Stratigraphic templates for ice core records of the past 1.5 million years

Eric W. Wolff[1], Hubertus Fischer[2], Tas van Ommen[3], David A. Hodell[1]

1. Dept of Earth Sciences, University of Cambridge, UK (ew428@cam.ac.uk)

2. Climate and Environmental Physics, Physics Institute & Oeschger Centre for Climate Change Research, University of Bern, Switzerland

3. Australian Antarctic Division and Australian Antarctic Program Partnership, University of Tasmania, Tasmania, Australia.

Correspondence to: Eric Wolff (ew428@cam.ac.uk)

Abstract. The international ice core community has a target to obtain continuous ice cores stretching back as far as 1.5 million years. This would provide vital data (including a CO_2 profile) allowing us to assess ideas about the cause of the Mid-Pleistocene Transition (MPT). The European Beyond EPICA project and the Australian Million Year Ice Core project each plan to drill such a core in the region known as Little Dome C. Dating the cores will be challenging, and one approach will be to match some of the records obtained with existing marine sediment datasets, informed by similarities in the existing 800 kyr period. Water isotopes in Antarctica have been shown to closely mirror deepwater temperature, estimated from Mg/Ca ratios of benthic foraminifera, in a marine core on the Chatham Rise near to New Zealand. The dust record in ice cores resembles very closely a South Atlantic marine record of iron accumulation rate. By assuming these relationships continue beyond 800 ka, our ice core record could be synchronised to dated marine sediments. This could be supplemented, and allow synchronisation at higher resolution, by the identification of rapid millennial scale-events that are observed both in Antarctic methane records and in emerging records of planktic oxygen isotopes and alkenone sea surface temperature (SST) from the Portuguese Margin. Although published data remain quite sparse, it should also be possible to match ^{10}Be from ice cores to records of geomagnetic palaeointensity and authigenic $^{10}Be/^{9}Be$ in marine sediments. However, there are a number of issues that have to be resolved before the ice core ^{10}Be record can be used. The approach of matching records to a template will be most successful if the new core is in stratigraphic order, but should also provide constraints on disordered records, if used in combination with absolute radiogenic ages.

1. Introduction

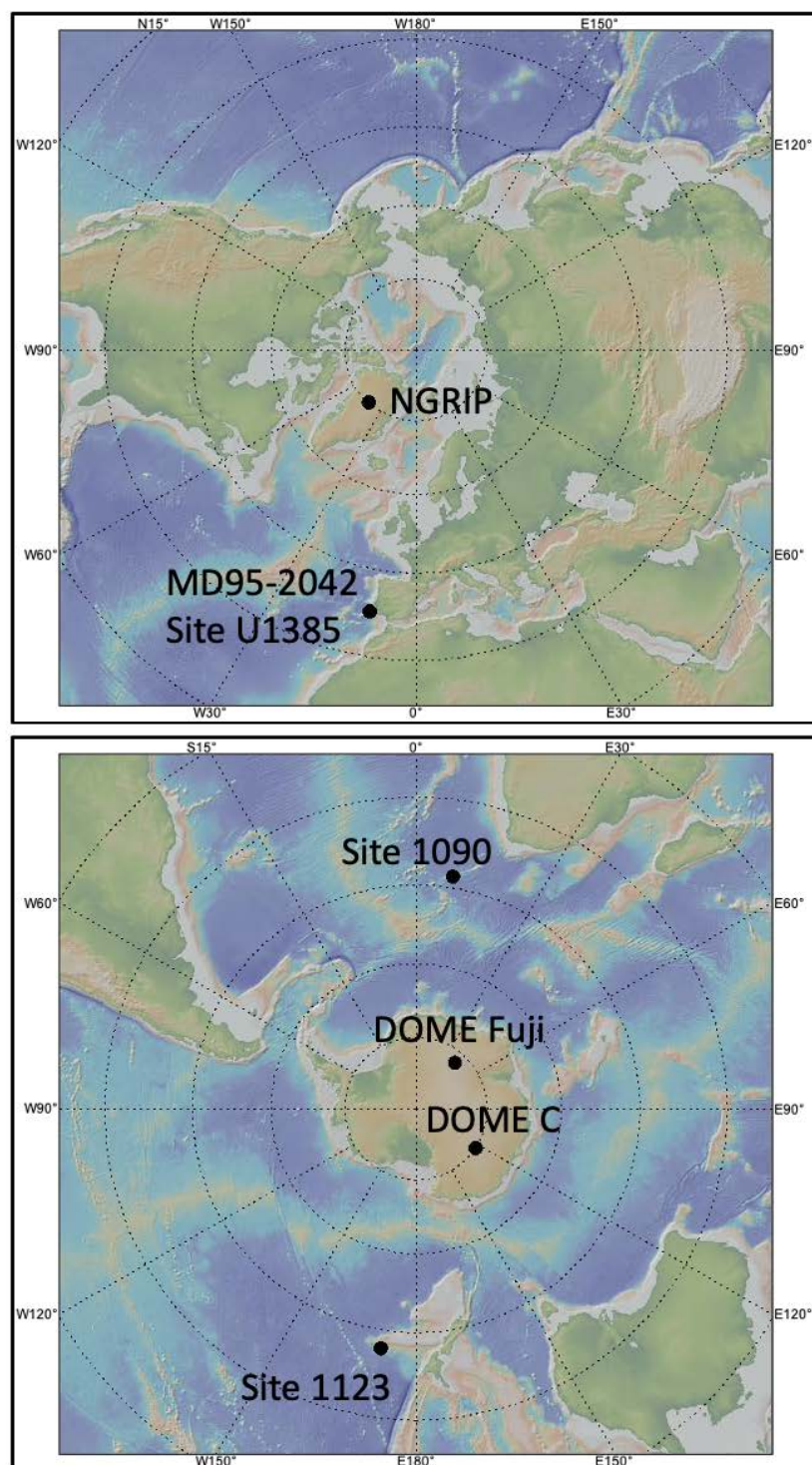
Ice cores have provided iconic records of changes in atmospheric composition and climate over glacial/interglacial cycles, with Antarctic datasets extending, so far, 800 kyr into the past (e.g. Bereiter et al., 2015; Jouzel et al., 2007; Wolff et al., 2010). While this illustrates what is often referred to as the "100 kyr world", marine (e.g. Lisiecki and Raymo, 2005) and terrestrial records indicate that a different style and strength of glacial cycle existed earlier in the Pleistocene, during the "41 kyr world". The change in amplitude and frequency is referred to as The causes of the so called mid-Pleistocene Transition (MPT) and occurs in the absence of any obvious change in astronomical forcing. The causes of the MPT remain hotly debated (Clark et al., 2006), with changes in CO_2 concentration or changes in the nature of the ice/rock interface underlying continental ice sheets often invoked.

Some of the issues surrounding these debates could be resolved if an ice core record, extending beyond the MPT and including records of past greenhouse gas concentrations, could be obtained. It has therefore become a key target of the ice core community to find a location to drill a core reaching as far back as 1.5 Ma (Fischer et al., 2013). Several projects to obtain such a core are partially underway, including the European Beyond EPICA project which plans to drill between 2021 and 2025 at a site known as Little Dome C (LDC). This site is only about 30 km from the site of the EPICA Dome C drilling (Fig. 1) that reached 800 ka, but is located on top of a subglacial highland, thus avoiding basal melting that led to loss of the oldest ice at Dome C. The Australian Million Year Ice Core (MYIC) project is targeting the same region of Antarctica.

A major challenge is to date such a core. Recently greenhouse gas concentrations were reported for ice as old as 2 Ma at a blue ice location of Allan Hills, Antarctica (Yan et al., 2019). While this provided tantalising snapshots of atmospheric composition, the dating, using the ^{40}Ar atmospheric increase method (see below), was too imprecise (with a quoted uncertainty of 110 kyr or 10% of age) to assign data unequivocally to particular parts of glacial cycles, or even to specific cycles. While this is a particular issue for discontinuous records such as those from blue ice, dating is also likely to be a major problem for a "standard" core, even assuming it is complete and continuous.

A number of methods can be used to try and date the ice older than 800 ka. As with the blue ice, absolute ages may be estimated from radiometric methods, including ^{81}Kr decay (Buizert et al., 2014; Crotti et al., 2021), and the growth in atmospheric concentration with time of ^{40}Ar (Bender et al., 2008; Yan et al., 2019), but both of these methods currently have large error bars at ages of 1 million years or more. The decay of cosmogenic isotopes (using the ratio of ^{10}Be/^{36}Cl to remove production rate variations) also has potential, but issues with ^{36}Cl loss at low accumulation rate sites (Delmas et al., 2004) have to be solved and the dating accuracy will likely be similar to the one using ^{81}Kr and ^{40}Ar.

While absolute methods can indicate the approximate age of the ice within the pre-MPT period, the uncertainty is currently too large to answer many of the questions that are relevant to such ice. For example, if changes in CO_2 did occur, it will be important to determine exactly when they occurred, and at what rate. Did the changes occur only in particular parts of each glacial cycle? In what part of glacial cycles did millennial events still occur before the MPT? All these questions require an age scale that is precise to within at worst a few millennia.

66

67   Figure 1. Location map. The maps show the locations of the ice and marine cores shown in this paper. Colours

68   represent topography and bathymetry. Figure made with GeoMapApp (www.geomapapp.org) / CC BY.

69 The main technique for dating the ice <800 ka in age has been to combine an estimate of past snow

70 accumulation rate and thinning with a range of fixed points that tie the ice core to known ages (Bazin et al.,

71 2013). These fixed points include the signal of low intensity of the geomagnetic dipole field associated with

72 polarity reversals recorded as increases in [10]Be deposition (Raisbeck et al., 2006), and various orbital tuning

73 targets including $\delta^{18}O_{atm}$ (Extier et al., 2018) and the ratio of O_2/N_2 (Kawamura et al., 2007). These methods, as

74 well as the radiometric ones, will certainly be applied to the new 1.5 Ma projects. However, diffusion, lack of

75 resolution and disturbed ice flow, with the possibility of folded ice near the bed, as has been seen at deep ice

76 core sites in Greenland (Grootes et al., 1993; NEEM Community Members, 2013), mean that further

77 stratigraphic methods to date the core may be needed.

78 One additional option is to create templates to which the records generated in the new projects can be matched.

79 The orbital targets (for tuning of O_2/N_2 and $\delta^{18}O_{atm}$) used to construct the 800 ka age model (Bazin et al., 2013)

80 are simple examples of the use of such templates, and will not be included here as they are very straightforward

81 to construct. Marine and terrestrial records that are rather well-dated extend beyond 1.5 million years. As an

82 example many marine records have been mapped, using benthic isotopes, onto the LR04 marine stack (Lisiecki

83 and Raymo, 2007), whose age uncertainty at 1.5 Ma is estimated at 6 kyr, or the more recent Prob-Stack (Ahn et

84 al., 2017), which also uses the LR04 age model. Alignments such as these would allow age uncertainties of the

85 order needed to answer the questions about timing of CO_2 and millennial change discussed above. The

86 drawback is that they obviously preclude the option of assessing phasing between ice records and the (marine)

87 templates, as such a phase has to be assumed. In the absence of better dating methods, this cannot be avoided.

88 In this paper, we consider which ice core parameters may have analogues in the marine record that could be

89 used as templates onto which a future ice core could be mapped. We focus particularly on the EPICA Dome C

90 ice core (EDC), because its close proximity to the planned ice cores at LDC leads us to expect a similar signal in

91 most parameters. We use ice core datasets which have already been shown to closely mirror a particular marine

92 record over the past 800 kyr. We consider the mechanistic basis for such agreement and whether it is likely to

93 apply through the MPT to 1.5 Ma. We then present "predictions" of what some parameters might look like in

94 the new ice core, which can be used as both a test of integrity and continuity, and as a first dating tool for the

95 core.

2. EPICA Dome C ice core records

97 In the following sections, we will consider possible analogues for 4 ice core parameters (Fig. 2). The water

98 isotope record ($\delta^{18}O$ and δD) is the most basic climate parameter (Jouzel et al., 2007) recorded in the ice,

99 generally considered to represent temperature at the ice core site. Dust is the insoluble component of impurities

100 trapped in the ice, and represents terrestrial material from the southern continents. Both dust and water isotopes

101 display particularly strong changes over glacial cycles with more subdued millennial scale variations. Methane

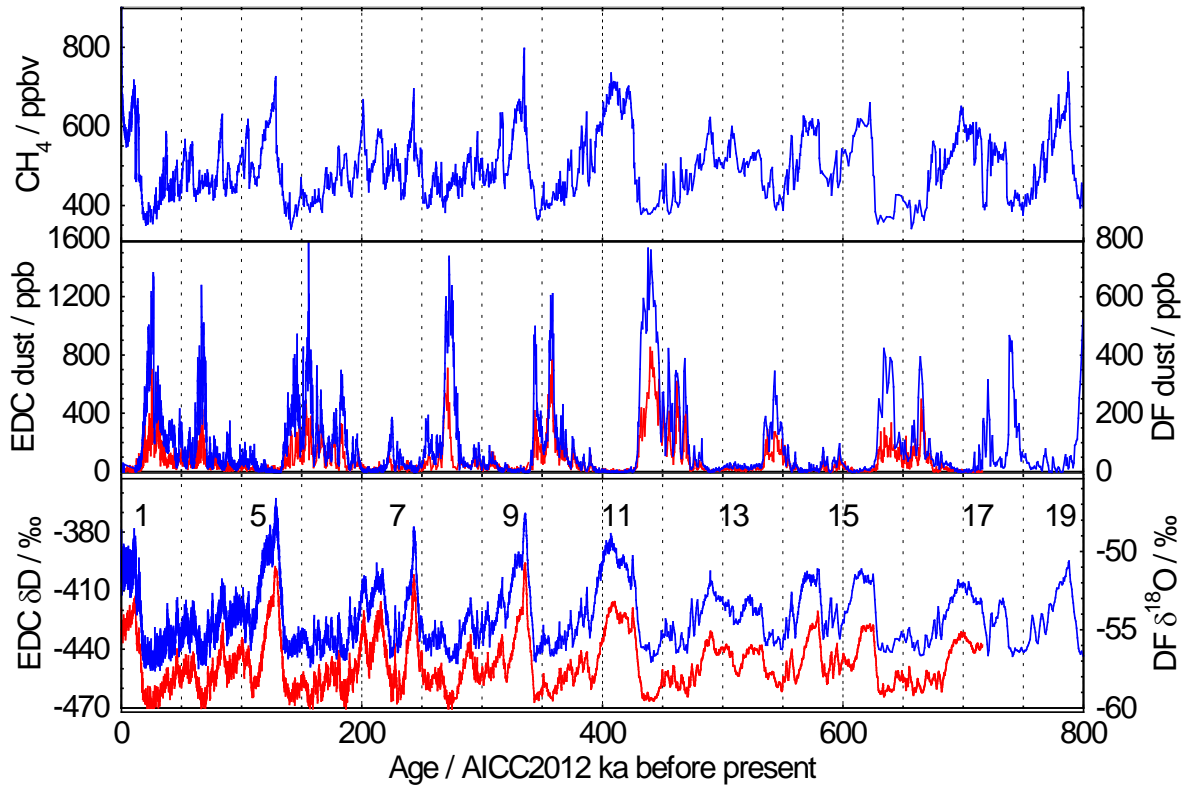
102 is the one component in the ice core record that displays abrupt events, parallel to the rapid Dansgaard-Oeschger

103 events seen in Greenland ice cores. [10]Be (not shown in Fig. 2) is the cosmogenic isotope most commonly

104 measured in ice, and its production is controlled by changes in Earth's and the Sun's magnetic fields which also

105 influence cosmogenic isotopes archived in other material. These 4 components will be considered in more

106 detail in the following sections.

107

108   Figure 2. Ice core data over the past 800 kyr. Ice core records covering the past 800 kyr from Dome C (blue) and

109   from the last 720 kyr from Dome Fuji (red). Top panel: methane (Loulergue et al., 2008); middle panel: dust

110   (Kawamura et al., 2017; Lambert et al., 2008); lower panel: water isotopes (Jouzel et al., 2007; Kawamura et al.,

111   2017), with interglacial marine isotope stage numbers marked.

112

113   Although we are specifically aiming here to create a template for the European or Australian drilling at LDC, we

114   note that in most details, the features and relative changes seen for water isotopes, dust and [10]Be are expected to

115   be similar across the East Antarctic plateau. This is illustrated in Fig. 2, where we have plotted $\delta^{18}O$ and dust

116   concentration from Dome Fuji (Fig. 1) (Kawamura et al., 2017) along with δD (Jouzel et al., 2007) and dust

117   concentration (Lambert et al., 2008) from EDC, all plotted on the AICC2012 age scale. The absolute level of

118   dust concentrations varies spatially across the Antarctic plateau, being dependent on travel distance from the

119   main Patagonian dust source region (Fischer et al., 2007a) and concentrations are higher at Dome Fuji than at

120   Dome C. This difference is explained in part because of the different analysis method used for Dome F and

121   Dome C that includes different size ranges, but in any case the pattern is almost identical on multimillennial

122   timescales; methane is of course expected to show the same concentrations across Antarctica. Our templates for

123   LDC are therefore likely to serve as equally valid for other sites across East Antarctica.

124   **3.   Water isotopes**

125   Water isotopes (δD, $\delta^{18}O$) in ice cores are generally taken to represent the temperature at the ice core site,

126   although the reality is actually much more complicated than that (Buizert et al., 2021; Jouzel et al., 1997). It

127   therefore makes sense to look for a potential marine analogue that also records mainly temperature. Although

128   water isotope records from ice are sometimes plotted along with oxygen isotope records from marine cores, the

129   latter reflect a combination of temperature and ice volume (as well as local salinity effects), and so the

130   variability of the two records may not be comparable on glacial-interglacial scales. A commonly used

131   geochemical temperature sensor in marine cores is the ratio of Mg/Ca in foraminifera.

132   Planktic Mg/Ca records, covering 800 ka and more, are available from a number of marine sites and should

133   reflect sea surface temperatures (SSTs) (e.g. Shakun et al., 2015). However while we expect some match

134   between Antarctic temperatures and those from the high southern latitudes, we would expect most other sites to

135   display a rather different pattern owing to the operation of the bipolar seesaw (e.g. Barker et al., 2011).

136   Elderfield et al. (2012) noticed a striking similarity between the deepwater temperature inferred from Mg/Ca of

137   benthic foraminifera at Ocean Drilling Program (ODP) site 1123 (Fig. 1), on the Chatham Rise east of New

138   Zealand, and the temperature inferred from δD in the EDC ice core. They hypothesised that this is because

139   deepwater temperature, particularly in the South Pacific, reflects the temperature of sinking surface waters and

140   of Antarctic and proximal air temperature. Mean ocean temperature (determined by analysing noble gas ratios

141   in ice cores) also shows a very similar pattern to Antarctic surface temperature across the last two glacial

142   terminations (Baggenstos et al., 2019; Bereiter et al., 2018; Shackleton et al., 2020; Shackleton et al., 2021),

143   which supports the interpretation. In recent years, deep water temperatures covering at least 1.5 Ma have been

144   obtained from two other sites in the North Atlantic (Sosdian and Rosenthal, 2009) and North Pacific (Ford and

145   Raymo, 2019), but given their location they are not expected to reflect Antarctic climate so directly, thus leaving

146   only ODP site 1123 as a suitable comparator.

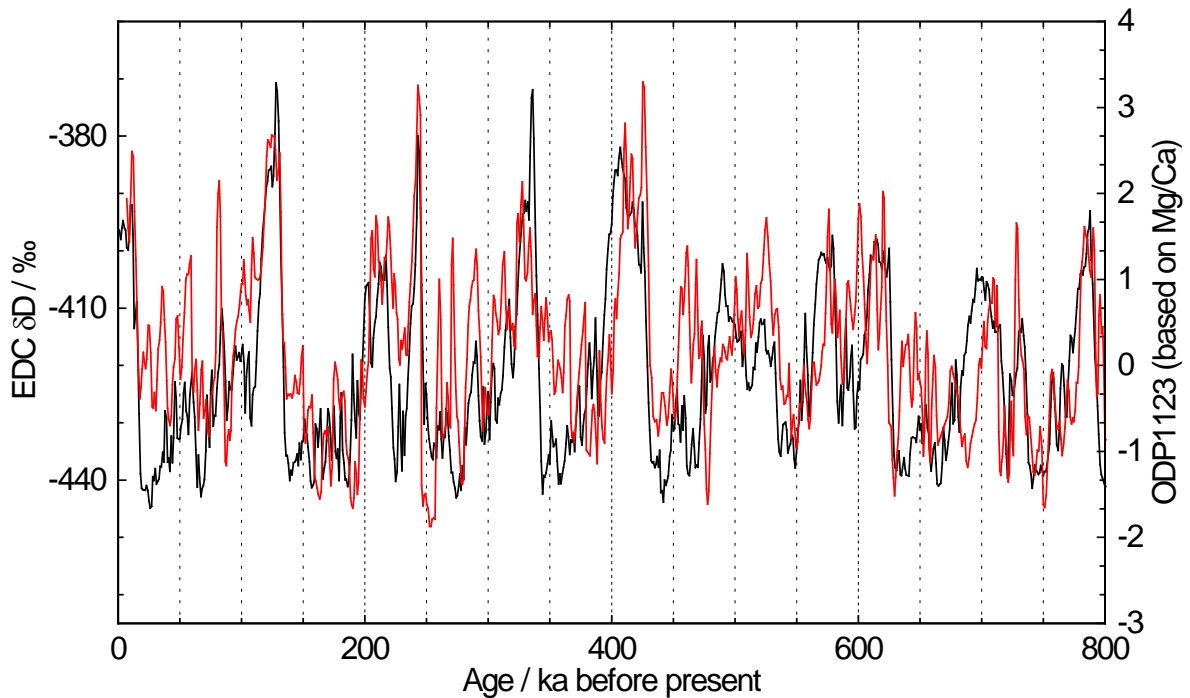
147   In Figure 3, we compare the record of δD from EDC with that of benthic Mg/Ca from site 1123 over the last 800

148   ka. The Mg/Ca record is presented as converted to temperature and interpolated (Elderfield et al., 2012), and is

149   on the LR04 age model (Lisiecki and Raymo, 2005), while the ice core data is on AICC2012 (Bazin et al.,

150   2013). By using a suitable amplitude scaling to overlay the two records we can compare their fidelity to each

151   other and observe the extended Mg/Ca record as a possible template for δD over 1.5 Ma.

152

153 Figure 3. Ice core and marine sediment data reflecting temperature for the past 800 kyr. EDC deuterium (black,

154 AICC2012 age scale) (Jouzel et al., 2007). ODP site 1123 deepwater temperature (red, LR04 age model), based

155 on Mg/Ca (Elderfield et al., 2012).

156

157 The similarity between the two records is strong at the orbital timescale where both the shape and the relative

158 amplitude of each glacial cycle is the same in the two records. The correlation coefficient between the two

159 records after they are aligned in time is 0.67 (Elderfield et al., 2012) ($r^2 = 0.45$). However, there are significant

160 mismatches at the shorter, multimillennial, timescale. Some very prominent millennial-scale AIM (Antarctic

161 isotopic Maximum) events in the ice core record are very weak, or in some cases not clearly resolved, in the

162 marine record. Some of the issues may actually be related to temporal synchronisation, and perhaps to the

163 resolution of the marine record. But still, it would be hard to use the marine record as a template for an ice core

164 record between 450 and 550 ka (MIS 13). This is a concern because some of the sections of Site 1123 beyond

165 800 ka have a similar nature (in terms of signal amplitude) to that section.

166 Despite these concerns over the fidelity of the marine record as a predictor of the ice core isotope signal, we

167 would expect the similarity to continue provided deepwater temperature at high southern latitudes continues to

168 be driven by surface temperatures around Antarctica before the MPT.   What could disrupt such a link would be

169 significant changes in ocean circulation and in the reach of different water masses. Such changes may well have

170 occurred over the MPT (Ford and Raymo, 2019), and one suggestion is that they are related to a hypothesised

171 change in the Antarctic Ice Sheet (Raymo et al., 2006) from largely terrestrial to marine-based. While such

172 changes would certainly have impacted the supply of water affected by Antarctic surface temperatures to the

173 deep ocean, the proximity of site 1123 to Antarctica makes it unlikely that a southern influence was completely

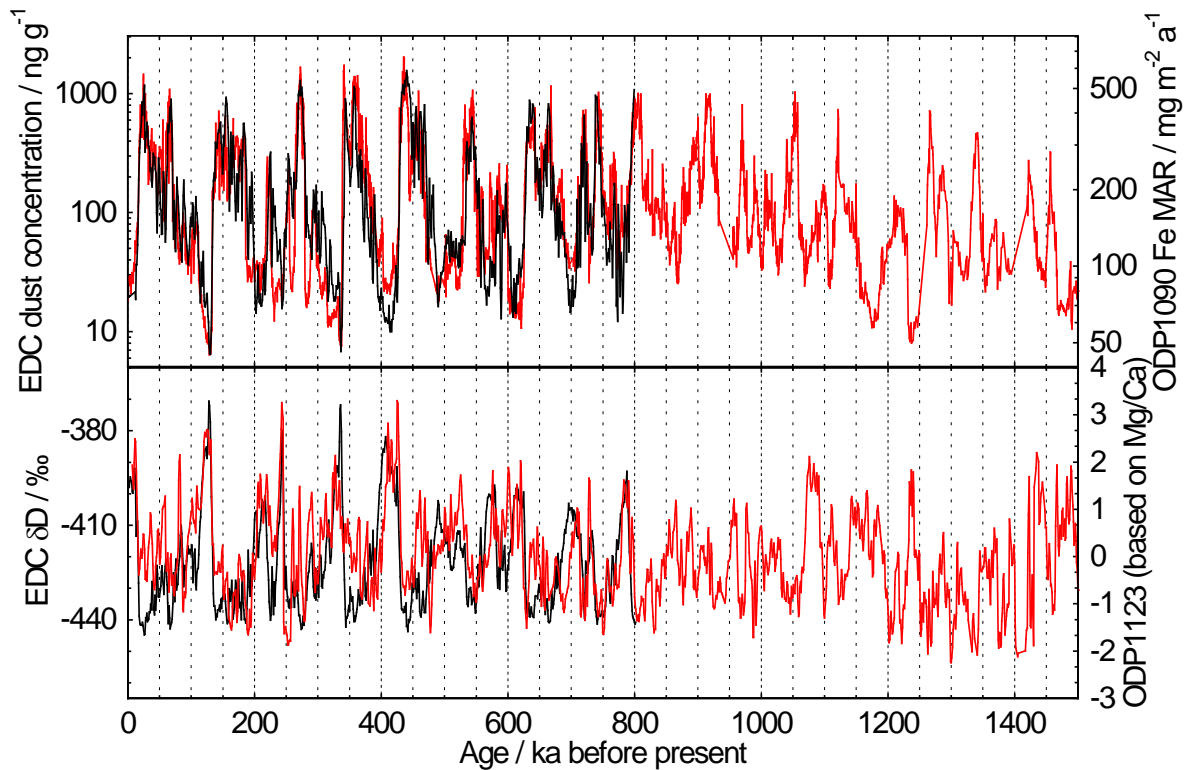
174 absent at that time. We therefore see it as likely that the site 1123 Mg/Ca record extended to 1.5 Ma (Fig. 4)

175 does serve as an approximate template for at least the glacial/interglacial variability in Antarctic temperature and

176 therefore LDC deuterium. However, we accept the possibility that the exact nature of the relationship between

177 the two records could have differed in the early part of the period from that observed after 800 ka, and indeed

178 should a mismatch be found in the ice core record it will provoke reconsideration of the assumptions made here.

179

180 Figure 4. Ice core records to 800 ka and marine records to 1500 ka. Lower panel: EDC deuterium (black)

181 (Jouzel et al., 2007) and Mg/Ca-based deepwater temperature (red) from site ODP1123 (Elderfield et al., 2012).

182 Upper panel: EDC dust (black) (Lambert et al., 2008) and Fe MAR from ODP site 1090 (red) (Martinez-Garcia

183 et al., 2011).

184

185 It would obviously be beneficial to search for other marine analogues of Antarctic temperature. The similarity of

186 benthic oxygen isotopes in cores on the Portuguese Margin to Antarctic temperature was noted previously,

187 albeit on a very short time period (Shackleton et al., 2000). The extension of this record, which is underway

188 (Birner et al., 2016) would provide a much better resolved record, with clear millennial scale signals, and its

189 applicability as a template could be assessed. The caveat is that the underpinning reason for similarity of a

190 benthic isotope record controlled by several factors (ice volume, temperature, hydrography and water mass

191 changes) with Antarctic temperature at such a distal site is unclear, making it difficult to assess the likelihood

192 that the relationship persisted before the MPT.

193 **4. Dust**

194 Terrestrial dust is measured directly in ice cores, as insoluble particle numbers and sizes which can be converted

195 to mass concentrations, and indirectly in marine sediments through the concentrations or ratios of elements that

196 are mainly (at appropriate sites) of windborne terrestrial origin. The 800 ka record of dust concentration in the

197   EDC ice core (Lambert et al., 2008) shows strong glacial-interglacial cycles, with high concentrations of dust in

198   glacial periods, and some multimillennial scale variability. Elemental and isotopic analysis indicates that the

199   dust mainly originates from South American sources, particularly in Patagonia (Delmonte et al., 2008). As a

200   result we would expect a close relationship between dust arriving in Antarctica and dust deposited onto the

201   South Atlantic during the early stages of the path to Antarctica.

202   ODP site 1090 (Fig. 1) is ideally located to sample dust during its transport in the westerly wind belt from the

203   Patagonian sources towards Antarctica. Martinez-Garcia et al. (2011) noted that different dust proxies in the

204   sediment core from site 1090 matched well with each other over 4 Ma, and with EDC dust flux over 800 ka.

205   Here we compare their preferred dust proxy (mass accumulation rate of iron, Fe MAR) with the dust

206   concentration at EDC (Lambert et al., 2008). We prefer to use concentration rather than flux because this is what

207   we will be able to measure in the deeper parts of the LDC core – the flux is a derived quantity that requires

208   knowledge of the snow accumulation rate. It is therefore a fairer test to assess the similarity of the measured

209   quantity (concentration) to the marine target. In the section of the paper on ^{10}Be, we do discuss the potential to

210   use water isotopes to derive snow accumulation rate and hence calculate fluxes. This could also be done for

211   dust, if it were considered essential, but it carries some risk because of the assumptions involved.

212   In Fig. 5 we compare the two records over the last 800 ka, showing the result both for EDC dust concentration

213   and for flux. Note that glacials have high values of dust, that both records have been smoothed to 1 ka averages,

214   and are plotted on log scales. With the appropriate amplitude scaling, the agreement between the two records is

215   remarkable. This applies both to the consistent amplitude relationship, to the shape of glacial-interglacial

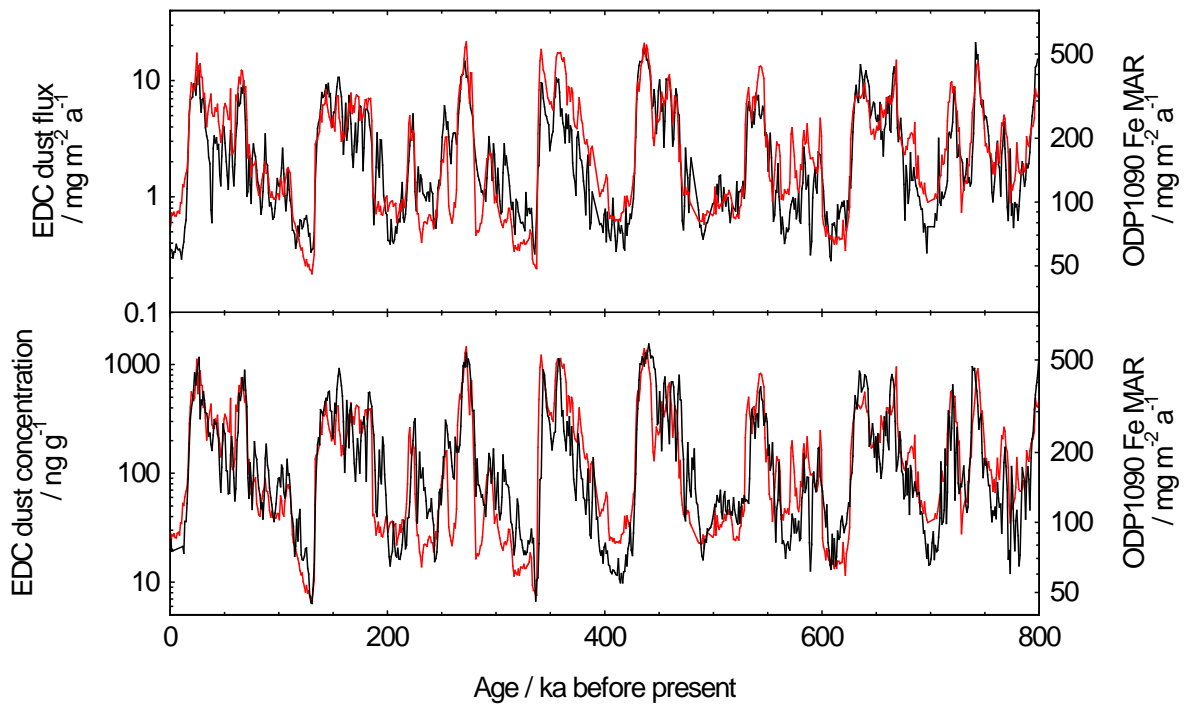
216   cycles, and to the identification of almost every multimillennial scale peak in both records. The section from

217   450-550 ka, which was problematical in the isotope records discussed above, shows a good match. The

218   correlation coefficient between EDC dust and ODP1090 Fe Mar is 0.83 (r^2=0.69) both for EDC dust

219   concentration and flux.

220

221

222 Figure 5. Ice core and marine sediment dust data for the past 800 kyr. EDC dust (black) (Lambert et al., 2008);

223 Fe MAR from ODP site 1090 (red) (Martinez-Garcia et al., 2011). Top panel uses EDC dust flux, while lower

224 panel uses EDC dust concentration. Data have been smoothed to 1 kyr averages and the marine data were

225 aligned (Martinez-Garcia et al., 2011) to the ice core age model.

226

227 The agreement is made more surprising by the fact that the dynamic range of the two records is very different:

228 the marine dust, being geographically closer to the dust production in Patagonia than is the long-range

229 transported ice core record, varies by a factor 10 (minimum in MIS 5e, maximum in MIS 13), while the ice core

230 dust concentration varies by a factor >100 (factor 200 between MIS 5e and MIS 13).   The range of dust flux at

231 EDC would be about a factor 50, because the snow accumulation rate is about four times higher in MIS 5e than

232 in MIS 13. This implies that the causes of dust variability are split into two halves: a factor of about 10 is due

233 mainly to changes at or near the source of the dust, another factor of about 5 is due to changes in lifetime during

234 the long meridional journey to Antarctica. This has been discussed several times before (Fischer et al., 2007b;

235 Lambert et al., 2008; Markle et al., 2018; Petit and Delmonte, 2009; Wolff et al., 2010) and although the

236 different approaches led to somewhat different amplification factors by dust source and transport processes, the

237 comparison shows that solutions that match the available data must consider changes both in source and in

238 lifetime. We note that it is the very high dynamic range of the dust concentration or flux record in ice that

239 makes it possible to use raw concentrations in our comparisons – the relatively small factor change in

240 accumulation rate is overwhelmed by the factor 50 flux change, so that the same features seen in marine and ice

241 dust flux are still seen in ice concentration.

242 This implies that the extended marine dust record (Fig. 4) could be an excellent template for the dust record

243 expected in the LDC ice cores. The part of the variance that is based on changes at or near the source should

244 remain, whatever occurred across the MPT. The second part of the variability, arising from changes in aerosol

245 lifetime over the Southern Ocean, has been in phase with changes at the source over the last 800 ka. This could
246 in theory have altered if there were major changes in atmospheric circulation across the MPT. Nonetheless, the
247 major part of the variability (that arising from changes at the source and at the start of the transport route) will
248 have remained unchanged. This implies it seems likely that the basic glacial-interglacial pattern, as well as the
249 imprint of millennial scale change will have persisted. The one circumstance in which this would not be the
250 case is that in which a substantial new, local source of dust from the Antarctic margins existed. It has been
251 suggested that one aspect of the MPT might have been a change in the Antarctic ice sheet, with more terrestrial
252 (rather than marine) margins before the MPT (Raymo et al., 2006). Before using the dust record in the way we
253 have proposed, it will be important to check for the presence of new dust sources, through for example isotopic
254 analysis of dust to fingerprint its source area (Delmonte et al., 2008).

255

5. Methane as a pattern for Dansgaard-Oeschger variability

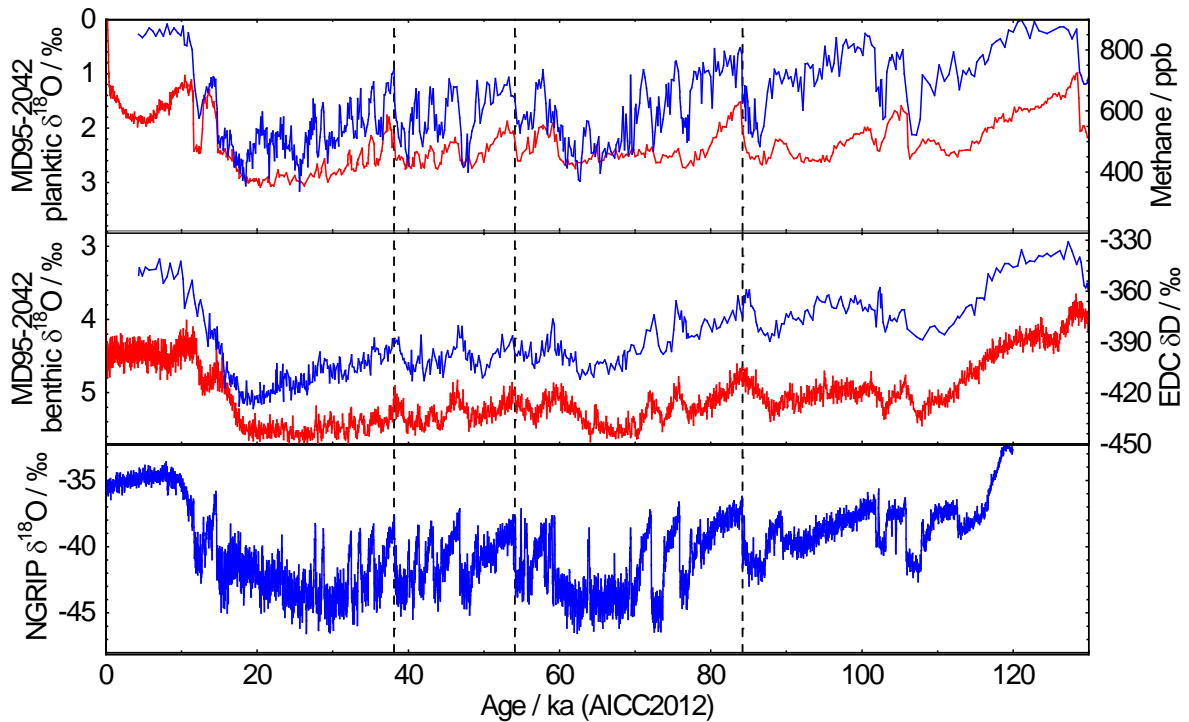
257 While the EDC water isotope and dust records show strong variability, particularly on orbital timescales, that
258 can be used for pattern matching, their variations tend to be smooth, so that correlation is clear but imprecise.
259 Records containing the imprint of Dansgaard-Oeschger (D-O) events have the capacity to identify sharp time
260 points, and therefore to give much closer synchronisation, and many more clear tie points. Using the model of
261 the bipolar seesaw, it is possible to rather convincingly reproduce D-O events from the Antarctic isotope record,
262 to produce what is known as the synthetic Greenland record (GL$_T$-syn) (Barker et al., 2011). However, the
263 synthetic record can never have the sharpness of the original signal and in particular for ice older than 800 kyr
264 diffusion in the ice may have smoothed the higher frequency climate signal in the water isotope record. The only
265 record in Antarctic ice that does retain the character of the D-O events is the methane record.

266 Over the last glacial cycle, every significant D-O event recorded in the Greenland ice core record (North
267 Greenland Ice-Core Project (NorthGRIP) Members, 2004) is also seen in the EDC methane record (Loulergue et
268 al., 2008) (Fig. 6). The same pattern of abrupt climate change is seen in many other northern hemisphere
269 climate records, with a particularly faithful representation observed in planktonic oxygen isotope and alkenone
270 SST data from marine sediment cores from the Portuguese Margin (Govin et al., 2014; Shackleton et al., 2000).
271 Note that the benthic δ^{18}O from the Portuguese Margin strongly resembles the water isotope record from
272 Antarctica (here, δD from EDC) and that the phasing of planktic and benthic δ^{18}O on the Iberian Margin is the
273 same as that seen between CH_4 and δD in the Antarctic ice core record. This pattern has been interpreted as
274 being indicative of a thermal bipolar seesaw, and offers another signature for matching ice core and marine
275 records.

276 While the planktonic oxygen isotope and alkenone SST records reproduce the NGRIP (Greenland) ice core
277 isotopic record well in terms both of shape and amplitude, the methane record is less easy to match to the marine
278 record. This is because the amplitude of methane change in comparison to isotopic change (in either the
279 Greenland ice or North Atlantic marine record) is very variable. For example Greenland Interstadial (GI) 19 (at
280 73 ka) is very strong in the isotope records but shows a methane amplitude of only 70 ppb (Baumgartner et al.,
281 2014), and a sensitivity (methane jump/Greenland temperature change) less than a third of some other events.

282   This means that, in an unknown section of older core, we could only expect to make unequivocal matches for

283   some D-O events.

284

285   Figure 6. Sharp millennial scale features in the last glacial cycle. Bottom panel: NGRIP δ^{18}O showing the

286   pattern of Dansgaard-Oeschger events (North Greenland Ice Core Project Members, 2004). Middle panel:

287   Benthic δ^{18}O (blue) from site MD95-2042 (Govin et al., 2014; Shackleton et al., 2000) and the deuterium

288   record from the Antarctic EDC ice core (Jouzel et al., 2007). Upper panel: Planktonic δ^{18}O (blue) from site

289   MD95-2042 (Govin et al., 2014; Shackleton et al., 2000) showing the same pattern as Greenland δ^{18}O; methane

290   from the Antarctic EDC ice core (red) (Loulergue et al., 2008) showing a more subdued version of the same

291   variability. Vertical lines mark examples of the sharp onsets of three interglacials (Greenland Interstadial (GI) 8,

292   14 and 21).

293

294   High resolution isotopic data and alkenone SST collected at site U1385 (Fig. 1), extending to 1.45 Ma (Hodell et

295   al., 2015), located close (25 km) to core MD95-2042 (discussed above and shown in Fig. 6) indicate that events

296   of a D-O nature extend throughout the past 1.45 Myr (Birner et al., 2016). Thus the planktonic isotope and SST

297   records from that site, soon to be published, should serve as a regional template for D-O variability. Using it

298   with the methane ice core record makes the assumption that the teleconnection between North Atlantic climate

299   variability and the (predominantly tropical) methane sources (Bock et al., 2017) remained intact before the

300   MPT. This could be tested if East Asian speleothem records extended deeper in time than is currently the case

301   (Cheng et al., 2016).

302   As an example of the potential for this method, we examine the relationship between the oldest part of the EDC

303   record (MIS 19) and the equivalent data from site U1385 (Fig. 7). Here we can clearly identify the three strong

304   millennial events on the MIS 19/18 boundary in both the marine and ice core record, with the sharp onsets in

planktonic $\delta^{18}O$ (marine) and methane (ice) and the more symmetric change in benthic $\delta^{18}O$ (marine) and δD

(ice). Carbon cycle data in both records also show the signature of the events. Radiometric ages are also

available in records that show these millennial events, adding further value to the correlations (Giaccio et al.,

2015). We note that one event (at about 780 ka) in the ice core record is not observed in the marine record,

despite the record having adequate resolution for its appearance.

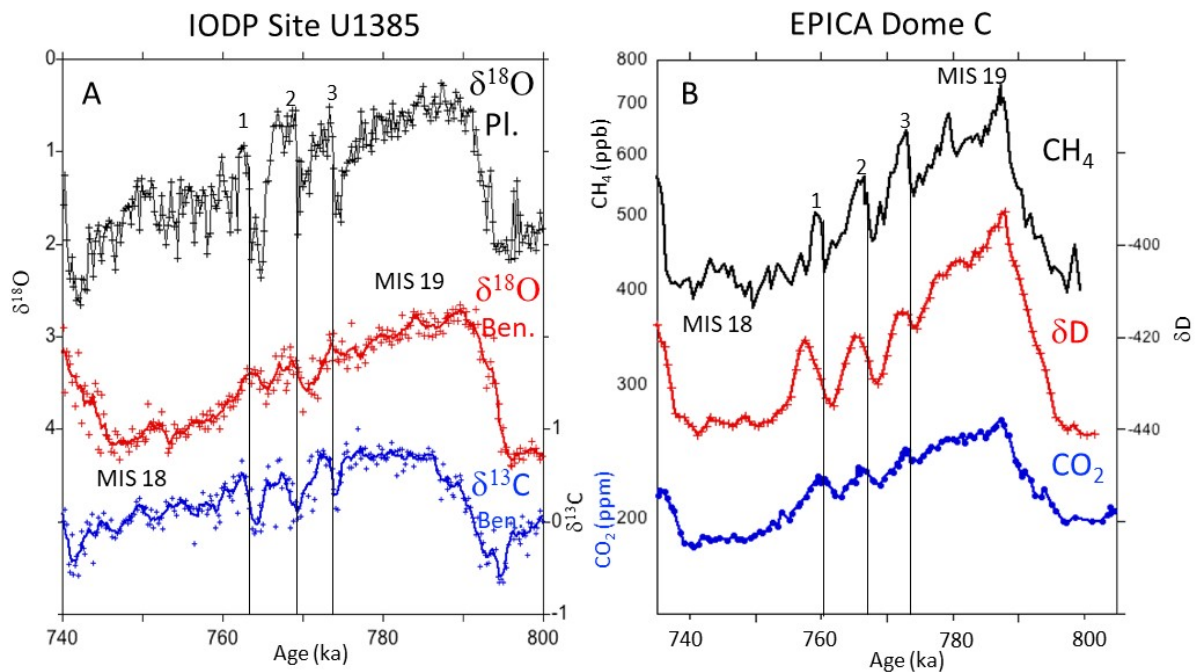



Figure 7. (A) Planktonic $\delta^{18}O$ (black), benthic $\delta^{18}O$ (red) and $\delta^{13}C$ (blue) over the MIS19-18 transition at Site

U1385 (Sánchez Goñi et al., 2016) compared to (B) CH_4 (black), δD (red) and atmospheric CO_2 (blue) in the

EPICA Dome C ice core. Three strong millennial events (labeled 1-3) occur on the MIS19-18 transition that are

recorded in both the marine sediment and ice cores. Vertical dashed lines are drawn at the abrupt transitions

from cold stadials to warmer interstadial conditions. Note that the phasing of ice core CH_4 and δD is not quite as

expected from later time periods (Fig. 6) and may reflect uncertainty in Δ-age (the age difference between the

ice and gas records).

The variable amplitude of methane peaks relative to North Atlantic records may make it harder to use than some

other records. Nonetheless the simplicity of the match at ~770 ka suggests that methane in ice for the most

prominent millennial-scale features, used in a complementary way with other records, and matched against the

Portuguese Margin datasets, will provide a viable way of aligning the marine and ice records rather precisely at

least for the cycles immediately below 800 ka. In the highly thinned ice over 1.2 Ma old, where there may be

>10 ka/m of ice (Lilien et al., 2021), the use of high-resolution continuous online laser spectrometric

measurement techniques to measure CH_4 (Chappellaz et al., 2013; Rhodes et al., 2015) should still allow

326 resolution of millennial features provided diffusion of methane (Bereiter et al., 2014) and of δD (Pol et al.,

327 2010) is limited.

6. ^{10}Be

329 The production of ^{10}Be in the atmosphere, and its subsequent deposition to Antarctic snow, is controlled by the

330 flux of cosmic rays, which in turn is influenced by the solar magnetic field (showing solar cycles), and on longer

331 timescales by changes in intensity of Earth's magnetic field. As examples, centennial scale variations in ^{10}Be in

332 ice over the last 14 kyr can be matched to variations in ^{14}C (Muscheler et al., 2014), while the Laschamp

333 magnetic excursion at about 41 kyr BP (Raisbeck et al., 2017) and the Brunhes-Matuyama magnetic reversal at

334 about 780 kyr BP (Raisbeck et al., 2006) are easily identified in ice cores. However there are, as with all

335 aerosol-bound proxies, atmospheric transport influences on the relative amount of produced ^{10}Be that is

336 transported to Antarctica. Additionally, in the central East Antarctic plateau the concentration of ^{10}Be shows a

337 very clear imprint of climate that is mainly removed by calculating the flux. We will therefore have to

338 independently estimate the snow accumulation rate in order to use any ^{10}Be template for dating.

339 In the marine record, the strength of Earth's magnetic field is imprinted in records of geomagnetic

340 palaeointensity. A number of reconstructions have been made using individual cores, but a carefully constructed

341 stack from different sites is especially valuable. The PISO-1500 stack of relative palaeointensity (RPI)

342 (Channell et al., 2009) is particularly widely used, and could serve as a template for long-term variations in ice

343 core ^{10}Be. In theory an even more direct comparator would be an index derived from the authigenic ^{10}Be/^{9}Be

344 ratios in marine sediments (Simon et al., 2018; Simon et al., 2016). Measurements extend beyond 2 Ma, and

345 show a good correlation with the RPI (Channell et al., 2009). However because detailed ^{10}Be data exist only for

346 a very few cores, the RPI might be considered a more robust dataset at this stage.

347 Both RPI and ^{10}Be/^{9}Be show the strong features that we know have been seen in the ice core record: in

348 particular the Laschamp excursion and the Brunhes-Matuyama boundary. It has been reported that the PISO-

349 1500 stack shows a good correlation with the unpublished record of ^{10}Be flux from 200-800 ka (Cauquoin,

350 2013), with a correlation coefficient reported as r=0.62 after the timescales have been aligned. Unfortunately,

351 we can only show the comparison for the few published sections of ice (Fig 8).

352 The extended datasets, both of palaeointensity (Channell et al., 2009) and authigenic ^{10}Be/^{9}Be ratios (Simon et

353 al., 2018) should therefore be useful templates with which to compare the ^{10}Be data obtained from the LDC ice

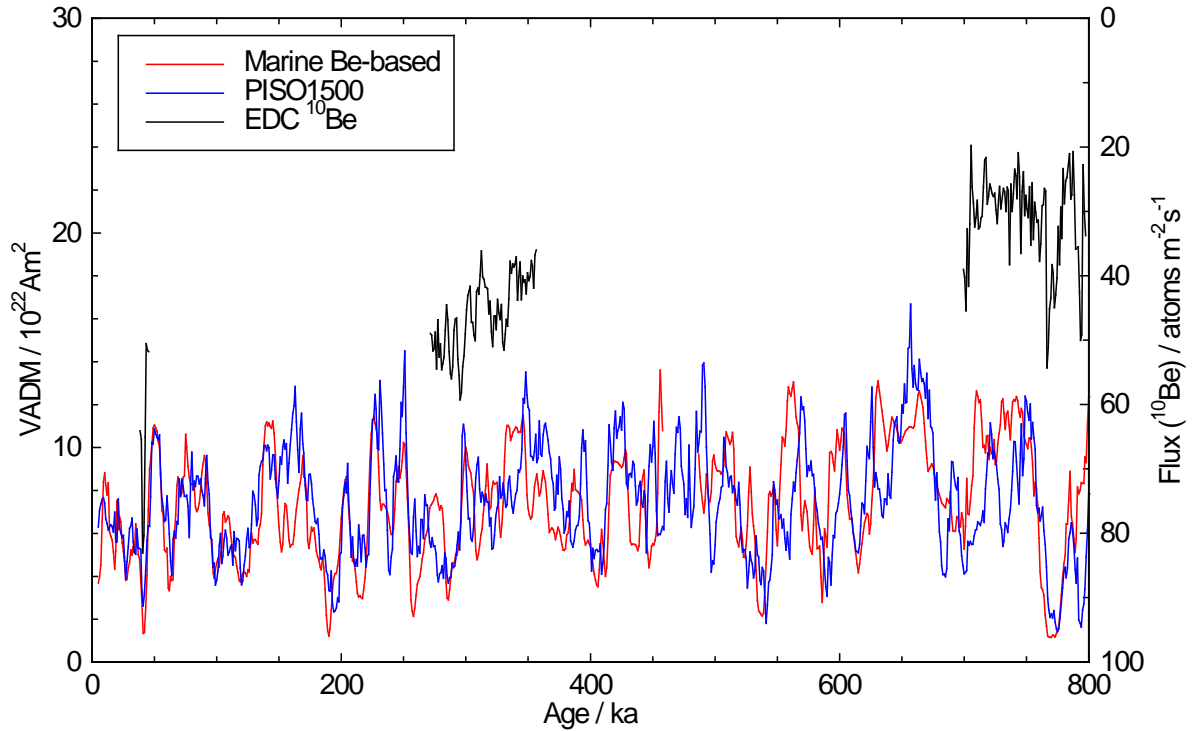
354 core. In Fig. 9 we show these two datasets, as an indication of what a ^{10}Be flux record from the new core should

355 show. Note that uncorrected ^{10}Be/^{9}Be data automatically include the degree of decay (1.39 Myr half-life) that

356 will also apply in the ice core, whereas the PISO1500 do not include that decay. The paleointensity lows

357 associated with polarity reversals in particular (Fig. 9) should be quite prominent in the ^{10}Be record (analogous

358 to the Brunhes/Matuyama boundary). Some of the other prominent excursions events should also be captured.

359

360 Figure 8. Palaeointensity and [10]Be data for the last 800 kyr. Virtual axial dipole moment (VADM) from the

361 PISO1500 palaeointensity stack (blue) (Channell et al., 2009); VADM derived from an authigenic [10]Be/[9]Be

362 ratio stack (Simon et al., 2016) using an empirical calibration (red); published [10]Be fluxes from the EDC ice

363 core (black, right axis) (Cauquoin et al., 2015; Raisbeck et al., 2017; Raisbeck et al., 2006).

364

365 There are two aspects that degrade the ability of [10]Be alone to provide a dating template. The first is that it is the

366 [10]Be flux that resembles marine data, and we will only have measurements of [10]Be concentration. This issue

367 applies also to dust (as discussed above), but the dynamic range between glacial and interglacial for dust is so

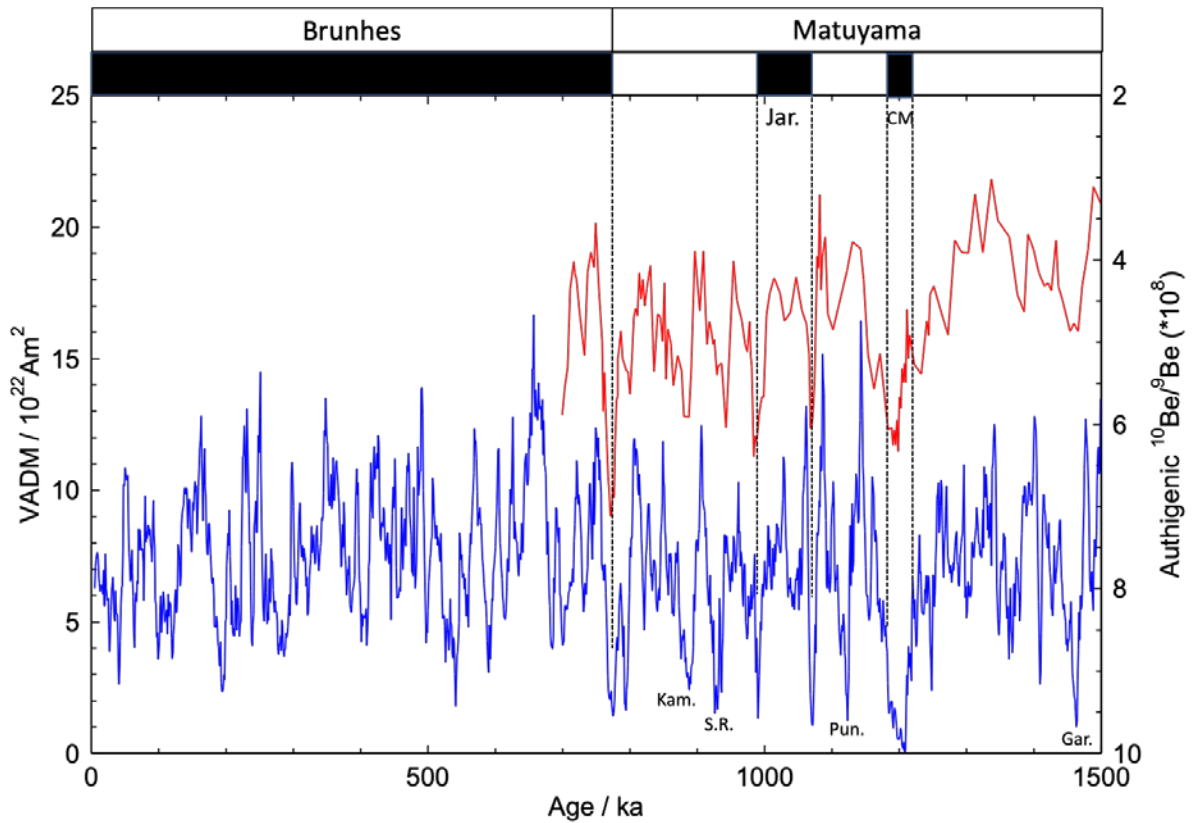
368 great (factor 10 in marine sediments, higher still in ice) that the influence of accumulation rate changes is second

369 order and does not mask the signal that is common between ice and marine sediments. For [10]Be the range of the

370 data (factor 2 between low and high) is similar to the range of accumulation rates, meaning that the

371 concentration is equally influenced by the cosmogenic production rate and the snow accumulation rate. By itself

372 the [10]Be concentration will be hard to place onto the template.

373

374 Figure 9. Palaeointensity and authigenic ^{10}Be/^{9}Be from marine sediments for the last 1.5 Myr. Virtual axial

375 dipole moment (VADM) from the PISO1500 palaeointensity stack (blue) (Channell et al., 2009); authigenic

376 ^{10}Be/^{9}Be (decay-corrected) from core MD97-2143 (red) (Simon et al., 2018). Each of the polarity reversals

377 (Brunhes, Jaramillo, Cobb Mountain) is associated with a palaeointensity low. Other prominent excursions in

378 the Matuyama Chron are labeled: Kam = Kamikatsura; S.R. = Santa Rosa; Pun = Punaruu; Gar = Gardar

379 (Channell, 2017).

380

381 There is one possible way to deal with this issue. The accumulation rate for the EDC core was actually a product

382 derived from the age modelling, but based on a prior where the accumulation rate was assumed to be directly

383 related to the temperature and hence to the water isotope ratios. If we assume that that relationship was

384 unchanged over 1.5 million years then the best fit values from the 800 kyr of EDC could be used, along with

385 water isotope ratios measured at LDC to estimate the accumulation rate for each depth and therefore calculate a

386 flux of ^{10}Be. This will have considerable uncertainties but is likely to allow identification of the main features in

387 the expected ^{10}Be record.

388 An additional problem is the one encountered when the Brunhes-Matuyama section of the EDC ice core was

389 analysed (Raisbeck et al., 2006), that ^{10}Be in deeper ice shows spikes that appear to be inhomogeneous across

390 the core and may be associated with high concentrations of dust and other chemical concentrations. The spikes

391 have been tentatively ascribed to a concentration effect where ^{10}Be becomes associated with dust particles which

392 also seem to clump together into aggregates in the deeper ice (de Angelis et al., 2013). For the Brunhes-

393 Matuyama section of the EDC ice core, the spikiness in ^{10}Be was bypassed using median concentrations

394 (Raisbeck et al., 2006), and it may be that such a strategy will continue to work in older ice. However, further
395 work is needed to understand the conditions that lead to this effect.

7. Discussion and conclusion

397 We have presented templates for what an undisturbed (i.e., where time is monotonic with depth) ice core from
398 LDC might be expected to show. We summarise the 4 methods we have considered in Table 1. The marine dust
399 record (represented here by Fe MAR at ODP site 1090) could, with reasonable assumptions, be an excellent
400 template for the LDC dust record. The Mg/Ca data from site 1123, matched against the LDC water isotope
401 record, could provide limited additional validation, although the correlation between records over the past 800
402 kyr is less strong than for dust. The methane data, matched against D-O variability at site U1385 may be capable
403 of adding some sharper tie points in a record that has already been matched to first order. ^{10}Be concentration,
404 converted to an estimated flux using water isotope data, should be a useful additional validationconstraint,
405 particularly in identifying the major features with low Vertical Axial Dipole Moment (VADM) and expected
406 high ^{10}Be concentration. All of the constraints provided by this method and others would be included within a
407 Bayesian framework using a program such as IceChrono (Parrenin et al., 2015), which would provide an
408 estimate of the uncertainty.

Ice core measure	Template	Assumptions	Comments
Dust	South Atlantic marine core dust proxy	Changes in atmospheric transport do not overwhelm the common source signature	Good matches at multimillennial scale even when using ice core concentration
Water isotopes	Southern marine benthic Mg/Ca	Antarctic surface temperatures continue to drive southern deepwater temperature	Good match at orbital scale, but less good for cycles of weaker amplitude
Methane	Portuguese Margin marine planktic δ^{18}O	Both records record common millennial variabiity	Millennial scale alignment possible, but different amplitudes for individual peaks would make it hard to use alone.
^{10}Be	Paleointensity measures in marine cores	Both records dominated at long timescales by strength of Earth's magnetic field	Requires estimate of ice accumulation rate to derive ^{10}Be flux; statistical issues with ^{10}Be spikes need to be solved.

409

410 Table 1: Characteristics of possible template matching methods for a 1.5 million year ice core

411

412 It will be a greater challenge to use these records to aid the age modelling if the record is disturbed, with folds or
413 missing ice, as has often been the case with ice near the bed of ice sheets (e.g. NEEM Community Members,
414 2013). In that case, one cannot rely on the shape of the signal to identify the time period represented. Instead, we
415 are dependent on using the absolute values – for example finding a time period where the values in the templates

416   are all consistent with the measured values. The derived [10]Be production may be particularly important in this

417   case, because it is independent of climate and, thus, may provide a more robust age assignment compared to the

418   other templates considered here, which are highly correlated on glacial/interglacial time scales. This will have to

419   be done with considerable caution, given the uncertainties involved in the assumptions about the unchanged

420   relationship between the measured values and their marine equivalents over time. Finally an age model for the

421   new core will of course also use other data, including those from gas measurements ($\delta^{18}O_{atm}$ and O_2/N_2, which

422   can be matched to calculated orbital targets), and any radiometric absolute ages that can be obtained from the

423   limited ice volumes available.

Data availability

425   All the datasets shown in this paper have already been published elsewhere, as indicated by the relevant

426   references.

Author contribution

428   All authors conceived the idea for this paper. EW prepared the first draft and all authors reviewed and edited the

429   text.

Competing interests

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

Acknowledgments

433   This publication was generated in the frame of Beyond EPICA. The project has received funding from the

434   European Union's Horizon 2020 research and innovation programme under grant agreement No. 815384

435   (Oldest Ice Core). It is supported by national partners and funding agencies in Belgium, Denmark, France,

436   Germany, Italy, Norway, Sweden, Switzerland, The Netherlands and the United Kingdom. Logistic support is

437   mainly provided by PNRA and IPEV through the Concordia Station system. The opinions expressed and

438   arguments employed herein do not necessarily reflect the official views of the European Union funding agency

439   or other national funding bodies. This is Beyond EPICA publication number XX. This publication is also

440   associated with the Million Year Ice Core (MYIC) Project of the Australian Antarctic Program (AAP). We

441   thank Alexander Cauquoin and Grant Raisbeck for advice about the published [10]Be data. EW was supported by

442   a Royal Society Professorship. HF acknowledges the long-term financial support of ice core science by the

443   Swiss National Science Foundation. TvO acknowledges support by the Australian Government Department of

444   Industry, Science, Energy and Resources (grant no. ASCI000002). We thank 4 reviewers for their helpful

445   comments.

446

References

447 **References**

448 Ahn, S., Khider, D., Lisiecki, L. E., and Lawrence, C. E.: A probabilistic Pliocene–Pleistocene stack of
449 benthic δ18O using a profile hidden Markov model, Dynamics and Statistics of the Climate System, 2,
450 doi: 10.1093/climsys/dzx002, 2017.

451

452 Baggenstos, D., Häberli, M., Schmitt, J., Shackleton, S. A., Birner, B., Severinghaus, J. P., Kellerhals, T.,
453 and Fischer, H.: Earth's radiative imbalance from the Last Glacial Maximum to the present,
454 Proceedings of the National Academy of Sciences, 116, 14881, doi: 10.1073/pnas.1905447116, 2019.

455

456 Barker, S., Knorr, G., Edwards, R. L., Parrenin, F., Putnam, A. E., Skinner, L. C., Wolff, E. W., and
457 Ziegler, M.: 800,000 years of abrupt climate variability, Science, 334, 347-351, 2011.

458

459 Baumgartner, M., Kindler, P., Eicher, O., Floch, G., Schilt, A., Schwander, J., Spahni, R., Capron, E.,
460 Chappellaz, J., Leuenberger, M., Fischer, H., and Stocker, T. F.: NGRIP CH4 concentration from 120 to
461 10 kyr before present and its relation to a delta N-15 temperature reconstruction from the same ice
462 core, Climate of the Past, 10, 903-920, doi: 10.5194/cp-10-903-2014, 2014.

463

464 Bazin, L., Landais, A., Lemieux-Dudon, B., Kele, H. T. M., Veres, D., Parrenin, F., Martinerie, P., Ritz, C.,
465 Capron, E., Lipenkov, V., Loutre, M. F., Raynaud, D., Vinther, B., Svensson, A., Rasmussen, S. O.,
466 Severi, M., Blunier, T., Leuenberger, M., Fischer, H., Masson-Delmotte, V., Chappellaz, J., and Wolff,
467 E. W.: An optimised multi-proxy, multi-site Antarctic ice and gas orbital chronology (AICC2012): 120-
468 800 ka, Climate of the Past 9, 1715-1731, 2013.

469

470 Bender, M. L., Barnett, B., Dreyfus, G., Jouzel, J., and Porcelli, D.: The contemporary degassing rate of
471 ^{40}Ar from the solid Earth, Proceedings of the National Academy of Sciences, 105, 8232, doi:
472 10.1073/pnas.0711679105, 2008.

473

474 Bereiter, B., Eggleston, S., Schmitt, J., Nehrbass-Ahles, C., Stocker, T. F., Fischer, H., Kipfstuhl, S., and
475 Chappellaz, J.: Revision of the EPICA Dome C CO2 record from 800 to 600 kyr before present,
476 Geophys. Res. Lett., 42, 542-549, doi: 10.1002/2014GL061957, 2015.

477

478 Bereiter, B., Fischer, H., Schwander, J., and Stocker, T. F.: Diffusive equilibration of N-2, O-2 and CO2
479 mixing ratios in a 1.5-million-years-old ice core, Cryosphere, 8, 245-256, doi: 10.5194/tc-8-245-2014,
480 2014.

481

482 Bereiter, B., Shackleton, S., Baggenstos, D., Kawamura, K., and Severinghaus, J.: Mean global ocean
483 temperatures during the last glacial transition, Nature, 553, 39, doi: 10.1038/nature25152

484 https://www.nature.com/articles/nature25152#supplementary-information, 2018.

485

486 Birner, B., Hodell, D. A., Tzedakis, P. C., and Skinner, L. C.: Similar millennial climate variability on the
487 Iberian margin during two early Pleistocene glacials and MIS 3, Paleoceanography, 31, 203-217, doi:
488 10.1002/2015pa002868, 2016.

489

Bock, M., Schmitt, J., Beck, J., Seth, B., Chappellaz, J., and Fischer, H.: Glacial/interglacial wetland, biomass burning, and geologic methane emissions constrained by dual stable isotopic CH4 ice core records, Proceedings of the National Academy of Sciences, doi: 10.1073/pnas.1613883114, 2017. doi: 10.1073/pnas.1613883114, 2017.

Buizert, C., Baggenstos, D., Jiang, W., Purtschert, R., Petrenko, V. V., Lu, Z. T., Muller, P., Kuhl, T., Lee, J., Severinghaus, J. P., and Brook, E. J.: Radiometric Kr-81 dating identifies 120,000-year-old ice at Taylor Glacier, Antarctica, Proc. Natl. Acad. Sci. U. S. A., 111, 6876-6881, doi: 10.1073/pnas.1320329111, 2014.

Buizert, C., Fudge, T. J., Roberts, W. H. G., Steig, E. J., Sherriff-Tadano, S., Ritz, C., Lefebvre, E., Edwards, J., Kawamura, K., Oyabu, I., Motoyama, H., Kahle, E. C., Jones, T. R., Abe-Ouchi, A., Obase, T., Martin, C., Corr, H., Severinghaus, J. P., Beaudette, R., Epifanio, J. A., Brook, E. J., Martin, K., Chappellaz, J., Aoki, S., Nakazawa, T., Sowers, T. A., Alley, R. B., Ahn, J., Sigl, M., Severi, M., Dunbar, N. W., Svensson, A., Fegyveresi, J. M., He, C., Liu, Z., Zhu, J., Otto-Bliesner, B. L., Lipenkov, V. Y., Kageyama, M., and Schwander, J.: Antarctic surface temperature and elevation during the Last Glacial Maximum, Science, 372, 1097, doi: 10.1126/science.abd2897, 2021.

Cauquoin, A.: Flux de 10Be en Antarctique durant les 800 000 dernières années et interprétation., Ph.D., Sciences de la Terre, Université Paris Sud, Paris, 205 pp., 2013.

Cauquoin, A., Landais, A., Raisbeck, G. M., Jouzel, J., Bazin, L., Kageyama, M., Peterschmitt, J. Y., Werner, M., Bard, E., and Team, A.: Comparing past accumulation rate reconstructions in East Antarctic ice cores using ¹⁰Be, water isotopes and CMIP5-PMIP3 models, Clim. Past, 11, 355-367, doi: 10.5194/cp-11-355-2015, 2015.

Channell, J. E. T.: Magnetic excursions in the late Matuyama Chron (Olduvai to Matuyama-Brunhes boundary) from North Atlantic IODP sites, J. Geophys. Res.-Solid Earth, 122, 773-789, doi: 10.1002/2016jb013616, 2017.

Channell, J. E. T., Xuan, C., and Hodell, D. A.: Stacking paleointensity and oxygen isotope data for the last 1.5 Myr (PISO-1500), Earth planet. Sci. Lett., 283, 14-23, doi: https://doi.org/10.1016/j.epsl.2009.03.012, 2009.

Chappellaz, J., Stowasser, C., Blunier, T., Baslev-Clausen, D., Brook, E. J., Dallmayr, R., Fain, X., Lee, J. E., Mitchell, L. E., Pascual, O., Romanini, D., Rosen, J., and Schupbach, S.: High-resolution glacial and deglacial record of atmospheric methane by continuous-flow and laser spectrometer analysis along the NEEM ice core, Climate of the Past, 9, 2579-2593, doi: 10.5194/cp-9-2579-2013, 2013.

Cheng, H., Edwards, R. L., Sinha, A., Spotl, C., Yi, L., Chen, S. T., Kelly, M., Kathayat, G., Wang, X. F., Li, X. L., Kong, X. G., Wang, Y. J., Ning, Y. F., and Zhang, H. W.: The Asian monsoon over the past 640,000 years and ice age terminations, Nature, 534, 640-+, doi: 10.1038/nature18591, 2016.

Clark, P. U., Archer, D., Pollard, D., Blum, J. D., Rial, J. A., Brovkin, V., Mix, A. C., Pisias, N. G., and Roy, M.: The middle Pleistocene transition: characteristics. mechanisms, and implications for long-term

535   changes in atmospheric PCO2, Quat. Sci. Rev., 25, 3150-3184, doi: 10.1016/j.quascirev.2006.07.008,
536   2006.

537

538   Crotti, I., Landais, A., Stenni, B., Bazin, L., Parrenin, F., Frezzotti, M., Ritterbusch, F., Lu, Z.-T., Jiang,
539   W., Yang, G.-M., Fourré, E., Orsi, A., Jacob, R., Minster, B., Prié, F., Dreossi, G., and Barbante, C.: An
540   extension of the TALDICE ice core age scale reaching back to MIS 10.1, Quat. Sci. Rev., 266, 107078,
541   doi: https://doi.org/10.1016/j.quascirev.2021.107078, 2021.

542

543   de Angelis, M., Tison, J. L., Morel-Fourcade, M. C., and Susini, J.: Micro-investigation of EPICA Dome
544   C bottom ice: evidence of long term in situ processes involving acid-salt interactions, mineral dust,
545   and organic matter, Quat. Sci. Rev., 78, 248-265, doi: 10.1016/j.quascirev.2013.08.012, 2013.

546

547   Delmas, R. J., Beer, J., Synal, H. A., Muscheler, R., Petit, J. R., and Pourchet, M.: Bomb-test Cl-36
548   measurements in Vostok snow (Antarctica) and the use of Cl-36 as a dating tool for deep ice cores,
549   Tellus Ser. B-Chem. Phys. Meteorol., 56, 492-498, doi: 10.1111/j.1600-0889.2004.00109.x, 2004.

550

551   Delmonte, B., Andersson, P. S., Hansson, M., Schoberg, H., Petit, J. R., Basile-Doelsch, I., and Maggi,
552   V.: Aeolian dust in East Antarctica (EPICA-Dome C and Vostok): Provenance during glacial ages over
553   the last 800 kyr, Geophys. Res. Lett., 35, L07703, doi: 10.1029/2008GL033382, 2008.

554

555   Elderfield, H., Ferretti, P., Greaves, M., Crowhurst, S., McCave, I. N., Hodell, D., and Piotrowski, A. M.:
556   Evolution of ocean temperature and ice volume through the Mid-Pleistocene Climate Transition,
557   Science, 337, 704-709, 2012.

558

559   Extier, T., Landais, A., Bréant, C., Prié, F., Bazin, L., Dreyfus, G., Roche, D. M., and Leuenberger, M.:
560   On the use of δ18Oatm for ice core dating, Quat. Sci. Rev., 185, 244-257, doi:
561   https://doi.org/10.1016/j.quascirev.2018.02.008, 2018.

562

563   Fischer, H., Fundel, F., Ruth, U., Twarloh, B., Wegner, A., Udisti, R., Becagli, S., Castellano, E.,
564   Morganti, A., Severi, M., Wolff, E. W., Littot, G. C., Rothlisberger, R., Mulvaney, R., Hutterli, M. A.,
565   Kaufmann, P., Federer, U., Lambert, F., Bigler, M., Hansson, M., Jonsell, U., de Angelis, M., Gabrielli,
566   P., Boutron, C., Siggaard-Andersen, M. L., Steffensen, J. P., Barbante, C., Gaspari, V., and Wagenbach,
567   D.: Reconstruction of millennial changes in transport, dust emission and regional differences in sea
568   ice coverage using the deep EPICA ice cores from the Atlantic and Indian Ocean sector of Antarctica.,
569   Earth planet. Sci. Lett., 260, 340-354, 2007a.

570

571   Fischer, H., Severinghaus, J., Brook, E., Wolff, E., Albert, M., Alemany, O., Arthern, R., Bentley, C.,
572   Blankenship, D., Chappellaz, J., Creyts, T., Dahl-Jensen, D., Dinn, M., Frezzotti, M., Fujita, S., Gallee,
573   H., Hindmarsh, R., Hudspeth, D., Jugie, G., Kawamura, K., Lipenkov, V., Miller, H., Mulvaney, R.,
574   Pattyn, F., Ritz, C., Schwander, J., Steinhage, D., van Ommen, T., and Wilhelms, F.: Where to find 1.5
575   million yr old ice for the IPICS "Oldest Ice" ice core, Climate of the Past, 9, 2489-2505, doi:
576   10.5194/cpd-9-2771-2013, 2013.

577

578   Fischer, H., Siggaard-Andersen, M. L., Ruth, U., Rothlisberger, R., and Wolff, E. W.: Glacial-interglacial
579   changes in mineral dust and sea salt records in polar ice cores: sources, transport, deposition, Rev.
580   Geophys., 45, RG1002, doi: 10.1029/2005RG000192, 2007b.

581

582 Ford, H. L. and Raymo, M. E.: Regional and global signals in seawater δ18O records across the mid-
583 Pleistocene transition, Geology, 48, 113-117, doi: 10.1130/G46546.1, 2019.

584

585 Giaccio, B., Regattieri, E., Zanchetta, G., Nomade, S., Renne, P. R., Sprain, C. J., Drysdale, R. N.,
586 Tzedakis, P. C., Messina, P., Scardia, G., Sposato, A., and Bassinot, F.: Duration and dynamics of the
587 best orbital analogue to the present interglacial, Geology, 43, 603-606, doi: 10.1130/G36677.1,
588 2015.

589

590 Govin, A., Chiessi, C. M., Zabel, M., Sawakuchi, A. O., Heslop, D., Hörner, T., Zhang, Y., and Mulitza,
591 S.: Terrigenous input off northern South America driven by changes in Amazonian climate and the
592 North Brazil Current retroflection during the last 250 ka, Clim. Past, 10, 843-862, doi: 10.5194/cp-10-
593 843-2014, 2014.

594

595 Grootes, P. M., Stuiver, M., White, J. W. C., Johnsen, S., and Jouzel, J.: Comparison of oxygen isotope
596 records from the GISP2 and GRIP Greenland ice cores, Nature, 366, 552-554, 1993.

597

598 Hodell, D., Lourens, L., Crowhurst, S., Konijnendijk, T., Tjallingii, R., Jiménez-Espejo, F., Skinner, L.,
599 Tzedakis, P. C., Abrantes, F., Acton, G. D., Alvarez Zarikian, C. A., Bahr, A., Balestra, B., Barranco, E. L.,
600 Carrara, G., Ducassou, E., Flood, R. D., Flores, J.-A., Furota, S., Grimalt, J., Grunert, P., Hernández-
601 Molina, J., Kim, J. K., Krissek, L. A., Kuroda, J., Li, B., Lofi, J., Margari, V., Martrat, B., Miller, M. D.,
602 Nanayama, F., Nishida, N., Richter, C., Rodrigues, T., Rodríguez-Tovar, F. J., Roque, A. C. F., Sanchez
603 Goñi, M. F., Sierro Sánchez, F. J., Singh, A. D., Sloss, C. R., Stow, D. A. V., Takashimizu, Y., Tzanova, A.,
604 Voelker, A., Xuan, C., and Williams, T.: A reference time scale for Site U1385 (Shackleton Site) on the
605 SW Iberian Margin, Global and Planetary Change, 133, 49-64, doi: 10.1016/j.gloplacha.2015.07.002,
606 2015.

607

608 Jouzel, J., Alley, R. B., Cuffey, K. M., Dansgaard, W., Grootes, P., Hoffmann, G., Johnsen, S. J., Koster,
609 R. D., Peel, D., Shuman, C. A., Stievenard, M., Stuiver, M., and White, J.: Validity of the temperature
610 reconstruction from water isotopes in ice cores, J. Geophys. Res., 102, 26471-26487, 1997.

611

612 Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., Nouet, J., Barnola,
613 J. M., Chappellaz, J., Fischer, H., Gallet, J. C., Johnsen, S., Leuenberger, M., Loulergue, L., Luethi, D.,
614 Oerter, H., Parrenin, F., Raisbeck, G., Raynaud, D., Schwander, J., Spahni, R., Souchez, R., Selmo, E.,
615 Schilt, A., Steffensen, J. P., Stenni, B., Stauffer, B., Stocker, T., Tison, J.-L., Werner, M., and Wolff, E.
616 W.: Orbital and millennial Antarctic climate variability over the last 800 000 years, Science, 317, 793-
617 796, doi: 10.1126/science.1141038, 2007.

618

619 Kawamura, K., Abe-Ouchi, A., Motoyama, H., Ageta, Y., Aoki, S., Azuma, N., Fujii, Y., Fujita, K., Fujita,
620 S., Fukui, K., Furukawa, T., Furusaki, A., Goto-Azuma, K., Greve, R., Hirabayashi, M., Hondoh, T., Hori,
621 A., Horikawa, S., Horiuchi, K., Igarashi, M., Iizuka, Y., Kameda, T., Kanda, H., Kohno, M., Kuramoto, T.,
622 Matsushi, Y., Miyahara, M., Miyake, T., Miyamoto, A., Nagashima, Y., Nakayama, Y., Nakazawa, T.,
623 Nakazawa, F., Nishio, F., Obinata, I., Ohgaito, R., Oka, A., Okuno, J., Okuyama, J., Oyabu, I., Parrenin,
624 F., Pattyn, F., Saito, F., Saito, T., Saito, T., Sakurai, T., Sasa, K., Seddik, H., Shibata, Y., Shinbori, K.,
625 Suzuki, K., Suzuki, T., Takahashi, A., Takahashi, K., Takahashi, S., Takata, M., Tanaka, Y., Uemura, R.,
626 Watanabe, G., Watanabe, O., Yamasaki, T., Yokoyama, K., Yoshimori, M., Yoshimoto, T., and Dome

627   Fuji Ice Core, P.: State dependence of climatic instability over the past 720,000 years from Antarctic
628   ice cores and climate modeling, Science Advances, 3, doi: 10.1126/sciadv.1600446, 2017.

629
630   Kawamura, K., Parrenin, F., Lisiecki, L., Uemura, R., Vimeux, F., Severinghaus, J. P., Hutterli, M. A.,
631   Nakazawa, T., Aoki, S., Jouzel, J., Raymo, M. E., Matsumoto, K., Nakata, H., Motoyama, H., Fujita, S.,
632   Azuma, K., Fujii, Y., and Watanabe, O.: Northern Hemisphere forcing of climatic cycles over the past
633   360,000 years implied by accurately dated Antarctic ice cores, Nature, 448, 912-916, 2007.

634
635   Lambert, F., Delmonte, B., Petit, J. R., Bigler, M., Kaufmann, P. R., Hutterli, M. A., Stocker, T. F., Ruth,
636   U., Steffensen, J. P., and Maggi, V.: Dust-climate couplings over the past 800,000 years from the
637   EPICA Dome C ice core, Nature, 452, 616-619, 2008.

638
639   Lilien, D. A., Steinhage, D., Taylor, D., Parrenin, F., Ritz, C., Mulvaney, R., Martín, C., Yan, J. B., O'Neill,
640   C., Frezzotti, M., Miller, H., Gogineni, P., Dahl-Jensen, D., and Eisen, O.: Brief communication: New
641   radar constraints support presence of ice older than 1.5 Myr at Little Dome C, The Cryosphere, 15,
642   1881-1888, doi: 10.5194/tc-15-1881-2021, 2021.

643
644   Lisiecki, L. E. and Raymo, M. E.: Plio-Pleistocene climate evolution: trends and transitions in glacial
645   cycle dynamics, Quat. Sci. Rev., 26, 56-69, doi: 10.1016/j.quascirev.2006.09.005, 2007.

646
647   Lisiecki, L. E. and Raymo, M. E.: A Pliocene-Pleistocene stack of 57 globally distributed benthic delta
648   O-18 records, Paleoceanography, 20, PA1003, doi: 10.1029/2004PA001071, 2005.

649
650   Loulergue, L., Schilt, A., Spahni, R., Masson-Delmotte, V., Blunier, T., Lemieux, B., Barnola, J. M.,
651   Raynaud, D., Stocker, T. F., and Chappellaz, J.: Orbital and millennial-scale features of atmospheric
652    $CH4$ over the last 800,000 years, Nature, 453, 383-386, 2008.

653
654   Markle, B. R., Steig, E. J., Roe, G. H., Winckler, G., and McConnell, J. R.: Concomitant variability in
655   high-latitude aerosols, water isotopes and the hydrologic cycle, Nature Geoscience, 11, 853-859, doi:
656   10.1038/s41561-018-0210-9, 2018.

657
658   Martinez-Garcia, A., Rosell-Mele, A., Jaccard, S. L., Geibert, W., Sigman, D. M., and Haug, G. H.:
659   Southern Ocean dust-climate coupling over the past four million years, Nature, 476, 312-U141, doi:
660   10.1038/nature10310, 2011.

661
662   Muscheler, R., Adolphi, F., and Knudsen, M. F.: Assessing the differences between the IntCal and
663   Greenland ice-core time scales for the last 14,000 years via the common cosmogenic radionuclide
664   variations, Quat. Sci. Rev., 106, 81-87, doi: 10.1016/j.quascirev.2014.08.017, 2014.

665
666   NEEM Community Members: Eemian interglacial reconstructed from a Greenland folded ice core
667   Nature, 493, 489-494, doi: 10.1038/nature11789, 2013.

668
669   North Greenland Ice-Core Project (NorthGRIP) Members: High-resolution record of Northern
670   Hemisphere climate extending into the last interglacial period, Nature, 431, 147-151, 2004.

671

672 North Greenland Ice Core Project Members: High-resolution record of Northern Hemisphere climate
673 extending into the last interglacial period, Nature, 431, 147-151, 2004.

674

675 Parrenin, F., Bazin, L., Capron, E., Landais, A., Lemieux-Dudon, B., and Masson-Delmotte, V.:
676 IceChrono1: a probabilistic model to compute a common and optimal chronology for several ice
677 cores, Geosci. Model Dev., 8, 1473-1492, doi: 10.5194/gmd-8-1473-2015, 2015.

678

679 Petit, J. R. and Delmonte, B.: A model for large glacial-interglacial climate-induced changes in dust
680 and sea salt concentrations in deep ice cores (central Antarctica): paleoclimatic implications and
681 prospects for refining ice core chronologies, Tellus B, 61, 768-790, doi: 10.1111/j.1600-
682 0889.2009.00437.x, 2009.

683

684 Pol, K., Masson-Delmotte, V., Johnsen, S., Bigler, M., Cattani, O., Durand, G., Falourd, S., Jouzel, J.,
685 Minster, B., Parrenin, F., Ritz, C., Steen-Larsen, H. C., and Stenni, B.: New MIS 19 EPICA Dome C high
686 resolution deuterium data: Hints for a problematic preservation of climate variability at sub-
687 millennial scale in the "oldest ice", Earth planet. Sci. Lett., 298, 95-103, doi:
688 10.1016/j.epsl.2010.07.030, 2010.

689

690 Raisbeck, G. M., Cauquoin, A., Jouzel, J., Landais, A., Petit, J. R., Lipenkov, V. Y., Beer, J., Synal, H. A.,
691 Oerter, H., Johnsen, S. J., Steffensen, J. P., Svensson, A., and Yiou, F.: An improved north–south
692 synchronization of ice core records around the 41 kyr 10Be peak, Clim. Past, 13, 217-229, doi:
693 10.5194/cp-13-217-2017, 2017.

694

695 Raisbeck, G. M., Yiou, F., Cattani, O., and Jouzel, J.: [10]Be evidence for the Matuyama-Brunhes
696 geomagnetic reversal in the EPICA Dome C ice core, Nature, 444, 82-84, 2006.

697

698 Raymo, M. E., Lisiecki, L. E., and Nisancioglu, K. H.: Plio-pleistocene ice volume, Antarctic climate,
699 and the global delta O-18 record, Science, 313, 492-495, 2006.

700

701 Rhodes, R. H., Brook, E. J., Chiang, J. C. H., Blunier, T., Maselli, O. J., McConnell, J. R., Romanini, D.,
702 and Severinghaus, J. P.: Enhanced tropical methane production in response to iceberg discharge in
703 the North Atlantic, Science, 348, 1016-1019, doi: 10.1126/science.1262005, 2015.

704

705 Sánchez Goñi, M. F., Rodrigues, T., Hodell, D. A., Polanco-Martínez, J. M., Alonso-García, M.,
706 Hernández-Almeida, I., Desprat, S., and Ferretti, P.: Tropically-driven climate shifts in southwestern
707 Europe during MIS 19, a low eccentricity interglacial, Earth planet. Sci. Lett., 448, 81-93, doi:
708 https://doi.org/10.1016/j.epsl.2016.05.018, 2016.

709

710 Shackleton, N. J., Hall, M. A., and Vincent, E.: Phase relationships between millennial-scale events
711 64,000-24,000 years ago, Paleoceanography, 15, 565-569, 2000.

712

713 Shackleton, S., Baggenstos, D., Menking, J. A., Dyonisius, M. N., Bereiter, B., Bauska, T. K., Rhodes, R.
714 H., Brook, E. J., Petrenko, V. V., McConnell, J. R., Kellerhals, T., Häberli, M., Schmitt, J., Fischer, H.,
715 and Severinghaus, J. P.: Global ocean heat content in the Last Interglacial, Nature Geoscience, 13,
716 77-81, doi: 10.1038/s41561-019-0498-0, 2020.

717

718 Shackleton, S., Menking, J. A., Brook, E., Buizert, C., Dyonisius, M. N., Petrenko, V. V., Baggenstos, D.,
719 and Severinghaus, J. P.: Evolution of mean ocean temperature in Marine Isotope Stage 4, Clim. Past,
720 17, 2273-2289, doi: 10.5194/cp-17-2273-2021, 2021.

721

722 Shakun, J. D., Lea, D. W., Lisiecki, L. E., and Raymo, M. E.: An 800-kyr record of global surface ocean
723 and implications for ice volume-temperature coupling, Earth planet. Sci. Lett., 426, 58-68, doi:
724 10.1016/j.epsl.2015.05.042, 2015.

725

726 Simon, Q., Bourlès, D. L., Thouveny, N., Horng, C.-S., Valet, J.-P., Bassinot, F., and Choy, S.:
727 Cosmogenic signature of geomagnetic reversals and excursions from the Réunion event to the
728 Matuyama–Brunhes transition (0.7–2.14 Ma interval), Earth planet. Sci. Lett., 482, 510-524, doi:
729 https://doi.org/10.1016/j.epsl.2017.11.021, 2018.

730

731 Simon, Q., Thouveny, N., Bourlès, D. L., Valet, J.-P., Bassinot, F., Ménabréaz, L., Guillou, V., Choy, S.,
732 and Beaufort, L.: Authigenic 10Be/9Be ratio signatures of the cosmogenic nuclide production linked
733 to geomagnetic dipole moment variation since the Brunhes/Matuyama boundary, Journal of
734 Geophysical Research: Solid Earth, 121, 7716-7741, doi: 10.1002/2016JB013335, 2016.

735

736 Sosdian, S. and Rosenthal, Y.: Deep-Sea Temperature and Ice Volume Changes Across the Pliocene-
737 Pleistocene Climate Transitions, Science, 325, 306-310, doi: 10.1126/science.1169938, 2009.

738

739 Wolff, E. W., Barbante, C., Becagli, S., Bigler, M., Boutron, C. F., Castellano, E., De Angelis, M.,
740 Federer, U., Fischer, H., Fundel, F., Hansson, M., Hutterli, M., Jonsell, U., Karlin, T., Kaufmann, P.,
741 Lambert, F., Littot, G. C., Mulvaney, R., Rothlisberger, R., Ruth, U., Severi, M., Siggaard-Andersen, M.
742 L., Sime, L. C., Steffensen, J. P., Stocker, T. F., Traversi, R., Twarloh, B., Udisti, R., Wagenbach, D., and
743 Wegner, A.: Changes in environment over the last 800,000 years from chemical analysis of the EPICA
744 Dome C ice core, Quat. Sci. Rev., 29, 285-295, doi: 10.1016/j.quascirev.2009.06.013, 2010.

745

746 Yan, Y., Bender, M. L., Brook, E. J., Clifford, H. M., Kemeny, P. C., Kurbatov, A. V., Mackay, S.,
747 Mayewski, P. A., Ng, J., Severinghaus, J. P., and Higgins, J. A.: Two-million-year-old snapshots of
748 atmospheric gases from Antarctic ice, Nature, 574, 663-666, doi: 10.1038/s41586-019-1692-3, 2019.

749

750