1-D models perform well in long-term forward simulations over glacial cycles and are able to
85 conduct many simulations with different parameters. In particular, Fischer et al. (2013) investigated
86 the influence of a wide range of parameters, including ice thickness, accumulation, and GHF on the
87 basal age of ice. Their key finding was that melting at the base reduces the likelihood of old ice, and
88 a lower ice thickness than that at previous ice core sites is a required condition to avoid basal melting.
89 Furthermore, a lower accumulation rate generally contributes to increasing the age of the ice at a
90 certain height from the bedrock but increases the chance of basal melting, owing to the reduced
91 vertical advection of cold ice. Other studies used an equivalent 1-D ice-flow model, investigated the
92 necessary conditions to keep the ice base frozen (Van Liefferinge and Pattyn, 2013; Van Liefferinge
93 et al., 2018), and examined the observed basal conditions of the ice (Passalacqua et al., 2017).
94 Parrenin et al. (2017) estimated ice-flow parameters and basal melting rate using internal layers of
95 the ice near EDC and proposed candidate sites for old ice. The reasonable resolution of ice core
96 containing climate signals which can be analyzed with current methods is important. Particularly,
97 Saito et al. (2020) presented a numerical scheme of ice advection calculation for an improved

98 representation of annual layer thickness of the ice, and conducted numerical simulations using
99 idealized glacial cycle forcings.

100 Simplified factors in previous modeling studies were the time-dependent climate forcing and
101 temperature profile, which are critical to basal ice melting. In particular, the basal temperature of the
102 ice sheet shows a minimum during interglacials because it takes a long time to advect and diffuse
103 surface temperature changes to the base of the ice sheet (Saito and Abe-Ouchi, 2004; Van
104 Liefferinge et al., 2018). In this context, the model used in Parrenin et al. (2007) assumed that basal
105 melting rates were constant over time, and Fischer et al. (2013) used pseudo steady-state assumption,
106 i.e., a constant climate forcing. Parrenin et al. (2017) assumed that the temporal variations in basal
107 melting rates are the same as accumulation rates. Some studies (Van Liefferinge and Pattyn, 2013;
108 Passalacqua et al., 2017; Van Liefferinge et al., 2018) have investigated ice temperature using
109 realistic climate forcing but did not investigate the resultant impact on the age of the ice. Similarly,
110 Hondoh et al. (2002) and Talalay et al. (2021) estimated GHF at DF and other Antarctic domes based
111 on observed vertical temperature profiles, but the observed age–depth profiles were not used as
112 constraints. The ice thickness at Antarctic domes also changes with time, and can be up to 150 m
113 thinner during glacial periods when surface mass balance (SMB) is reduced (Saito and Abe-Ouchi,
114 2010).

115 Despite the close link between the temperature and age of ice owing to basal melting, the
116 coupled simulations of thermodynamics and age of ice were not represented under transient climate
117 forcing in previous modeling studies of old ice. In this study, we use a 1-D ice-flow model, which
118 simultaneously computes the evolution of ice temperature and age, and the model is forced by past
119 climate history. The remainder of the article is organized as follows: Section 2 describes the 1-D
120 model used in this study. In Sect. 3, we apply this model to DF and conduct systematic sensitivity
121 experiments to calibrate GHF and a tuning parameter of the vertical profile of ice velocity by
122 comparing simulated age and temperature profiles with observations. We also use parameters at EDC
123 to examine whether the model can simulate temperature and age profiles under different
124 glaciological conditions. In Sect. 4, using the results of the tuned vertical velocity parameters, we
125 investigate the influences of ice thickness, SMB, and GHF on the basal temperature and age. In Sect.
126 5, we apply the 1-D model to the DF–NDF transect (over a distance of ~ 50 km) and compare the
127 results with the internal layers of the ice.

128 2. Method

129 2.1. Model description

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

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

$$133 \frac{\partial A}{\partial t} = -w \frac{\partial A}{\partial z} + 1, \quad (1)$$

134 where A is the age of the ice, defined as the duration since deposition, and w is the vertical velocity
135 of the ice (a positive value indicates upward velocity). Here, ζ is a normalized coordinate defined as
136 $\zeta = \frac{z}{H}$, where z is the height above bedrock, and H is the ice thickness (thus $\zeta = 1$ and 0 correspond
137 to the ice surface and base, respectively). The first and second terms on the right-hand side of
138 Equation (1) represent the vertical advection and aging owing to time-lapse, respectively.

139 The vertical velocity of the ice is assumed to be represented as:

$$140 w(\zeta) = - \left[\left(M_s + M_b - \frac{\partial H}{\partial t} \right) \omega(\zeta) - M_b \right], \quad (2)$$

141 where the terms M_s and M_b represent surface (positive indicates ice gain) and basal (negative
142 indicates ice melt) mass balance caused by accumulation and basal melting, respectively, and $\frac{\partial H}{\partial t}$
143 is the change in ice thickness over time. The normalized vertical velocity profile, ω , is given as a
144 function of the normalized coordinate derived from Parrenin and Hindmarsh (2007), and Lliboury
145

146 (1979):

147
$$\omega(\zeta) = 1 - \frac{p+2}{p+1}(1 - \zeta) + \frac{1}{p+1}(1 - \zeta)^{p+2}, \quad (3)$$

148 where ω is 1 at the surface and 0 at the base. Hence, in the case of steady state, $\frac{\partial H}{\partial t} = 0$, the vertical
149 velocity of the ice at the surface and base equates to $-M_s$ and M_b , respectively. The shape of ω with
150 different p parameters is demonstrated in Fig. 2, indicating that a larger p -value yields a larger
151 downward ice velocity. Compared with Fischer et al. (2013), who used a different formulation of the
152 vertical velocity profile with an m parameter (similar role as p of this study) of $m = 0.5$ (Fig. 2
153 dashed lines), $p = 3$ from Equation (3) gives a different vertical temperature profile, with a smaller
154 vertical velocity, particularly near the base of the ice.

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

157
$$\frac{\partial T}{\partial t} = -w \frac{\partial T}{\partial z} + \frac{1}{\rho_I c_p} \frac{\partial}{\partial z} \left(\kappa \frac{\partial T}{\partial z} \right), \quad (4)$$

158 where T is the temperature of the ice [K], κ is the thermal conductivity, ρ_I is the ice density, and c_p is
159 the heat capacity of the ice. The density of ice is set as a constant (910 kg m^{-2}), i.e., we ignore the
160 effects of lower density in the firn column. The strain heating term is neglected in the present study,
161 given that deformation of the ice would be minor near Antarctic domes because of very low
162 horizontal shear. The thermal conductivity and specific heat capacity of the ice are functions of
163 temperature (Greve and Blatter, 2009, following Ritz, 1987):

164
$$\kappa = 9.828e^{-0.0057T} \text{ W m}^{-1} \text{ K}^{-1}, \quad (5)$$

165
$$c_p = (146.3 + 7.253T) \text{ J kg}^{-1} \text{ K}^{-1}, \quad (6)$$

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

170
$$\frac{\partial T}{\partial z} \Big|_b = -\frac{G}{\kappa} \text{ if no melting,} \quad (7)$$

171
$$T_b = T_{pm} \text{ if melting,} \quad (8)$$

172 where G is the geothermal heat flux (GHF) at the ice–bedrock boundary, and T_{pm} is the pressure-
173 melting point of the ice, which is given as a function of depth using a Clausius–Clapeyron gradient
174 ($8.7 \times 10^{-4} \text{ K m}^{-1}$). The basal melting rate at the ice–bedrock interface is determined by the
175 conservation of heat:

176
$$M_b \rho_I L = G - \kappa \frac{\partial T}{\partial z}, \quad (9)$$

177 where L is the latent heat of the ice (335 kJ kg^{-1}), and $\frac{\partial T}{\partial z} \Big|_b$ is the temperature gradient at the
178 ice–bedrock interface. This model assumes basal melting only occurs at ice–bedrock interfaces, and
179 the temperature gradient at the ice–bedrock interface is calculated using a one-sided difference
180 discretization. The calculated basal melting rate M_b influences the velocity field according to
181 Equation (2). The model in the present study forecasts temperature in the bedrock, and thus the GHF
182 at the ice–bedrock interface has temporal variations. The bedrock is 3000 m thick divided vertically
183 into 17 equal layers; constant physical parameters are used for the bedrock (density = 2700.0 kg m^{-3} ,
184 heat capacity = $1000.0 \text{ J kg}^{-1} \text{ K}^{-1}$, and heat conductivity = $3.0 \text{ W m}^{-1} \text{ K}^{-1}$), used in Parizek and Alley
185 (2004).

186 We adopted different vertical resolution setups in computations of the temperature and age
187 of the ice. The ice profile was discretized with 101 even vertical layers for thermodynamics; it was
188 discretized with 2661 unevenly spaced vertical layers (finer near the base to resolve the thin layers of
189 old ice) for age calculations, which was optimized following Saito et al. (2020). In the typical ice
190 column thickness of 3000 m near DF, the vertical resolution was set to approximately 20 m near the
191 surface and 20 cm near the bedrock, which is sufficient to resolve paleoclimate information

192 (glacial–interglacial annual layer variations) of ~ 1 ka. We used the rational function-based
 193 constrained interpolation profile (RCIP) scheme in the advection equation for the numerical scheme,
 194 as in Saito et al. (2020). One significant advantage of this scheme is the avoidance of numerical
 195 diffusion and ability to reasonably preserve the time derivative of age, which is critical to the
 196 resolution of old ice. We have tested the sensitivity to the vertical resolution of temperature
 197 calculation and found that using fine vertical resolution leads to the formation of a temperature
 198 inversion layer in the bottom of the ice, which can be a significant error in estimating basal
 199 temperature gradient and basal melting. Therefore, we set the number of vertical layers of the model
 200 for thermodynamics as 100 (each approximately 30 m thick) to prevent the representation of
 201 temperature inversion layers. The time steps of the calculation of temperature and age were set to 20
 202 years.

203

204 **3. Model calibration using DF age and temperature profiles**

205 **3.1. Experimental design**

206 This section applies the 1-D model to DF under a realistic climate history for model
 207 calibration and parameter constraint. Parrenin et al. (2007) determined the p -value as ~ 3.7 for DF,
 208 but the chronology of ice older than 335 ka BP was not established at that time; therefore, we
 209 revisited DF to determine the p -value covering the entire DF ice core age–depth dataset. The
 210 glaciological boundary conditions at DF are summarized in Table 1: we used an ice thickness of
 211 3028 m, a present-day SMB of 30 ice equivalent mm a^{-1} (equivalent to 27.3 freshwater mm a^{-1} ,
 212 based on Kameda et al., 2008 and Fujita et al., 2011), and a mean ice surface temperature at present
 213 of -55.5 °C. We determined the boundary condition of ice surface temperature by calibrating the
 214 temperature profile to be consistent with measured temperature profiles of the top 500 m of the ice,
 215 within uncertainty ranges of the observations. The observed present-day 10-m-depth annual mean
 216 snow temperature is -57.3 °C (Kameda et al., 1997), which was also used in Parrenin et al. (2007).
 217 We note that the annual mean surface air temperature (SAT) based on meteorological observations
 218 was -54.4 °C during the period 1995–1997 (Yamanouchi et al., 2003).

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

$$224 \Delta T_s = \alpha(\beta - \delta^{18}O), \quad (10)$$

225 where $\delta^{18}O$ is the benthic marine oxygen isotope value [‰]; we set $\alpha = 4.5$, and $\beta = 3.23$
 226 to scale the amplitude of the glacial cycles, which generated a time series of temperature change over
 227 the last 2 Ma, as shown in Fig. 3a. We used past SMB as a function of temperature anomaly
 228 compared with the present day following Huybrechts and Oerlemans (1990), which is based on
 229 saturation vapor pressure:

$$230 a(t) = a(\text{ref}) \cdot \exp\left\{22.47 \left[\frac{T_0}{T_f(\text{ref})} - \frac{T_0}{T_f(t)} \right] \right\} \left\{ \frac{T_f(\text{ref})}{T_f(t)} \right\}^2, \quad (11)$$

231 where $a(t)$ and $a(\text{ref})$ represents past and present SMB rates, respectively. $T_0 = 273.16$ K is
 232 the triple point of water, and T_f is the atmospheric temperature above the inversion layer as a function
 233 of surface temperature (T_f [K] = $0.67T_s$ [K] + 88.9). From this function, an increase in surface air
 234 temperature of 1 °C increases SMB by approximately 7% (Fig. 3b). At the Last Glacial Maximum
 235 (LGM, approximately 20 ka BP), when SAT was 8 °C cooler, the SMB was approximately 60% of
 236 that of the present day, which is consistent with reconstructions based on the isotopic content of the
 237 ice (Parrenin et al., 2016). This relationship between SAT and precipitation changes used herein was
 238 within uncertainties estimated from observations and climate model simulations, following a
 239 summary by IPCC AR6 (Chapter 9.4.2.3; Fox-Kemper et al., 2021), which used the studies of
 240 Bracegirdle et al. (2020) and Frieler et al. (2015). Although this relationship is not based on SMB,

241 but rather on precipitation, herein we assume the precipitation change ratio is the same as that of the
 242 SMB. The other boundary conditions (ice thickness and GHF) were set as constants in the present
 243 study.

244 We used a result of transient simulation obtained by a 3-D ice sheet model IcIES, which
 245 computes dynamics and thermodynamics of ice sheets using the shallow-ice approximation to
 246 simulate past ice thickness history. The experimental design was similar to that of Saito and Abe-
 247 Ouchi (2004, 2010) with some changes; the domain of the 3-D model was the whole Antarctic
 248 continent, and the horizontal resolution was set to 32 km. The spatial distribution of the GHF was
 249 from Martos et al. (2017). The model was initialized using the present-day condition, and forced by
 250 the same temperature and SMB changes as those of the 1-D model forcing for the past 2 Ma (Fig. 3a).
 251 The migrations of the grounding lines were not forecasted, instead the positions of grounding lines
 252 were fixed to the present day. We note that the advancement of grounding lines during glacial
 253 periods has a minor impact on the ice thickness, in particular around the DF region, compared with
 254 the changes in climate forcing (Saito et al., 2010). We extracted the history of changes in the ice
 255 thickness at DF and EDC, which showed that the ice thickness was reduced by ~ 200 m during glacial
 256 periods, mainly because of reduced SMB (Fig. 3c).

257 Using this set of boundary conditions, we conducted simulations with different GHFs
 258 ($50\text{--}70$ mW m $^{-2}$) to calibrate the model with observed values at the DF ice core. We used the
 259 depth–age profile of the DF ice core, which was constructed by orbital tuning of a gas record above
 260 ~ 2500 m, and by matching to the AICC2012 chronology below that depth (Kawamura et al., 2017).
 261 We also used the measured depth–temperature profiles from the JARE54 surveys conducted during
 262 the 2012–2013 Antarctic summer (Buizert et al., 2021). The model was initialized with the
 263 conditions of 2 Ma BP, where the initial age and temperature were set to 0 years and -10 °C,
 264 respectively, for the entire ice column. All experiments were integrated for 2 Ma to reach the present
 265 day; therefore, the age of any ice older than 2 Ma did not appear in the experiments. These simplified
 266 initial conditions generated unrealistic temperature fields in the early stage of the simulation, but
 267 realistic glacial cycle forcing prevailed over the entire ice column within approximately 100 ka.
 268 Therefore, we mainly analyzed the results of the last 1.5 Ma, which is sufficient to discuss old ice in
 269 this study. Furthermore, we also applied this model to the conditions at EDC to check whether the
 270 model could simulate the observed temperature and age profiles at this location (Table 1).

271 We also conducted three sensitivity experiments to investigate the impacts of the p
 272 parameters, uncertainty in the amplitude of past temperature changes, and inclusion of past ice
 273 thickness changes, respectively. We found that $p = 3$ gave one good age profile when compared with
 274 the ice-core data; hence, we set $p = 3$ as the reference in Sect. 3. The uncertainty in the past
 275 temperature change was based on a study that proposed that the temperature change at the LGM in
 276 interior regions of the East Antarctic ice sheet was less than previously estimated (Buizert et al.,
 277 2021). We conducted a set of experiments where SAT anomalies were set to 0%, 25%, 50%, and
 278 75% of the standard experiments, while keeping changes in SMB the same.

279

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

280 **Table 1:** List of parameters used in Sect. 3. Ice thickness (DF and EDC), surface mass balance rate,
 281 and surface temperature at EDC come from Parrenin et al. (2007); surface mass balance rate at DF
 282 comes from Kameda et al. (2008) and Fujita et al. (2011); surface temperature at DF is calibrated in
 283 this study and is within previously observed ranges (Kameda et al., 1997; Yamanouchi et al., 2003).

284

285 3.2. Results for DF

286 In Fig. 4, the simulated temperature profiles at 0 ka (end of the simulations) with different
287 GHFs under the same p -value ($p = 3$) are compared with observations (Fig. 4a). The close-up of the
288 bottom 120 m of the ice column is shown in Fig. 4b; the basal temperature was well below melting
289 point with a GHF of 54 and 56 mW m^{-2} , and at the melting point with a GHF $> 58 \text{ mW m}^{-2}$.
290 Compared with the observed temperature profile (Fig. 4, black lines), the simulated temperature near
291 the ice base was colder by approximately 1 °C. In all simulations, the simulated temperature profiles
292 were generally colder than observed temperature profiles, especially in the middle of the ice columns
293 (Fig. 4a). The generally colder temperature of the ice may have several explanations. One is related
294 to the pressure melting point of the ice. We used a pressure melting point of ice that depended only
295 on local pressure, but there is also a dependence on the impurities and air content of the ice (e.g.,
296 Parrenin et al., 2017; Passalacqua et al., 2017). A second explanation is related to the uncertainty in
297 vertical velocity of the ice parameterized with p because a larger vertical advection contributes to a
298 colder ice temperature.

299 The time series of simulated basal ice melting rates over the last 500 ka show that there have
300 been significant temporal changes in these rates over time (Fig. 5a). With a GHF of 54 mW m^{-2} , the
301 temperature at the ice base has been below the melting point through the last 500 ka. In contrast, in
302 the case of a GHF of 56 mW m^{-2} , the basal melting rate is zero at 0 ka, while the maximum basal
303 melting rate of 1 mm a^{-1} occurs at the later stages of interglacial periods (e.g., 100 ka BP). This
304 temporal variation in basal melting rate is caused by glacial-cycle forcing in SAT and SMB, and
305 minimum basal melting tends to occur at the end of glacial periods as it lags SAT. This result is
306 broadly consistent with previous studies (Saito and Abe-Ouchi, 2004; Van Liefferinge et al., 2018) in
307 that colder ice, which accumulated during glacial maximums, advects towards the ice base owing to
308 an increased SMB during interglacials. A larger GHF ($\geq 60 \text{ mW m}^{-2}$) results in basal melting
309 occurring most of the time, with an increase in basal melting rate of approximately 1 mm a^{-1} for
310 every 5 mW m^{-2} increase in GHF.

311 The simulated age profiles at the present day are compared with the ice core-based profiles
312 in Fig. 6a. With a small GHF (54 mW m^{-2}) where basal melting does not occur, the ice age at the
313 ice–bedrock interface is $> 1.5 \text{ Ma}$. In contrast, if basal melting occurs, the ice age at the ice–bedrock
314 interface can be much younger; for example, 761 or 620 ka for a GHF of 60 or 62 mW m^{-2} ,
315 respectively. The result obtained with a GHF of 60 mW m^{-2} exhibits the closest fit to the data in
316 terms of the age of ice at the base of the ice column. In this article, we define the “resolution of age”
317 (ka m^{-1}) as the inverse of annual layer thickness as an indicator of sufficient resolution for the
318 chemical and isotopic contents of the ice (Lilien et al., 2021). In Fig. 6b, the resolution of old ice is
319 compared with the actual DF ice core. The model results largely reproduced the glacial–interglacial
320 contrasts in annual layer thickness caused by the temporal variations of SMB at this locality. The
321 observed resolution of age was approximately 0.5–1 ka m^{-1} near the base of the ice core, and the
322 model results using a GHF of 60 mW m^{-2} reproduced similar values. Furthermore, in a scenario with
323 no significant basal melting, the annual layer thickness of 1.5 Ma BP ice is approximately 0.1 mm
324 because 1.5 Ma ice appears directly above the bedrock (Fig. 6b, dark blue lines). In accordance with
325 the results described above, a larger GHF tends to result in a higher basal melting rate and younger
326 age of ice at the base of the column. One critical point is that an excessive GHF (i.e., an increase of
327 the order of 2 mW m^{-2}) can have a considerable effect on the age of the ice and the likelihood of old
328 ice.

329 **3.3. Results for EDC**

331 We also applied this model using the conditions at EDC to enable performance checks at an
332 additional location. We used the parameters listed in Table 1 and conducted sensitivity experiments
333 with different GHFs. For the vertical velocity profile, we used $p = 2.3$ following Parrenin et al.
334 (2007). The model generally resulted in colder temperatures compared with observations, similar to
335 that found at DF (Fig. 7). We note that the pressure melting point of the ice depended only on local

336 pressure in Fig. 7, but several studies have considered the pressure melting point of the ice as a
337 function of the pressure and air content of the ice, which has shown that the basal temperature is at
338 the pressure melting point (Buizert et al., 2021). Modeling using a GHF of 56 mW m^{-2} gave a basal
339 ice age of approximately 800 ka (Fig. 8a), which is similar to the value (802 ka) presented in Veres et
340 al. (2013), and the resolution of age closely fits the chronology estimated from ice-core analysis (Fig.
341 8b). One important result is that the threshold of GHF that allows basal melting is 4 mW m^{-2} lower at
342 EDC compared with DF. This lower GHF can be attributed to the combination of larger ice thickness,
343 smaller SMB, and higher SAT at the present day. The estimated GHF at EDC is smaller than that
344 given by Parrenin et al. (2017), who estimated it to be 60 mW m^{-2} . This difference can be attributed
345 to the difference in the history of basal melting, or the application of past climate history derived
346 from DF to EDC. The results from the application of our model to EDC suggest that it may be
347 applicable to different glaciological conditions, particularly different ice thicknesses and SMBs.

348

349 **3.4. Sensitivity to vertical velocity profiles, temperature amplitudes, and ice thickness changes**

350 Next, we evaluated the sensitivity of the temperature and age profiles to different vertical
351 velocity profiles, temperature amplitudes, and ice thickness changes over glacial cycles. In Fig. 9,
352 results using different p -values under an identical GHF (60 mW m^{-2}) are compared. A larger p -value
353 induced a lower basal melting rate because of a larger vertical velocity and downward advection of
354 cold ice from the surface, although this only had a minor impact on the temperature profile. The
355 simulated age profiles indicate that a larger p -value induces a younger age of ice at mid-depths
356 within the ice column (Fig. 9b), which is also a result of a larger vertical velocity. The age of the ice
357 at the base of the column was approximately 800 ka BP in all five of the variable p -value simulations,
358 partly because of the compensating effects of greater advection and less basal melting.

359 The results using DF conditions with different amplitudes of temperature change but constant
360 GHF and p parameters (GHF = 60 mW m^{-2} and $p = 3$) are summarized in Fig. 10. Here, we changed
361 the α -value in Equation 10 (1 is the control case). In the smallest amplitude experiment ($\alpha = 0$), the
362 temperature was set to the interglacial level and did not change in time. Note that the SMB variation
363 was the same in all sensitivity experiments. The control experiments exhibited colder ice
364 temperatures near the middle of the ice column compared with observations, and this cold bias was
365 reduced when a smaller temperature amplitude over the glacial cycles was used (Fig. 10a), broadly
366 consistent with Buizert et al. (2021). A smaller amplitude of the glacial cycle resulted in a younger
367 age of ice at the bottom of the ice column (Fig. 10b) because of larger basal melting rates (Fig. 10c).
368 This is because the mean temperature over the glacial cycles increases if the temperature amplitude
369 of glacial–interglacial cycles is reduced. The results using a fixed surface temperature ($dTs = 0.0$)
370 corresponded to the same present-day SAT for the last 2 Ma, which induced basal melting of ~ 1.5
371 mm a^{-1} during most of this time. A slight fluctuation in basal melting still occurred owing to time-
372 dependent SMB.

373 The results without ice thickness changes did not impact temperature profiles at the present-
374 day (Fig. 11a), but impacted the history of basal melting (Fig. 11c). The mean basal melting rates at
375 constant GHF can be reduced if ice thickness changes are included because the reduced ice thickness
376 during glacial periods decreases the pressure-melting point. Moreover, the inclusion of ice thickness
377 changes affects the phase of basal melting rates because it reflects the reduction in ice thickness and
378 pressure-melting point at the base of the ice during glacials. The minimum in basal melting during
379 the last glacial cycle occurs at the end of the LGM in the control experiment; in contrast, it occurs at
380 the present-day in the no ice thickness change scenario. The absence of ice thickness changes results
381 in larger mean basal melting rates and a younger age of ice at the base of the ice column (Fig. 11b).
382 These results suggest that the basal melting rate in the past can be larger than the present-day rate.

383

384 **3.5. Summary of Sect. 3**

385 On the basis of the results described in this section, we conclude that using a combination of

386 $p = 3$ and $\text{GHF} = 60 \text{ mW m}^{-2}$ gives reasonable temperature and age profiles. Therefore, we decided
 387 to use these values as calibrated parameters for the DF region; this was performed for the following
 388 reasons. Later in the article, we investigate the possibility of old ice in the DF region using different
 389 parameters of ice thickness and GHF because glaciological surveys have suggested that there are
 390 spatial variations in these parameters (e.g., Carson et al., 2013). Hence, obtaining precise tuning at
 391 one specific DF location is unnecessary. In this study, we calibrated the GHF under a vertical
 392 velocity profile of $p = 3$, but calibrating the model with the combination of an uncertain GHF and
 393 vertical velocity profile is possible. According to the age profile, the results with $p = 3$ may not
 394 necessarily be the best because the simulated age profile tends to underestimate the age of ice,
 395 particularly 500 m above the bedrock. Therefore, we do not state that a GHF of 60 mW m^{-2} is a
 396 single best estimate for the DF location compared with previous estimates (Burton-Johnson et al.,
 397 2020; Talalay et al., 2021) because there were assumptions made in the vertical velocity profiles and
 398 experimental design of this study. Furthermore, the calibrated GHF has some dependence on the
 399 uncertainty in temperature and ice thickness changes over the glacial cycles.

400

401 **4. Sensitivity studies using various parameters around DF**

402 **4.1. Experimental design**

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

409

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

410 Table 2: List of experiments in Sect. 4.

411

412 **4.2. Results**

413 In Fig. 12a, the relative effects of ice thickness and GHF on basal temperature are compared,
 414 using a constant SMB (30 mm a^{-1}). As in Sect. 3, we used an ice thickness of 3028 m, which is
 415 comparable to that at DF, and a GHF for basal melting of 60 mW m^{-2} . On the basis of the gradient of
 416 contours in Fig. 12a, an increase in ice thickness of 100 m has a comparable impact on the basal
 417 temperature as does an increase in GHF of 2 mW m^{-2} . In Fig. 12b, the relative effects of ice
 418 thickness and SMB are compared using a constant GHF (60 mW m^{-2}). A larger SMB results in a
 419 colder temperature; a 10% change in GHF leads to a $\sim 4 \text{ }^\circ\text{C}$ change in the basal temperature, while a
 420 10% change in SMB leads to a $\sim 1 \text{ }^\circ\text{C}$ change. These results are generally consistent with those of
 421 Fischer et al. (2013), and suggest that the spatial distribution of SMB ($\sim 20\%$ for the DF area) has a
 422 minor impact on the basal temperature compared with that of the ice thickness.

423 We further investigated the impact of different ice thicknesses on age profiles using the
 424 climatic conditions at DF (SMB = $30 \text{ ice equivalent mm a}^{-1}$) and a calibrated GHF (60 mW m^{-2}).
 425 Figure 13a shows the simulated age of the ice at 50 and 100 m above the ice–bedrock interface,
 426 which were used as indicator depths for potential coring sites by Fischer et al. (2013). The results
 427 indicate that the rate of aging of ice decreases with ice thickness between 2800 and 3200 m owing to
 428 the occurrence of basal melting. Note that the age of 2 Ma BP is the limit of the experiments, and the
 429 results indicate that the old ice exists 50 m above the bedrock if the ice thickness is thicker than
 430 $\sim 2100 \text{ m}$. Figure 13b shows the age resolution of the 1.5 Ma BP ice, indicating that a larger ice
 431 thickness tends to show a finer age resolution. The vertical age profiles and resolution of ice ages at

432 five selected ice thicknesses with constant GHF are shown in Fig. 14. According to Figure 14b, the
433 expected age resolution of 1.5 Ma ice is approximately 10 ka m^{-1} with an ice thickness of 2800 m,
434 and 20 ka m^{-1} with a smaller ice thickness of 2200 m.

435

436 **5. Application to the DF–NDF transects**

437 **5.1. Experimental design**

438 In this section, we apply the 1-D model to interpret the internal layers of the ice near DF
439 under idealized boundary conditions. Here, we used the dataset from 17 December 2017 obtained by
440 ground surveys during JARE59 (2017–2018), which comprises a 54 km-long transect from DF to
441 NDF (Fig. 1). The horizontal axis of Fig. 15 indicates the distance from DF, and the vertical axis
442 indicates the depth from the surface. The gray shading indicates the reflectivity, which is an indicator
443 of contours representing ice of the same age. The bedrock elevation, shown by brown lines, was
444 detected based on the maximum reflectivity from the base (Tsutaki et al., 2022). The bedrock
445 elevation was calibrated to match the observed bedrock elevation at DF. We calculated the 1-D age
446 and temperature profiles of the ice at approximately 400 m intervals along the transect. We assumed
447 that the vertical profile of vertical velocity could be determined locally, and that there were no
448 horizontal interactions in temperature and age in this simulation. The present-day SMB was linearly
449 interpolated between DF ($30 \text{ ice equivalent mm a}^{-1}$) and NDF ($25.5 \text{ ice equivalent mm a}^{-1}$). Note
450 that the estimated SMB at NDF is 13% smaller than that at DF based on shallow ice cores (Oyabu et
451 al., 2023). Because only very limited information on the spatial distribution of GHF is available, we
452 set a uniform value of 60 mW m^{-2} following the discussion in Sect. 3. As described in Sect. 3, the
453 initial age of the ice was set to 0, the temperature set to $-10 \text{ }^\circ\text{C}$, and the model was integrated over
454 the last 2 Ma of forcing until it reached the present day (Fig. 3).

455

456 **5.2. Results**

457 In Fig. 15, the computed vertical profiles of the age are overlaid on a radargram using seven
458 selected ages (colored lines), and the simulated basal temperature is indicated by shading in the
459 bottom panel. The colored bar below the radargram indicates the simulated present-day basal
460 temperature. The simulated distribution of ice age captured large-scale features in the black–white
461 contour lines derived from the radargram signal (grayscale color in Fig. 15). The simulated age
462 contours of 21 ka BP (approximately 500 m depth) and 128 ka BP (approximately 1500 m depth) can
463 be traced from DF, although the deepest horizon corresponding to an age older than 300 ka BP is
464 hard to see in this image. Where ice is relatively thick (e.g., 20–25 km from DF), the simulated age
465 of the ice at the ice–bedrock interface is younger than 700 ka BP, while ice older than 1.5 Ma BP
466 occurs where the ice is relatively thin. On the basis of the results shown in Fig. 13b, we note that thin
467 ice gives a poorer age resolution for the old ice. A comparison of the simulated ice age and
468 radargram signal gives an opportunity to examine the validity of the model results. For example,
469 between 5 and 35 km from DF, the computed 128 ka BP contour deviates to shallower levels (by 150
470 m) compared with the traced horizon for the age obtained from the radar measurements, suggesting
471 that the model overestimates the age of the ice near the bedrock in such locations.

472

473 **6. Discussion**

474 In this study, we used a 1-D ice-flow model, which computes the temporal evolution of age
475 and temperature profiles. We used glaciological conditions at DF to tune some unknown parameters
476 according to the observed temperature and age profiles. The results showed that the age profile is
477 sensitive to the choice of GHF, but one experiment using a specific combination of GHF and vertical
478 velocity profile exhibited reasonable temperature and age profiles (Figs 4 and 6). One important
479 result is that the melting rate at the base of the ice exhibits temporal changes associated with
480 glacial–interglacial forcing. This is caused by relatively cold ice deposited during glacial periods
481 being pushed towards the bottom of the ice column by increased SMB and downward advection

482 during interglacial periods, as shown in previous studies (e.g., Van Liefferinge et al., 2018). This
483 point is critical for preserving old ice because basal melting rates during past interglacials can be
484 higher than that of the present day (Fig. 5). Our sensitivity experiments highlighted the relative
485 effects of ice thickness and GHF, whereby a small GHF excess above the condition that induces
486 basal melting can result in a considerable reduction in the age of ice at the ice–bedrock interface (Fig.
487 6a). Below, we discuss the limitations of the interpretations of our results, their relevance to previous
488 ice-flow modeling studies, and uncertainty factors.

489 On the basis of data presented in Fig. 6, a GHF of 60 mW m^{-2} sufficiently explains the
490 observed temperature and age–depth profiles of the DF ice core. However, there is considerable
491 uncertainty in the estimation of the actual GHF value at DF because of some simplifications in the
492 model experiments and limited representations in physics. One point of difference is that the model
493 tends to give a generally colder temperature profile compared with the observations (Fig. 4), which
494 suggests that the model overestimates the GHF threshold of basal freezing. One possible reason for
495 this difference is that the basal melting of ice can occur within a certain ice thickness; the
496 extrapolation of observed temperature profiles at DF and EDC (Figs 4 and 7, black lines) shows that
497 the ice reaches the pressure-melting point approximately 30 m above the bedrock. This feature
498 cannot be simulated in the model of the present study, which assumes that basal melting can only
499 occur at the ice–bedrock interface. These representations in the physics of basal melting can be
500 improved by using enthalpy as a state variable and adopting polythermal ice sheet models (e.g.,
501 Aschwanden et al., 2012). There is also uncertainty in the parameterization of the conductivity and
502 heat capacity of the ice. We use these parameters as a function of temperature, but they can depend
503 on the fabric of the ice, which makes it challenging to estimate them. Hence, these physical
504 parameters can be a source of uncertainty in estimating GHF, and can be a source of difference from
505 other studies. Another important factor in the temperature profiles is the temperature anomaly over
506 glacial cycles, as a smaller glacial–interglacial temperature change tends to result in a warmer, more
507 linear temperature profile compared with the control experiment (Fig. 10a). The surface air
508 temperature change over the last glacial cycle used in this study is based on deuterium and oxygen
509 isotopes (Uemura et al., 2018), which exhibit an LGM temperature anomaly of approximately $8 \text{ }^\circ\text{C}$
510 (Fig. 3a). A recent study proposed that the temperature anomaly at the LGM at DF and EDC was
511 approximately half of previous estimates based on the observed temperature profiles and other
512 independent methods (Buizert et al., 2021). This study is in agreement with Buizert et al. (2021) in
513 that our control experiment exhibits colder ice temperatures, especially at mid-depth within the ice
514 column, and a smaller temperature difference between glacial and interglacial periods improves the
515 modeled temperature profiles (Fig. 10a). If this is indeed the case, the actual threshold of the GHF
516 value for basal freezing should be lower than that used in the control experiment. We also found that
517 if the temperature anomaly is half that of the control case, a GHF smaller than the control value (58
518 mW m^{-2}) gives the closest age profile. We investigated the sensitivity to ice thickness as in Fig. 13,
519 and obtained comparable results in terms of the age near the bottom of the ice column (not shown).
520 These results indicate that several uncertainties (e.g., climate forcing and vertical velocity) can affect
521 the temperature and age profiles under a certain condition, but if we calibrate the GHF with the DF
522 ice-core age profile as in Sect. 3, we obtain comparable results regarding the sensitivity to ice
523 thickness.

524 We note that the simulated age of the ice depends on the shape of the vertical velocity profile
525 of the ice. The formulation of the present study uses a smaller vertical ice velocity, especially near
526 the base, compared with that used in Fischer et al. (2013). Because the age of the ice is related to the
527 inverse of the vertical velocity, a different vertical velocity profile or p parameter can lead to a
528 quantitatively different result. Moreover, vertical velocity profiles represented by a single p -value are
529 merely one assumption; this formulation is derived from a solution of an idealized ice-sheet
530 configuration (Lliboutry, 1979), which may not be the case for realistic ice sheets. For example, the
531 observed magnitude of layer thinning of the DF ice core exhibits a decreasing trend over the bottom

532 500 m (Fig. 6). According to analyses of the DF ice core (Azuma et al., 1999; Saruya et al., 2022) or
533 3-D ice sheet modeling (Seddik et al., 2011), deformation of the ice or flow regime towards the
534 bottom of the ice is complex, suggesting parameterizing vertical velocities is difficult particularly
535 near ice bottom. Improving velocity fields in ice sheet model would be an important issue for future
536 studies

537 We also note that the resolution of 1.5 Ma ice depends on ice thickness. In particular, Lilien
538 et al. (2021) presented similar 1-D ice-flow model results from BELDC (Beyond EPICA Little Dome
539 C, ice thickness of ~ 2765 m) constrained by radar-imaged internal layers and estimated the
540 resolution of 1.5 Ma ice as 19 ± 2 ka m^{-1} . Our results for EDC conditions (with a small enough GHF
541 to keep the base of the ice frozen) have an ice age resolution of approximately 10 ka m^{-1} (Fig. 8,
542 dark blue lines), which is approximately half that of Lilien et al. (2021). This difference can be
543 attributed to the combination of model parameters, such as ice thickness, p of the vertical velocity
544 profile, or SMB history (3233 m and $p = 2.3$ in this study), because the two studies adopted the same
545 formulation of the vertical velocity profile. According to Figs. 13 and 14, a larger ice thickness leads
546 to a better resolution of the ice age if the base of the ice remains frozen throughout time. It is worth
547 mentioning that the approach in ice thickness are different between Lilien et al. (2021) which used
548 ice thickness of 2765 m, including a thickness of a basal unit of ~ 200 m and thus an effective ice
549 thickness of 2565 m. Therefore, the different effective ice thickness (3233 m for EDC) would be the
550 most critical factor for the difference of the age resolution of 1.5 Ma ice when compared with Lilien
551 et al. (2021), who used BELDC conditions.

552 Application of the 1-D model to the transect between DF and NDF provides an opportunity to
553 examine the influence of spatially varying glaciological conditions (e.g., ice thickness and GHF) on
554 the age of the ice. The simulated age–depth distributions with constant GHF but different ice
555 thickness and SMB exhibit general agreement with observed internal horizons (Fig. 15). One
556 noticeable model–data discrepancy occurs at 14–18 km from DF, where the simulated age contours
557 of 128 ka BP are ~ 150 m above the isochrone horizons traced from DF. This model–data discrepancy
558 indicates that the effects of vertical or horizontal advection (Huybrechts et al., 2007; Sutter et al.,
559 2021), or spatial variation of GHF may have contributed to this difference. Although the relative
560 importance of the spatial distributions of GHF, SMB, and horizontal flow is difficult to assess in the
561 present study, we expect that future glaciological data constraints and model developments will
562 better constrain these uncertain parameters and the spatial distribution of old ice. One recently
563 published present-day SMB from the vicinity of the DF region exhibits spatial variabilities reflecting
564 surface topographical features (Van Liefferinge et al., 2021). On the basis of systematic sensitivity
565 experiments (Sect. 4), we have shown that the impact of SMB on the age of the ice is relatively
566 minor compared with that of ice thickness, but the small-scale features present in internal reflection
567 horizons of the ice can be improved by using the spatial distribution of present-day SMB, and this
568 will contribute to the selection of the most suitable drilling site.

569 7. Conclusions

570 We draw the following conclusions from this study:

- 571 1. In experiments using the DF configuration, the model largely reproduced the observed age and
572 temperature profiles under a calibrated GHF. If the GHF is small enough to keep the basal
573 temperature below the melting point, it is expected that ~ 1.5 Ma ice could be present. According
574 to Figs. 14 and 15, the simulated annual layer thickness of ~ 1.5 Ma ice is approximately 0.05 to
575 0.1 mm, which corresponds to 10 to 20 ka m^{-1} . According to IPICS, this is a feasible resolution
576 for analysis with minimized effects of diffusion. This is also true for EDC, but the threshold of
577 GHF for basal melting is different because of a different ice thickness and SMB.
- 578 2. Under the configuration and range of parameters of the present study, the ice thickness has a
579 larger impact on basal melting than does the present-day SMB; an ice thickness difference of
580 ~ 100 m corresponds to an SMB difference of 5 ice equivalent $mm a^{-1}$ (Fig. 12). Near the DF
581

582 region, the ice thickness exceeds such a spatial variability, while SMB does not. Although there
583 is considerable uncertainty in the spatial distribution of GHF, ice thickness is suggested to be
584 one of the most critical factors for the preservation of old ice.

- 585 3. The calibrated GHF in this study, which is based on an ice-core age profile, has uncertainties.
586 The basal melting rate, which is critical to the age of ice near the bottom of the column, is
587 determined by the thermal conditions. The basal melting exhibits temporal variability as a result
588 of glacial–interglacial changes in climate, and the maximum basal melting tends to occur at the
589 end of interglacials. Thus, the basal melting is influenced by climate forcing of past temperature
590 and ice thickness changes, which have uncertainties. Furthermore, a vertical velocity profile
591 parameterized with a uniform p -value can be a source of uncertainty, and may have a limited
592 ability to represent complex ice flow near the bottom of the ice column.
- 593 4. From the simulation of the DF–NDF transect, a small ice thickness and colder basal temperature
594 are the necessary conditions for the presence of old (~1.5 Ma) ice. However, a small ice
595 thickness contributes to a coarser resolution of the old ice (small annual layer thickness), which
596 may make it difficult to extract paleoclimate information on glacial-interglacial times scales. As
597 discussed in Pattyn (2010), ice thickness is found to be a compromising factor in the selection of
598 a drilling site.
- 599 5. The simulation along the DF–NDF transect does not reproduce the depth of the internal layers of
600 the ice corresponding to 128 ka BP at some locations (e.g., at distances 5–35 km from DF),
601 suggesting a possible error in the simulated age of ice near the bottom of the ice column. The
602 simulated age of ice in this area, especially where there is a large discrepancy between the
603 simulation and radar images, could be caused by uncertainties derived from several assumptions
604 or uncertainty in the model or methods, including spatial distributions of GHF, representation in
605 vertical temperature profile that depends only on normalized height (DF ice core suggests
606 complex ice-flow near its base), representation in thermodynamics associated with basal
607 melting, or history of surface temperature changes. Therefore, future improvements in numerical
608 models and methods would contribute to better constraining the age of the ice.

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

614 **Code availability:**

615 The numerical model is available from Github. <https://github.com/saitofuyuki/icies2.git>

616 **Data availability:**

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

621 **Author contribution**

622 T. O., A. A-O., and F. S. conceived the study, developed the numerical model, designed and carried
623 out the experiments, and analyzed the results. T. S., S. F., K. K., and H. M. provided glaciological
624 data from JARE surveys and contributed to the experimental design. T. O. prepared the manuscript
625 with contributions from all co-authors.

626 **Competing interests**

631 The authors declare that they have no conflict of interest.

632

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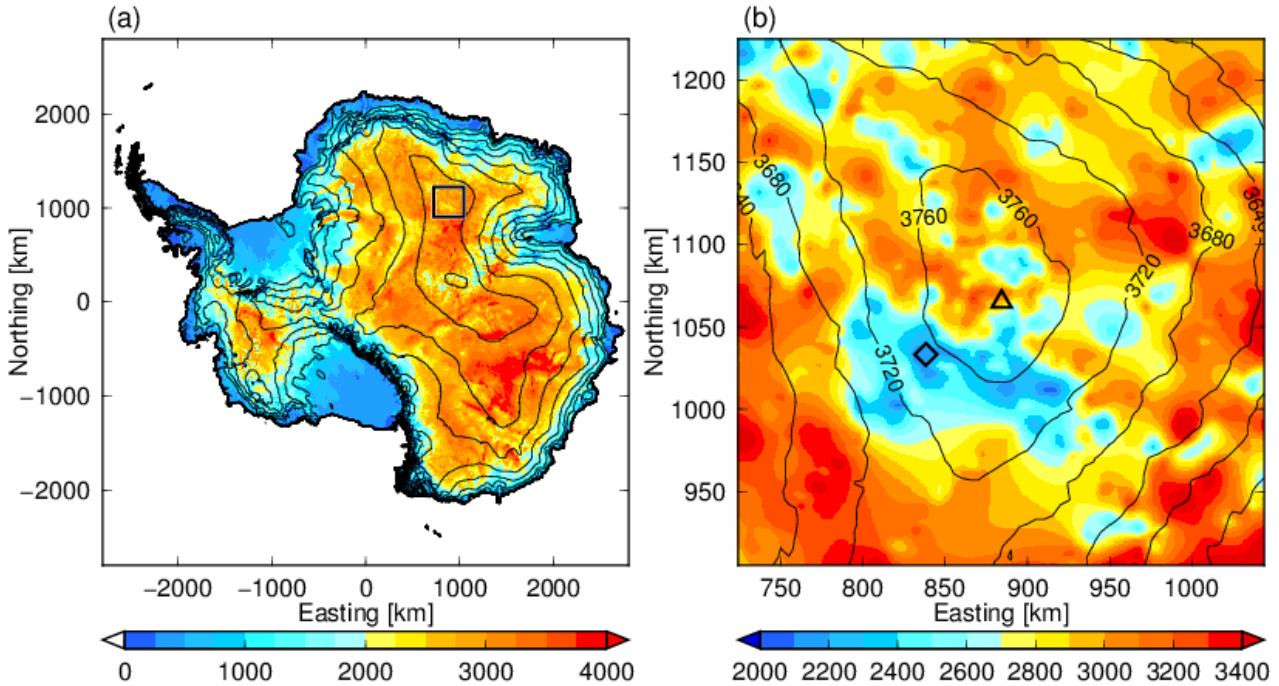
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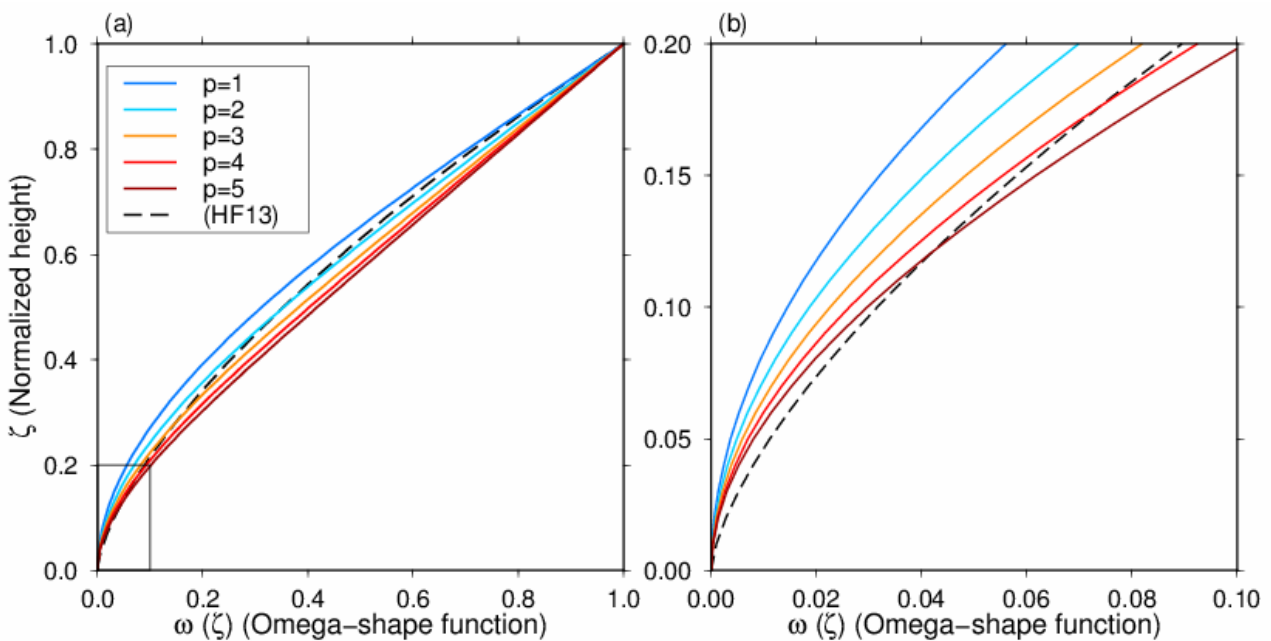
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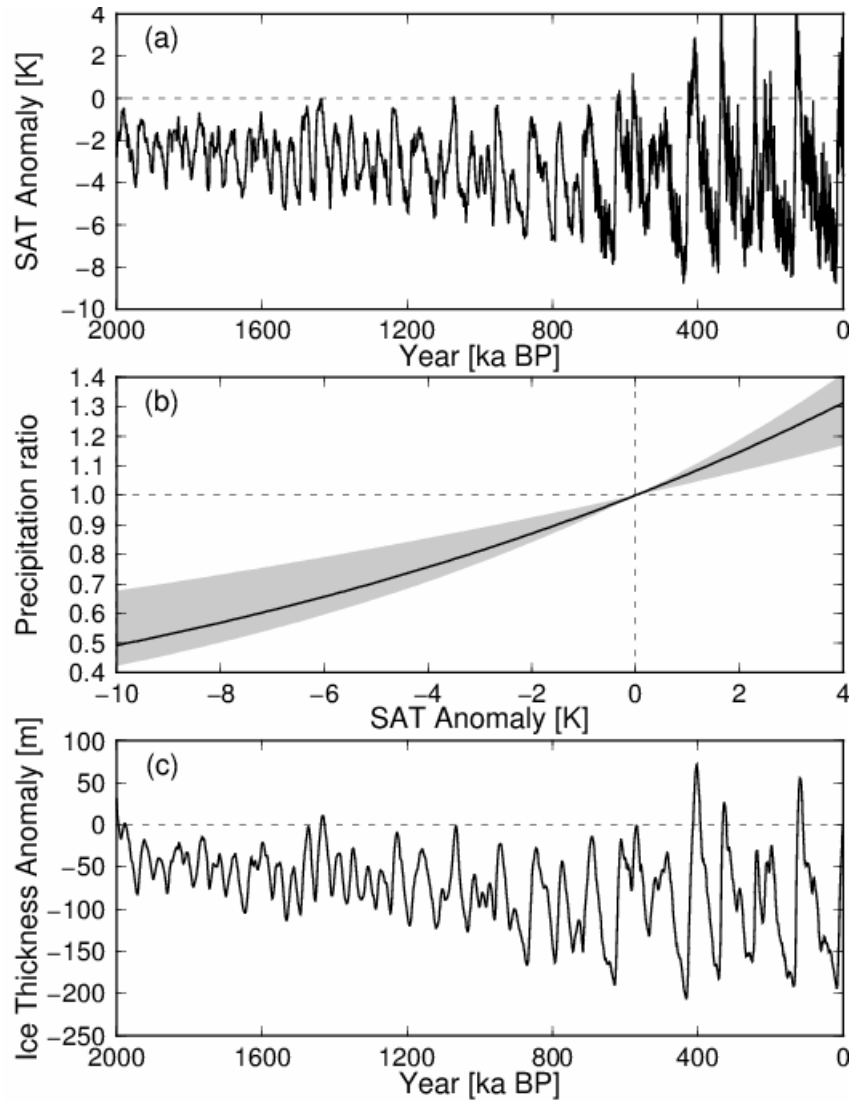
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Fig. 1: (a) Map of Antarctica. The contours (every 500 m) indicate surface elevation, and colors indicate ice thickness, using BEDMAP2 (Fretwell et al., 2013). The square indicates the location of the inset shown in (b). (b) Enlarged view near DF (Dome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

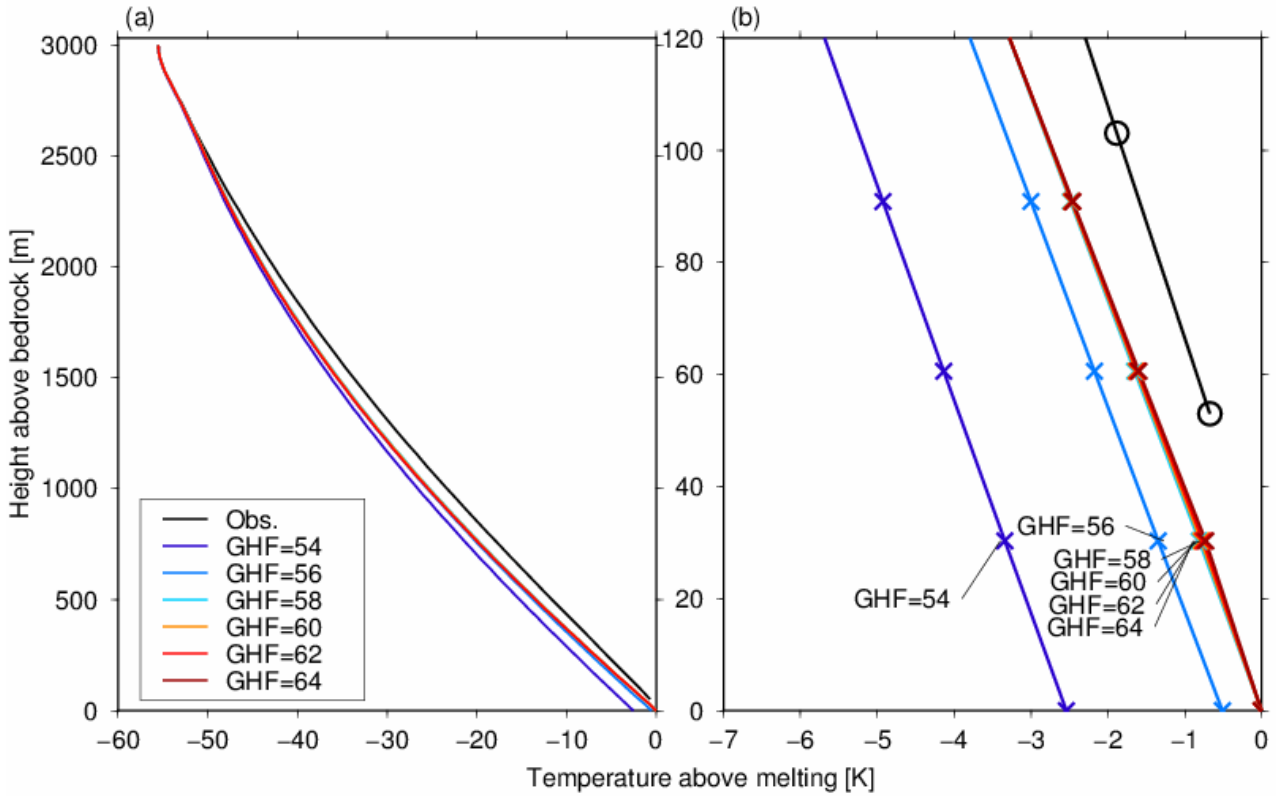


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895 Fig. 2: (a) Normalized vertical velocity profiles adopted from Equation [3] with different p
 896 parameters. The dashed black line (HF13) indicates the vertical velocity profile used in Fischer et al.
 897 (2013) with $m = 0.5$. (b) Enlarged view near the bottom of the ice column (see black rectangle in (a)).
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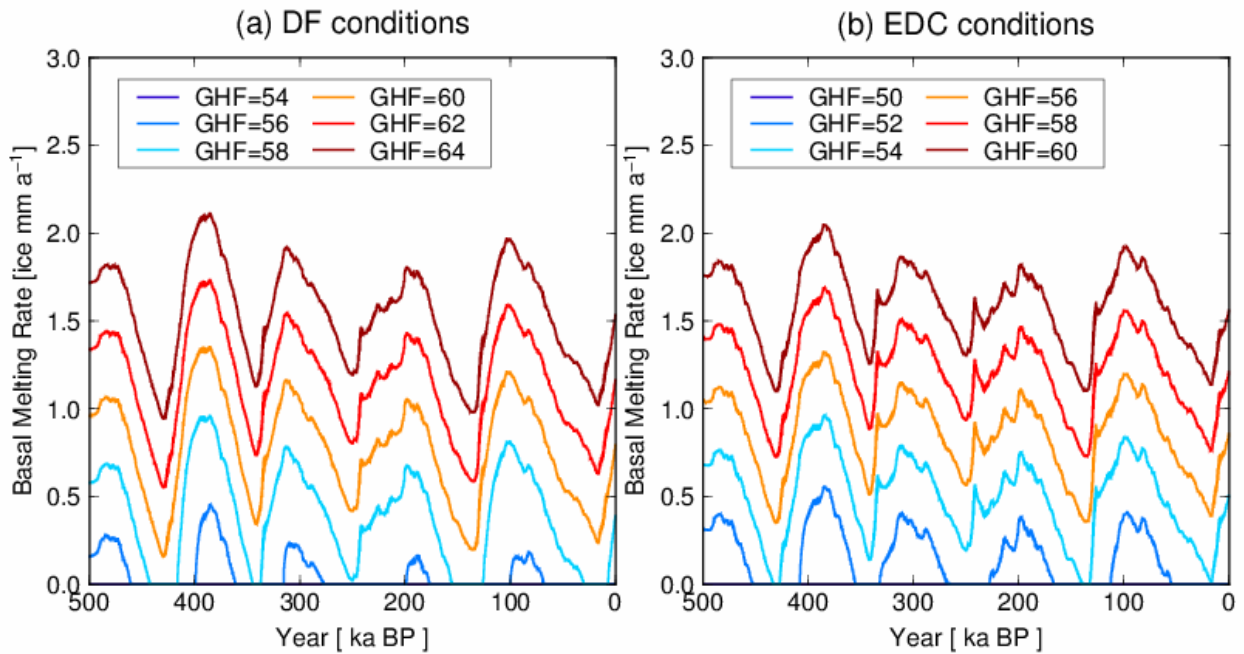


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 901 Fig. 3: Glacial cycle forcing used in the present study. (a) Surface air temperature (SAT) anomaly
 902 from the present day for the last 2 Ma. (b) Relationship between SAT anomaly and precipitation ratio.
 903 The black line corresponds to the relationship used in the present study; the gray shading indicates a
 904 4%–9% increase per degree, summarized in Fox-Kemper et al. (2021). (c) Ice thickness anomaly at
 905 DF from a 3-D ice sheet model in the present study.



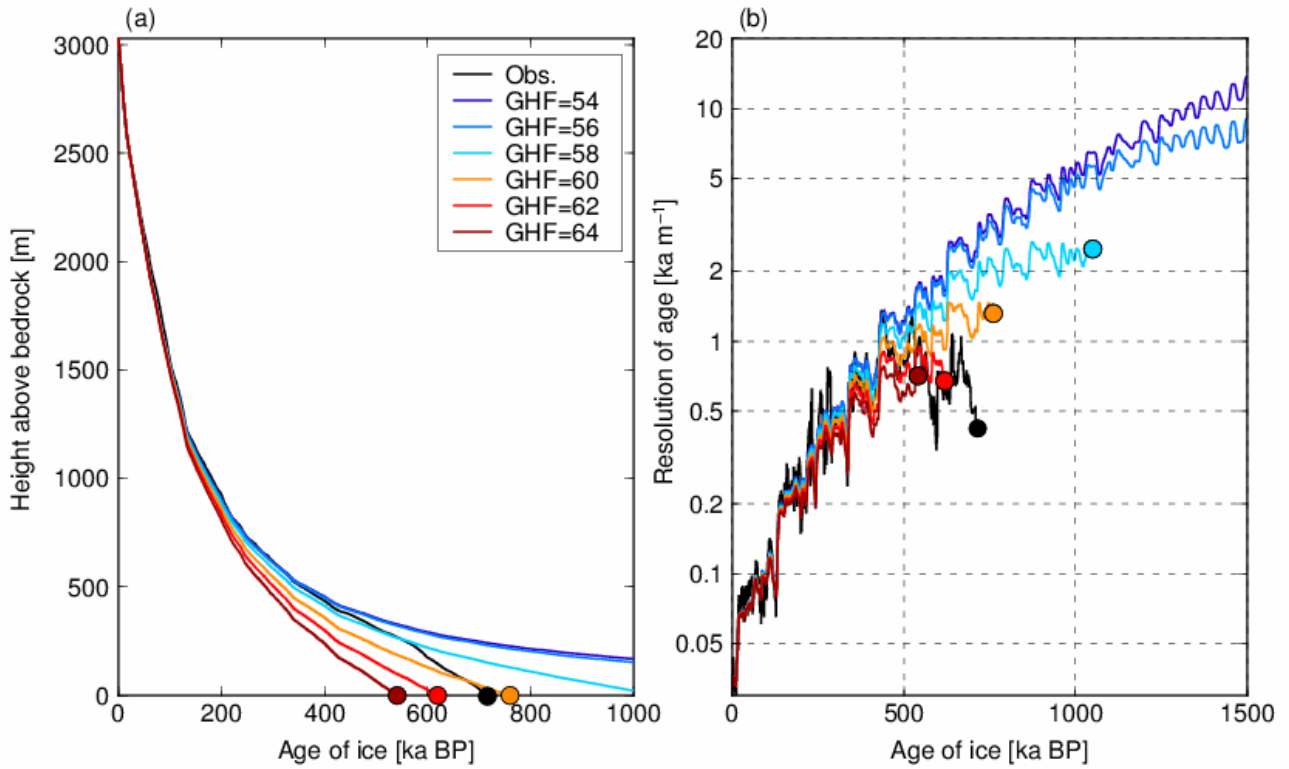
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Fig. 4: Simulated vertical temperature profiles under the DF configuration (Table 1) with different geothermal heat fluxes (GHF; units are mW m^{-2}). (a) Simulated temperature profiles at 0 ka (end of the simulation) from the surface to the base. (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.



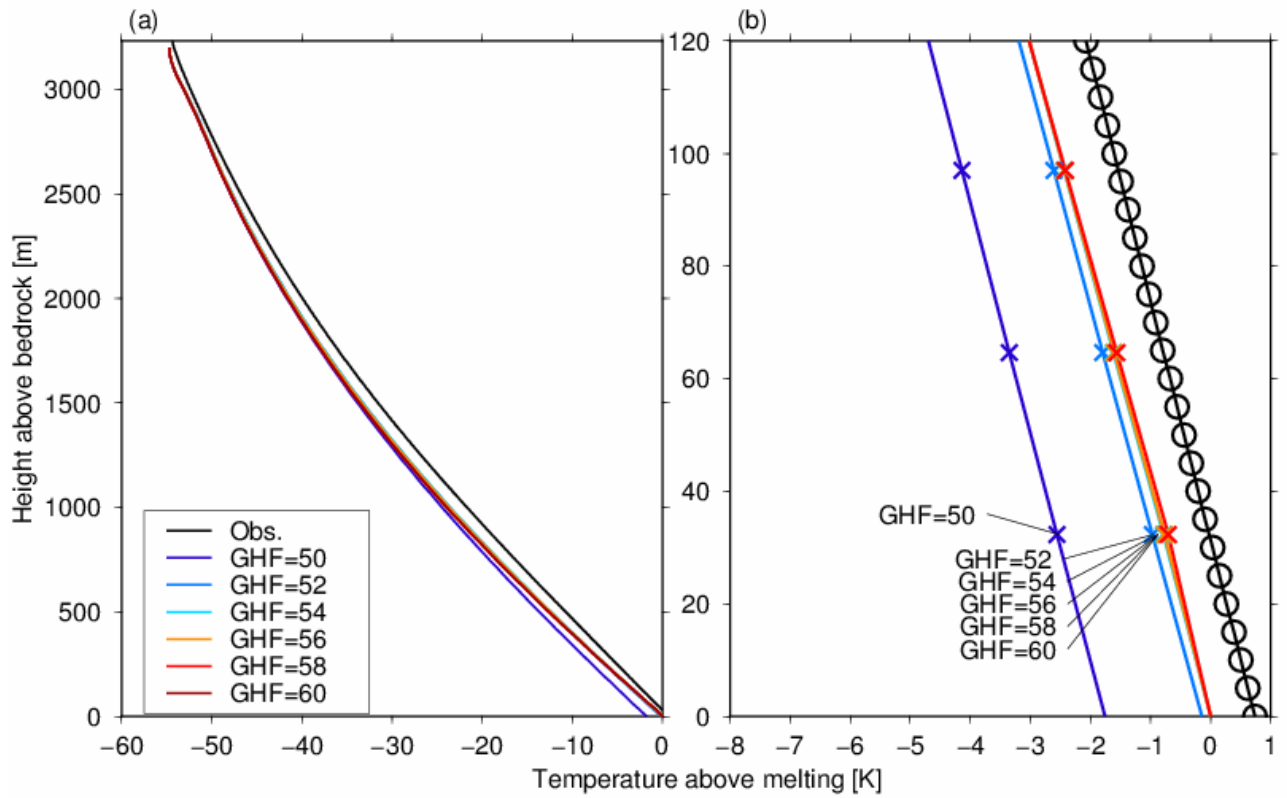
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Fig. 5: Time series of the simulated basal melting rates of the last 500 ka under the DF and EDC configurations (Table 1) with different geothermal heat fluxes (GHF; units are mW m^{-2}).



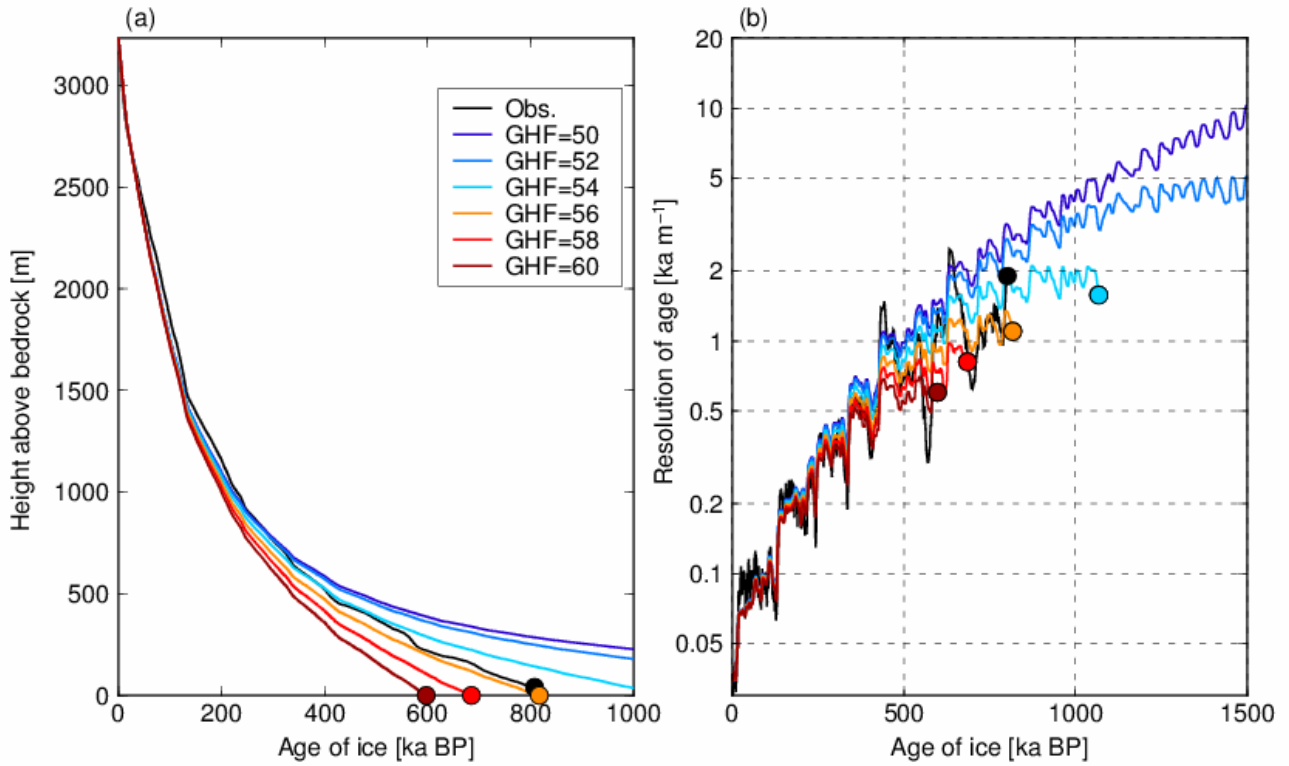
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Fig. 6: Simulated vertical ice age profiles under the DF configuration (Table 1) with different geothermal heat fluxes (GHF; units are mW m^{-2}). (a) Vertical age profiles at present (0 ka). The black line represents the reconstructed depth–age profile 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).



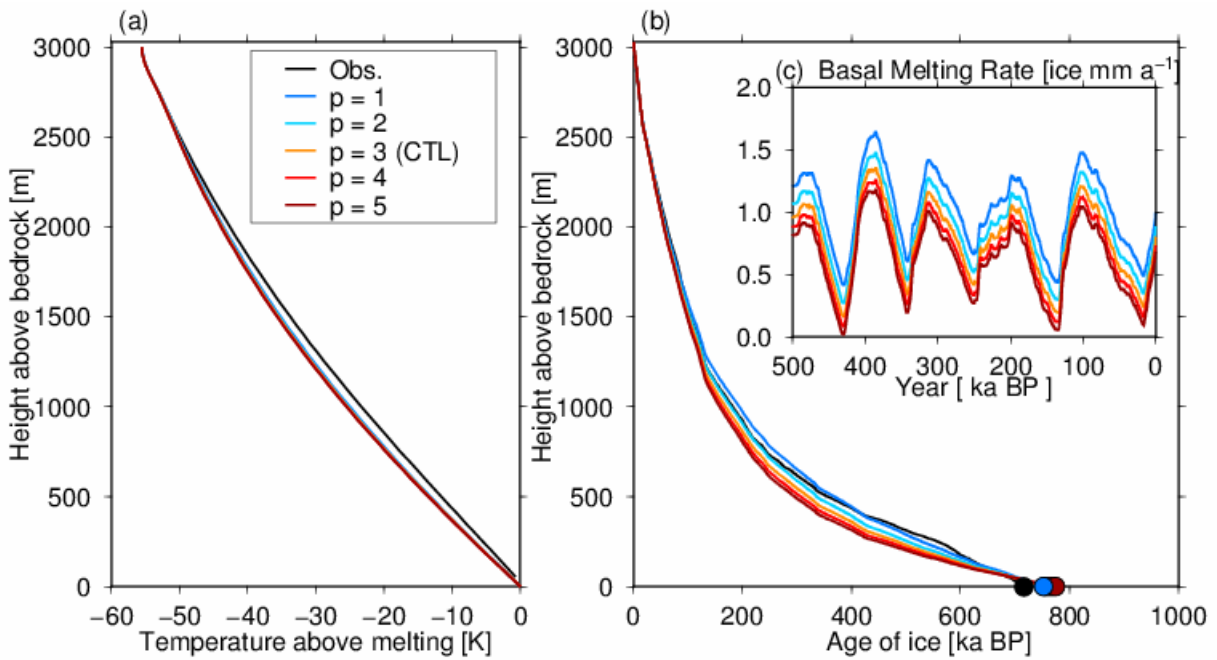
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Fig. 7: Same as Fig. 4, but under the EDC configuration (Table 1) with different geothermal heat fluxes (GHF; units are mW m^{-2}). The black lines represent the measured temperature profiles and the black circles in (b) indicate the location of data points, while the colored crosses in (b) represent the model grid points.



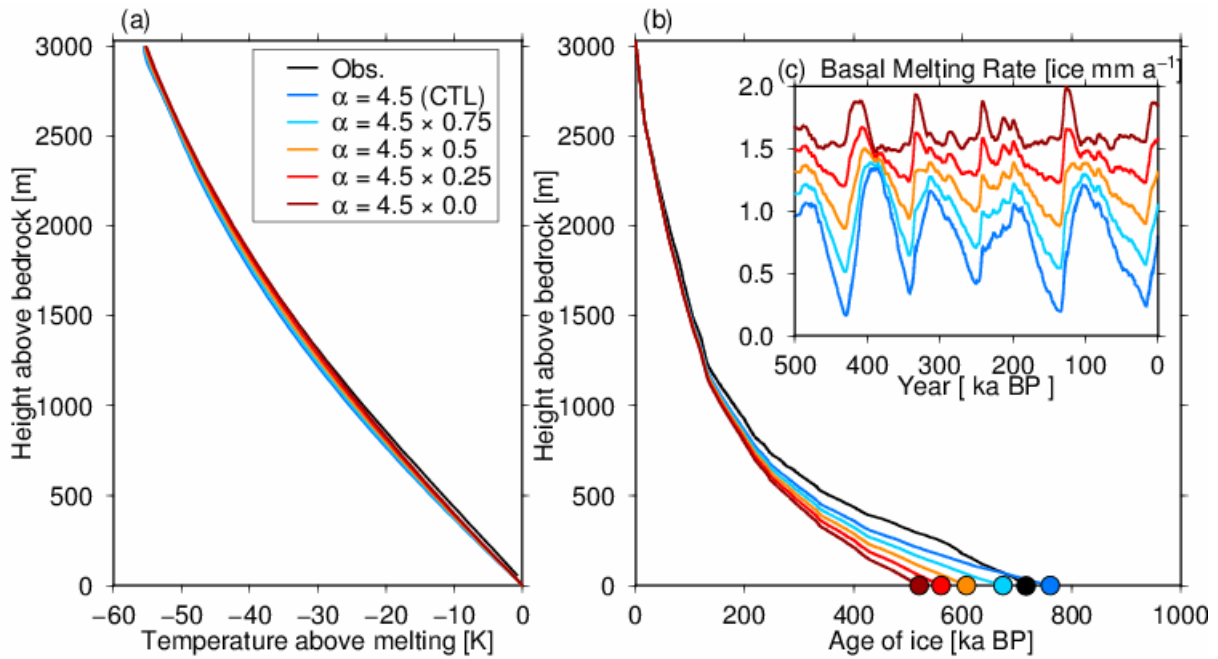
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Fig. 8: Same as Fig. 6, but results under the EDC configuration (Table 1). The AICC2012 chronology (Veres et al., 2013) is used in this figure for the observed depth–age profile.



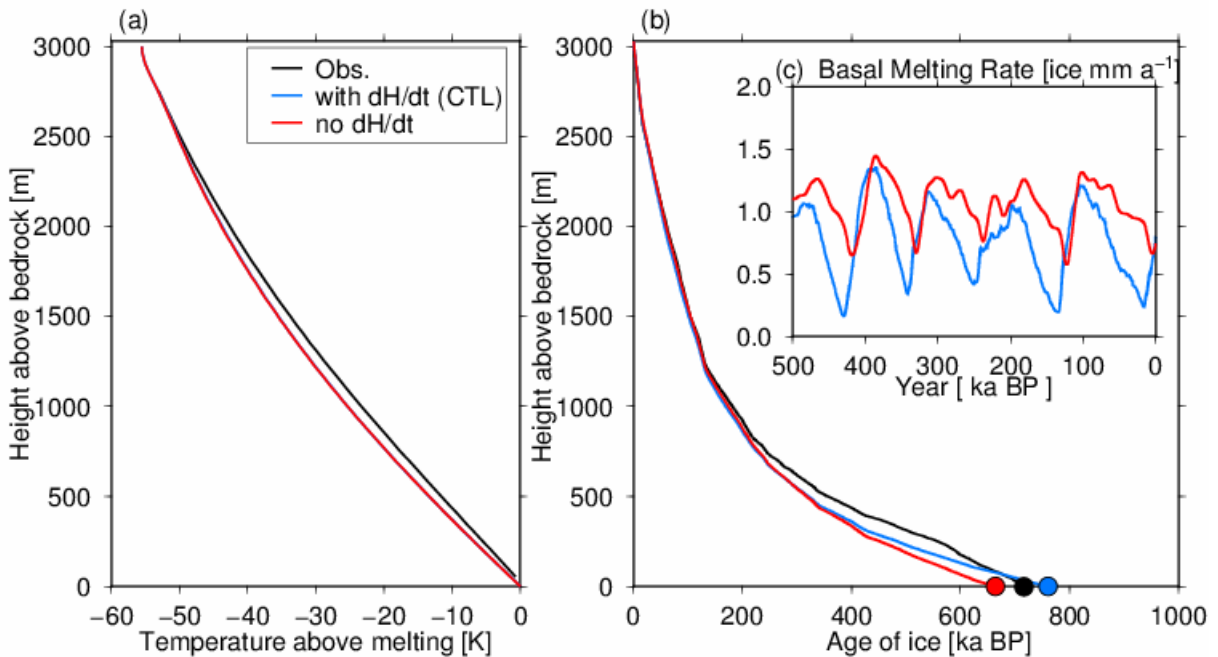
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Fig. 9: Results of the DF configuration (Table 1) with different p parameters. (a) Simulated temperature profiles at present (0 ka) from the surface to the base. (b) Vertical age profiles at present (0 ka). (c) Time series of basal melting rates over the last 500 ka. A geothermal heat flux of 60 mW m^{-2} is adopted in these experiments.



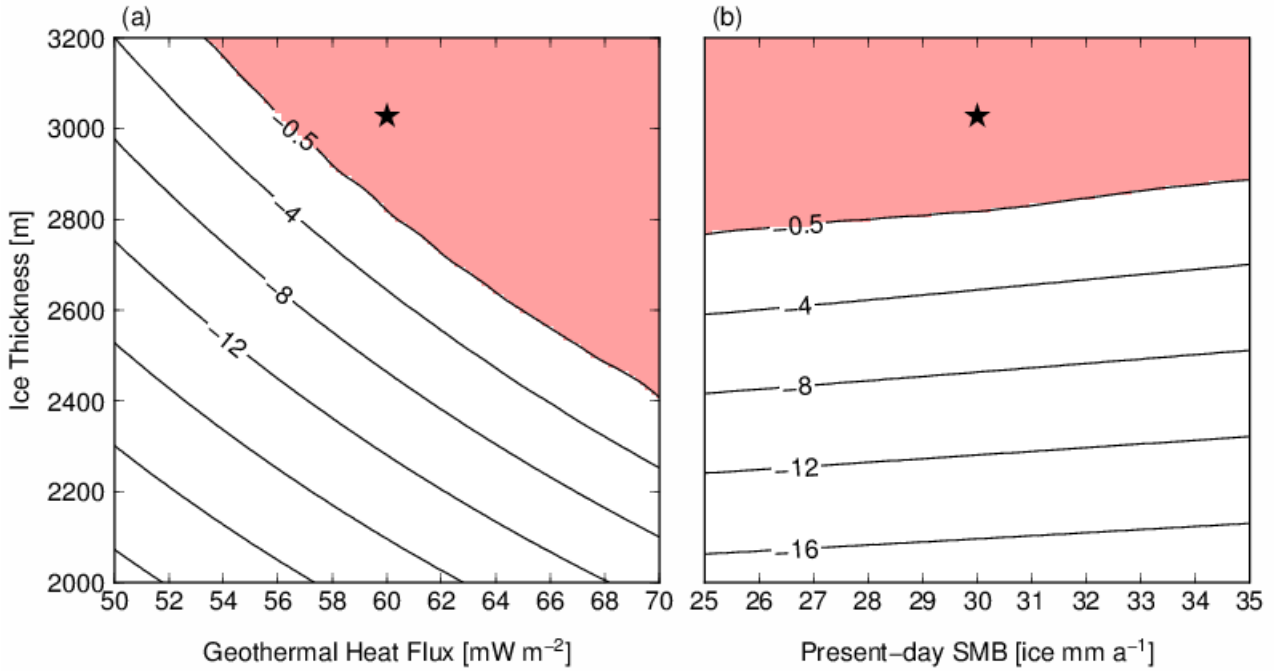
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Fig. 10: Results of the DF configuration (Table 1) with different temperature amplitudes over glacial cycles in Equation 10. A combination of $p = 3$ and $\text{GHF} = 60 \text{ mW m}^{-2}$ is adopted in these experiments. (a) Simulated temperature profiles at present (0 ka) from the surface to the base. (b) Vertical age profiles at present (0 ka). (c) Basal melting rates of the last 500 ka.

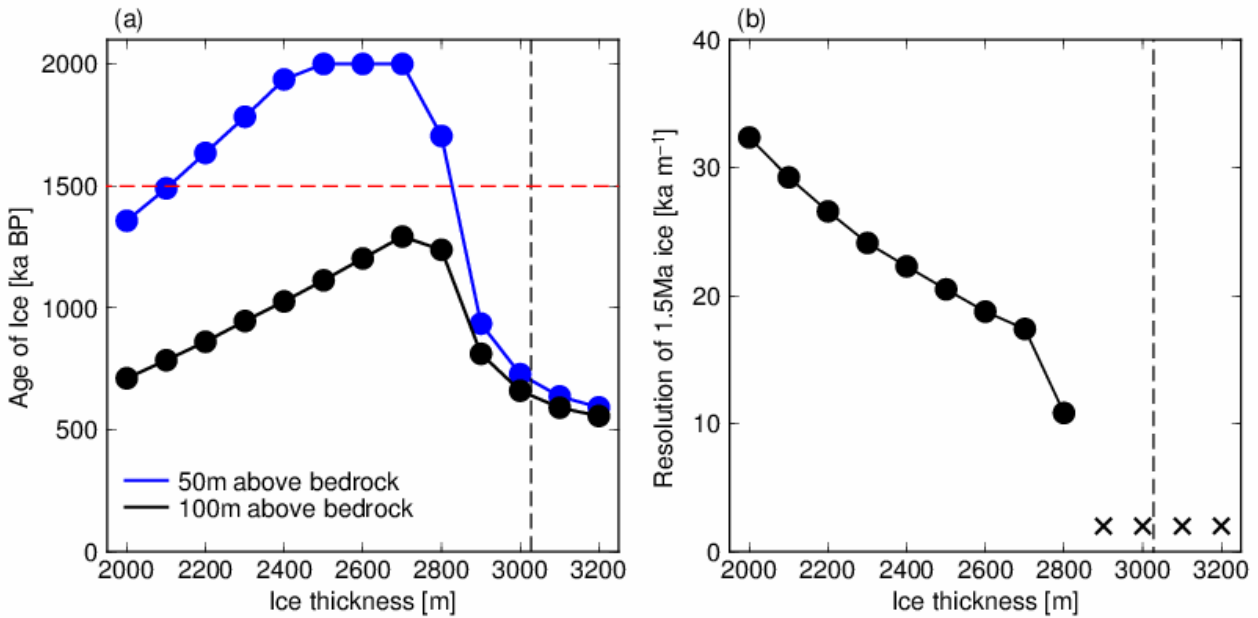


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Fig. 11: Results of the DF configuration (Table 1) with and without ice thickness changes in the past. A combination of $p = 3$ and $\text{GHF} = 60 \text{ mW m}^{-2}$ is adopted in these experiments. (a) Simulated temperature profiles at present (0 ka) from the surface to the base. (b) Vertical age profiles at present (0 ka). (c) Basal melting rates of the last 500 ka.

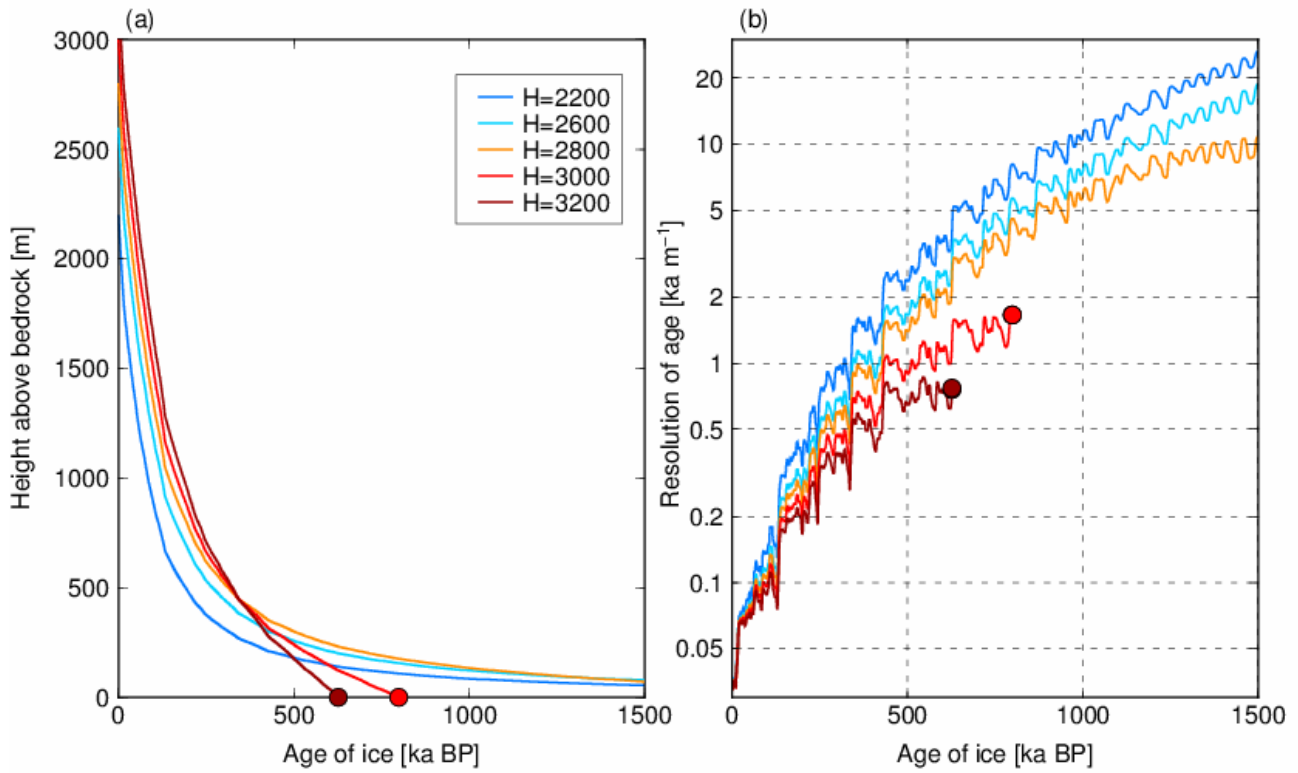


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 952 Fig. 12: Simulated basal temperature at the present day with combinations of ice thickness,
 953 geothermal heat flux, and present-day SMB. (a) Red shading indicates a basal temperature -0.5°C
 954 below the pressure-melting point. (b) Basal temperature at the present day with $\text{GHF} = 60 \text{ mW m}^{-2}$.
 955 The black star represents the condition at the DF ice core ($H = 3028 \text{ m}$, $\text{SMB} = 30 \text{ ice mm a}^{-1}$), with
 956 a calibrated geothermal heat flux (60 mW m^{-2}).
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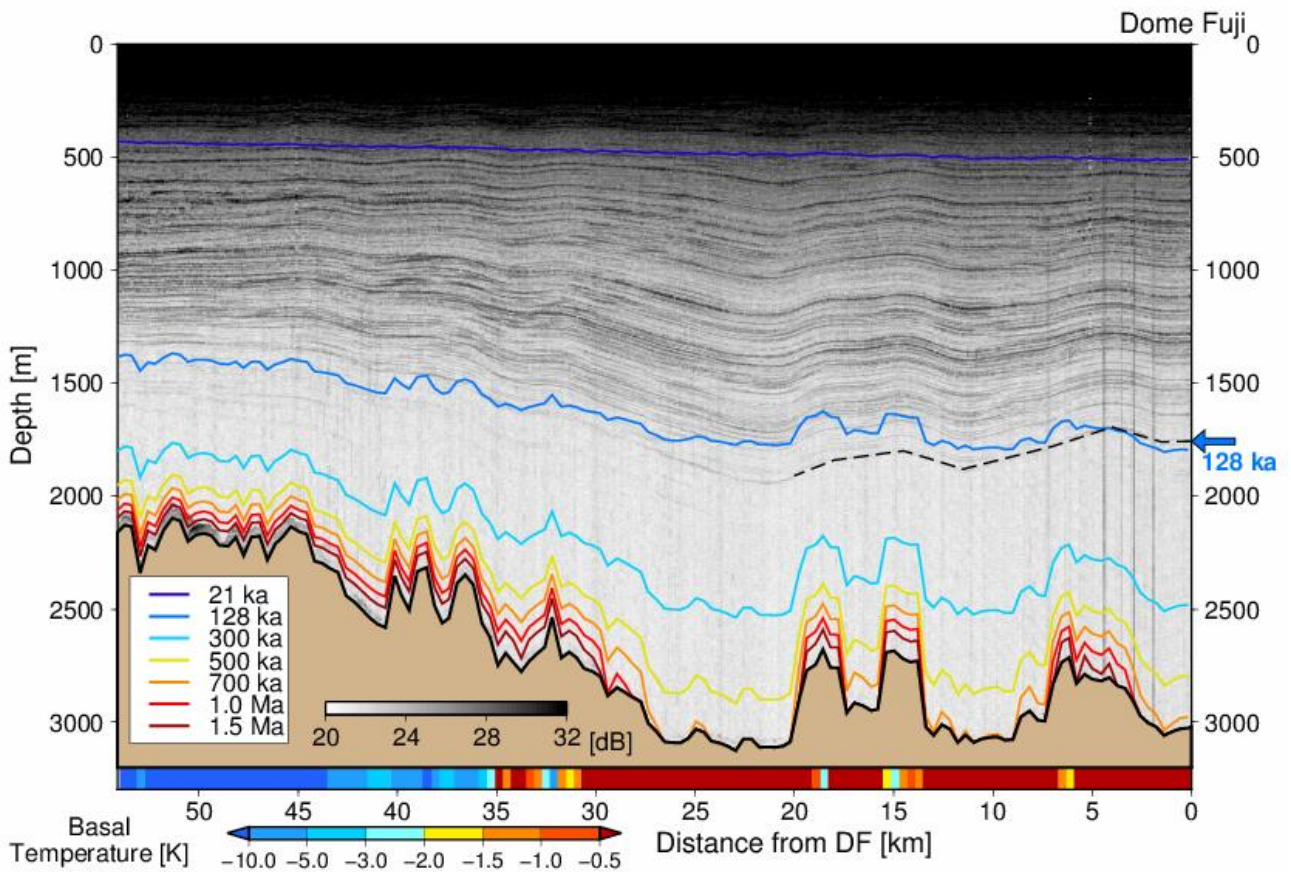


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 959 Fig. 13: Results with different ice thicknesses at the DF configuration ($\text{SMB} = 30 \text{ ice equivalent mm a}^{-1}$
 960 and $\text{GHF} = 60 \text{ mW m}^{-2}$). (a) The black and blue lines indicate the simulated ages of the ice at 100
 961 and 50 m above the bedrock, respectively. The vertical dashed line ($H = 3028 \text{ m}$) indicates the
 962 condition at DF, and the horizontal red dashed line indicates the age of 1.5 Ma. Note that an age of 2
 963 Ma is the limit of the experiments. (b) The vertical axis indicates the resolution of the ice age (ka m^{-1})
 964 at 1.5 Ma BP. The crosses indicate that the 1.5 Ma age of ice does not exist under these

965 conditions.



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967 Fig. 14: Results with different ice thicknesses (2200, 2600, 2800, 3000, and 3200 m) and calibrated
968 geothermal heat flux (60 mW m^{-2}) and SMB ($30 \text{ ice equivalent mm a}^{-1}$) at DF. (a) Vertical age
969 profiles at present (0 ka). (b) Vertical resolution of the ice age.
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 972 Fig. 15: Results of the experiments overlaid with the observed radargram for the DF–NDF transect.
 973 A combination of $p = 3$ and $\text{GHF} = 60 \text{ mW m}^{-2}$ is adopted in these experiments. The horizontal axis
 974 indicates the distance from DF (km), and the vertical axis indicates the depth from the surface (m).
 975 The gray coloring indicates the reflection intensity from the ground radar surveys, and the color
 976 contours indicate the simulated age of the ice using the 1-D model. The black dashed line indicate
 977 the traced isochrone horizon from DF, corresponding to $\sim 128 \text{ ka}$. The bottom color bar indicates the
 978 simulated basal temperature (relative to the melting point) at the present-day.