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Citation for final published version:

Doughty, Alice M., Kaplan, Michael R., Peltier, Carly and Barker, Stephen  
ORCID: <https://orcid.org/0000-0001-7870-6431> 2021. A maximum in global glacier extent during MIS 4. Quaternary Science Reviews 261 , 106948.  
10.1016/j.quascirev.2021.106948 file

Publishers page: <https://doi.org/10.1016/j.quascirev.2021.106948>  
< <https://doi.org/10.1016/j.quascirev.2021.106948> >

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# A maximum in global glacier extent during MIS 4

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## ABSTRACT

The most recent maximum in global ice volume occurred around 23,000 to 19,000 years ago, during Marine Isotope Stage 2 (MIS 2; ~29-14 ka) according to benthic  $\delta^{18}\text{O}$  and sea level records. However, evidence from cosmogenic surface exposure dating indicates that world-wide many glacier systems of different sizes as well as portions of some ice sheets were more extensive during MIS 4 (~71-57 ka) and MIS 3 (~57-29 ka) than they were during MIS 2. This discrepancy between global ice volume and ice extent must be explained in order to understand Earth's recent paleoclimate history. Here, we review MIS 4 moraine chronologies based on  $^{10}\text{Be}$  exposure dating, and we describe additional paleoclimate proxy records that indicate similar magnitudes of cooling during MIS 4 and MIS 2. While certain regions may have benefited from a wetter MIS 4 relative to MIS 2, it is unlikely that precipitation alone can explain more extensive glaciation on a global scale between 71 and 57 ka. Our review supports the hypothesis that the discrepancy between ice volume and ice extent during MIS 4 can be attributed to

26 the growth of the North American ice sheets (and perhaps other northern ice sheets).  
27 Glaciers ultimately respond to changes in climate, however, large northern ice sheets also  
28 were affected by factors involving topography, isostasy, and glaciologic and mass  
29 balance dynamics. Given these feedbacks, the North American ice sheets' dominant role  
30 in global ice volume, sea level, and benthic  $\delta^{18}\text{O}$  signals might therefore result in a  
31 skewed picture of global climate. If maximum global ice volume during MIS 2 is mainly  
32 a function of North American ice sheet volume and not necessarily directly connected to  
33 global temperatures, then other records with extremes during MIS 2, such as dust and  
34  $\text{CO}_2$ , could be primarily reflecting ice volume change.

35

## 36 **1. Introduction**

37

38 The cause of ice ages is one of the major unresolved mysteries in the Earth  
39 sciences. The theory of ice ages began with the study of glacial geology and mapping of  
40 past glacial extents, mainly in Europe and North America and correlated them with  
41 calculations of the secular changes in Earth's orbit around the sun (e.g., Milankovitch,  
42 1941; Imbrie and Imbrie, 1986). The theory gained momentum with continuous and  
43 semi-continuous records of global ice volume changes represented by oxygen isotope  
44 variation and sea level change (e.g., Shackleton, 1967; Hays et al., 1976; Yokoyama et  
45 al., 2000; Waelbroeck et al., 2002; Raymo and Nisancioglu, 2003; Lisiecki and Raymo,  
46 2005; Arz et al., 2007; Grant et al., 2012). The classic 'sawtooth' pattern (Broecker and  
47 van Donk, 1970; Lisiecki and Raymo, 2005; Fig. 1) found in records of benthic  
48 foraminiferal  $\delta^{18}\text{O}$ , sea level, and  $\text{CO}_2$  reflects a relatively slow or step-wise descent into

49 glacial conditions and a rapid termination toward interglacial conditions. Spectral  
50 analysis of benthic  $\delta^{18}\text{O}$  records revealed peaks at ~23-24 kyr, 40-43 kyr, and 94-106 kyr,  
51 with the ~100-kyr cycle constituting a major feature of the record (e.g., Hays et al.,  
52 1976). A 100-kyr cycle likely relates to the wavelength of eccentricity but the influence  
53 of eccentricity on Earth's climate is thought to be too small to pace ice ages (Imbrie et al.,  
54 1993). The seeming ubiquity of the ~100-kyr 'sawtooth' pattern in so many records may  
55 lead to the inference that the largest ice volume, which occurred ~21 ka (Mix et al.,  
56 2001), must coincide with world-wide maximum glacier extent and the coldest climates  
57 of the last ~125,000 years (e.g., Lisiecki and Raymo, 2005; Mix et al., 2001; Bereiter et  
58 al., 2012; Fig. 1; Table 1). However, several researchers have pointed out that this  
59 correlation is not necessarily correct, at least with respect to glacier extent or temperature  
60 depression (e.g., Gillespie and Molnar 1995; Berger et al., 1999; Bintanja and van de  
61 Wal, 2008; Schaefer et al., 2015; Tulenko et al., 2018 and references therein). In  
62 particular, glacier records do not necessarily follow the asymmetric 'sawtooth' pattern of  
63 the large North American ice sheets. Before firm chronological evidence was available,  
64 Gillespie and Molnar (1995) concluded that the global ice volume record does not  
65 describe the pattern of alpine glacier advances. However, they could not decipher  
66 geographic patterns or the timing of glacier behavior prior to the maximum in global ice  
67 volume.

68         Stacked benthic foraminiferal  $\delta^{18}\text{O}$  stack (LR04; Lisiecki and Raymo, 2005; Fig.  
69 1) represents changes in both land-ice volume and deep-water temperature. The isotopic  
70 values of this record have been used to define the structure of the last glacial cycle  
71 including Marine Isotope Stage (MIS) 5 (130-71 ka), MIS 4 (71-57 ka), MIS 3 (57-29

72 ka), MIS 2 (29-14 ka), and MIS 1 (14-0 ka) (Lisiecki and Raymo, 2005), where even-  
73 numbered MISs relate to glacial periods (blue bars in Fig. 1). Modeling studies have  
74 been used to separate the relative contributions of ice sheet volume and ocean  
75 temperature to  $\delta^{18}\text{O}$ , and demonstrated that the North American ice sheets play an  
76 important role in the 'sawtooth' pattern, the mechanism of glacial terminations in the last  
77 1 Myr, and the possible switch from  $\sim 41$ -kyr to  $\sim 100$ -kyr glacial cycles during the  
78 Middle Pleistocene transition (Berger et al., 1999; Bintanja and van de Wal, 2008).  
79 Records of  $\delta^{18}\text{O}$  and sea level, therefore, are skewed by the waxing and waning of North  
80 American ice volume (Bintanja and van de Wal, 2008), and it is possible that these large  
81 ice sheets vary somewhat independently from global climatic drivers in part due to their  
82 internal mechanical and dynamical feedbacks.

83       Ultimately, it is vital to know whether past global temperature varied in a  
84 'sawtooth' pattern similar to ice volume or not (e.g., Table 1). By viewing total ice  
85 volume and climate as potentially independent entities, it is possible to gain fresh insights  
86 into connections between insolation and climate conditions including temperature (e.g.,  
87 Huybers and Denton, 2008; Raymo and Huybers, 2008; Bajo et al., 2020; Liautaud et al.,  
88 2020; Wu et al., 2020). One obstacle to this approach is identifying paleoclimate signals  
89 that are not dominated by variations in North American ice volume (which include e.g.,  
90 eustatic sea level, oxygen isotopes).

91       Moraines are unambiguous and direct evidence of past glacial extents by marking  
92 where glaciers terminated on the landscape. Moraine dating reveals that in some places  
93 glaciers were larger during the middle of the last ice age cycle (MIS 4) than they were  
94 during the global ice volume maximum of MIS 2 ( $\sim 21$ ka). The baseline connection

95 between moraine ages and climate is that glacier size depends on changes in local  
96 temperature especially during the ablation season, and precipitation to a lesser extent in  
97 moist regions (e.g., Oerlemans, 1991; 2001; Mackintosh et al., 2017). Evidence of  
98 glacier extents prior to MIS 2 is sparse due to moraine preservation issues such as  
99 erosion, burial, or obliteration by younger advances (Gibbons et al., 1984). Thus the  
100 preservation of MIS 4 moraines is evidence that all subsequent glacier advances were less  
101 extensive because glaciers typically destroy moraines if they readvance over these  
102 deposits (excluding cold-based systems). Glaciers at these locations therefore must have  
103 been more extensive during MIS 4 relative to MIS 2. Although discontinuous by nature,  
104 dated terrestrial glacial geomorphic records are the best proxy to address the issue of  
105 glacier extents during the last glacial cycle. With the increased use of cosmogenic  
106 exposure dating and our ability to date glacier deposits older than the  $^{14}\text{C}$  limit, more  
107 moraine chronologies appear to contain remnants of similar or slightly more extensive  
108 glaciers during MIS 4. Individual publications of moraines dating to MIS 4 often relate  
109 their presence to a local or regional effect of climate (e.g., increased precipitation) or  
110 glacier dynamics, or simply overlook these ages altogether if the number of samples is  
111 low. While it is not yet possible to reject these possible explanations, the abundance of  
112 MIS 4 moraine chronologies found in different locations with different regional climates,  
113 latitudes, proximity to bodies of water, geology and topographic settings suggests a  
114 possible collective advance of glaciers due to global cooling at that time.

115 Other paleoclimate proxy records showing similar conditions during MIS 4 and  
116 MIS 2 (Fig. 2) include isotope records such as those from Greenland (e.g., adjusted  $\delta^{18}\text{O}$ ;  
117 Huber et al., 2006) and Antarctica (e.g.,  $\delta\text{D}$  from Vostok; Petit et al., 1999), and marine

118 records, such as sea surface temperature from the Iberian margin (Martrat et al., 2007)  
119 and Southern Chile (Kaiser et al., 2005) and polar species from southern Cape Basin  
120 (Barker and Diz, 2014). Pacific Mg/Ca ratios (Martin et al., 2002; Elderfield et al., 2012)  
121 reflect changes in temperature and suggest similar temperatures during MIS 4 and MIS 2  
122 (Fig. 2).  $\delta D_{\text{wax-IV}}$  from Gulf of Aden (core RC09-166; Tierney et al., 2017) suggests a  
123 cold and dry climate in East Africa during MIS 4 and MIS 2.

124 Clarifying MIS 4 climate is important for understanding ice ages as well as  
125 studying the impacts of climate on early humans. Patterns of human migration during  
126 MIS 4 were likely driven by changes in climate. For example, an 'Out-of-Africa' event  
127 occurred between 65 and 55 ka (Soares et al., 2012; Mellars et al., 2013) during a cold  
128 and dry period in East Africa according to  $\delta D$  from leaf wax (Tierney et al., 2017).  
129 Humans expanded into southeast Asia at ~63 ka (Demeter et al., 2015) and into Australia  
130 at ~65 ka (Clarkson et al., 2017; De Deckker et al., 2019). A better understanding of  
131 regional climate conditions during MIS 4 could therefore help to explain what drove  
132 these pulses of mass migration.

133 The objectives of this review are to (1) present previously published  $^{10}\text{Be}$   
134 exposure ages, mostly from boulders on moraines, dating to MIS 4 and supplement these  
135 ages with other geochronologic and paleoclimate proxy data. Many studies only present a  
136 few MIS 4 ages, in part because this period has not been a major target of study due to  
137 dating method limitations, not expecting to find MIS 4 moraines, and a lack of interest.  
138 A goal of this review is to highlight the global prevalence of MIS 4 moraines to inspire  
139 future targeted MIS 4 studies; (2) discuss the geographic pattern of where MIS 4 moraine  
140 sites have been found and to examine possible causes for the MIS 4 glacial maximum; (3)

141 discuss possible implications for marine benthic  $\delta^{18}\text{O}$  records, which are incongruent  
142 with MIS 4 global moraine chronologies, to understand the magnitude of climate change  
143 during MIS 4; and (4) examine possible connections between worldwide glaciations and  
144 insolation forcing.

145

## 146 **2. MIS 4 moraine chronologies**

147 Dating tools, mainly the cosmogenic exposure age approach, have advanced the  
148 understanding of the glacial geomorphic record to a new level of chronologic detail.  
149 Geomorphologic maps document the context of each moraine and multiple ages per  
150 landform allow statistical analysis to reveal age consistency. In this study, the clearest  
151 moraine chronologies include statistically coherent ages along a stable moraine crest or  
152 crests, and they show moraine ages in stratigraphic order, such that younger moraines are  
153 clearly inboard or up valley from older moraines. While not explored here, the use of  
154 multiple isotopes can help with deciphering complicated exposure histories (i.e., repeat  
155 exposure and burial).

156 We focus on studies that used the cosmogenic nuclide  $^{10}\text{Be}$ , because it is  
157 commonly applied worldwide and the improvements in analysis (precision) and in the  
158 constraints of its production rate and other systematics over the last  $\sim 10\text{-}20$  years allow it  
159 to be one of the most accurate and precise surface exposure dating chronometers. We  
160 mention supporting studies that used  $^{36}\text{Cl}$ ,  $^3\text{He}$ , and  $^{26}\text{Al}$ , as well as other  
161 geochronometers such as optically-stimulated luminescence (OSL) and  $^{14}\text{C}$  (e.g., Phillips  
162 et al., 1990; Barrows et al., 2011; Eaves et al., 2016).



163 We recalculated  $^{10}\text{Be}$  exposure ages from existing studies (that we are aware of)  
164 that overlap or are close to, MIS 4. These chronologies needed to be recalculated with  
165 up-to-date systematics due to new production rate calibrations, geomagnetic models,  
166 muon considerations (Balco et al., 2008; Borchers et al., 2016), refinement of the  $^{10}\text{Be}$   
167 half-life (Nishiizumi et al., 2007), and more precise definitions of some AMS standards  
168 (see supplementary data). We use version 3 of the online CRONUS calculator (Balco et  
169 al., 2008). In the supplement, we present ages with three scaling models for position and  
170 elevation, and for most places 2 to 4 production rate calibrations, to demonstrate that our  
171 interpretations and findings are not dependent on our choice of scaling parameter or  
172 production rate. In the text below, we show  $^{10}\text{Be}$  ages using the time dependent version  
173 of Lal (1991) reformulated by Stone (2000). With only a small number of individual-age  
174 exceptions, all the  $^{10}\text{Be}$  ages we highlight in the supplementary data remain overlapping  
175 with MIS 4 regardless of the scaling model or production rate calibration used.

176 We prefer to show ages in the text calculated using hemispherically or even  
177 regionally derived production rate calibrations. We use local production rates for New  
178 Zealand (Putnam et al., 2010), Peru (Kelly et al., 2015; Martin et al., 2015), and  
179 Patagonia (Kaplan et al., 2011). For the northern hemisphere, we use: (1) the mid-high  
180 latitude (Baffin Bay-Greenland) production rate of Young et al. (2013) given it is from  
181 similar latitudes to several chronologies we recalculated (e.g., sites in NW North  
182 America); (2) in addition, a second production rate, Putnam et al. (2019), for Asia; and  
183 (3) the CRONUS default production rate from Borchers et al. (2016) for comparison,  
184 given a regional production rate is not available for northwestern North America and

185 Asia. We also present recalculated  $^{10}\text{Be}$  ages from Barrows et al (2001), for Australia,  
186 with the production rate from Borchers et al. (2016).

187 All ages are calculated with an erosion rate set to zero, as there are no data in any  
188 of the papers to define a widely applicable value for all boulders, even within individual  
189 studies. Any assumed erosion correction would increase the ages; if we assume a  
190 relatively high erosion rate of 1mm/1000 years, ages would increase by 4-6% for 70-60  
191 ka ages and ~7% for 75-70 ka ages. These increases would not affect our conclusions; in  
192 fact, more ages would fall into the MIS 4 age bounds, as there are more ages in the range  
193 ~60-50 ka compared with ages ~70-75 ka that become too old.

194 Here, we summarize the recalculated MIS 4 cosmogenic ages presented in the  
195 supplementary data and shown in Table 2, Table 3, Fig. 3, and Fig. 4. All studies  
196 discussed here include ages between ~75 and ~55 ka, which have been rounded to the  
197 nearest millennium. We only recalculated ages in studies that published four or more  
198 exposure ages within the general range of MIS 4 and we discuss geomorphic context and  
199 outliers as designated in the original publication. Although there are locations  
200 demonstrably without MIS 4 moraines (e.g., Preusser et al., 2003; Ward et al., 2008;  
201 Hein et al., 2009; Putnam et al., 2013; Laabs et al., 2020), summarizing them is beyond  
202 the scope of this study.

203

#### 204 *2.1. North America*

205 Evidence for more extensive glaciers during MIS 4 (locally referred to as 'early  
206 Wisconsinan' glaciation) relative to MIS 2 exists in the northwest part of North America  
207 based on studies from Alaska and the Yukon (Fig. 4; Table 2).

208           Nine ages from the Revelation Mountains in the western Alaska Range date from  
209 ~63 to ~56 ka (Tulenko et al., 2018; Fig. 4; Fig. 5). All nine ages are from boulders  
210 embedded in a left lateral moraine ridge adjacent to an up-valley moraine complex with  
211 ages of ~21-19 ka. Tulenko et al. (2018) produced detailed maps showing moraines from  
212 four separate glaciers, with only two of the valleys showing possible MIS 4 moraine  
213 remnants. The authors hypothesize that the larger extent during MIS 4 in this area could  
214 be linked to atmospheric re-organization driven by the Laurentide Ice Sheet causing  
215 higher temperatures and drier conditions during MIS 2 relative to MIS 4 (Tulenko et al.,  
216 2018).

217           Eight ages from the Nenana River Valley in the central Alaska Range date from  
218 ~69 to ~55 ka (Dortch et al, 2010a) during the local 'Healy' glaciation. Samples Ala-11,  
219 Ala-12, and Ala-13 come from boulders on the Healy moraine, whereas Ala-23, Ala-24  
220 and Ala-25 come from boulders on drumlins, and Ala-107 and Ala-108 come from  
221 glacially eroded bedrock (Dortch et al., 2010a). These ages are in morphostratigraphic  
222 order with older ages on distal deposits (Lignite Creek glaciation during MIS 5 or 6) and  
223 younger ages up valley (Carlo Creek phase landforms produce ages of 22 to 13 ka)  
224 (Dortch et al., 2010a). Sample Ala-156 also dates to MIS 4, but its geomorphic context is  
225 as an outlier among MIS 5 and MIS 6 aged deposits in Lignite Creek.

226           Four ages from Donnelly Dome in the central Alaska Range date from 68 to 54 ka  
227 (Matmon et al., 2010). Samples DDDL-2 and DDDL-3 come from boulders on an  
228 eastern lateral moraine. Samples DR2-2 and DR2-4 come from gravel on ground  
229 moraine located between older 'Delta' glaciation moraines (which is associated with MIS  
230 6 because the Old Crow Tephra (~140 ka) overlies 'Delta' age outwash (Bégét and

231 Keskinen, 2003)) and younger 'Donnelly' stage moraines (~17 ka) (Matmon et al., 2010).  
232 Sample DR1-5 dates to MIS 4, but Matmon et al. (2010) designated it as an outlier  
233 because it is from a boulder on MIS 2 deposits.

234 Briner et al. (2005) reported seven  $^{10}\text{Be}$  ages from four different valleys in Alaska  
235 that fall within MIS 4 (Fig. 3; supplementary data). Samples SR 1-00-2 and SR-1-00-4  
236 are from the 'Swift River Farewell I' moraine in the Lime Hills region, sample KH 1-3 is  
237 from the outer moraine of the Kokrines Hills, samples WM00-06B and WM00-07A come  
238 and from the Eagle and Mt. Harper moraines, respectively, in the Yukon-Tenana Upland,  
239 and two samples BR02-15 and BR02-8 come from the Okpilak River Valley lateral ridge  
240 and the Jago River Valley lateral ridge, respectively, in the Northeastern Brooks Range  
241 (Briner et al., 2005). Each of these sites contains MIS 2 aged moraines up valley of the  
242 MIS 4 moraine limits and, thus, the MIS 4 moraines are in proper morphostratigraphic  
243 context (Briner et al., 2005).

244 Lastly, four ages from the Ruby Range in the southwestern Yukon Territory date  
245 from 58 to 54 ka (Ward et al., 2007). Samples YUK-05-002 to YUK-05-005 come from  
246 erratic boulders on a plateau above the Isaac Creek Valley in the Aishihik Lake area and  
247 are part of the penultimate 'Reid' glaciation. The lithology supports the transportation of  
248 these boulders by a portion of the Cordilleran Ice Sheet, rather than by a mountain glacier  
249 or ice cap (Ward et al., 2007).

250 Additional support for more extensive glaciers in North America comes from  
251 studies with other geochronometers or smaller  $^{10}\text{Be}$  datasets. Briner et al. (2001) dated  
252 four boulders on ground moraine in the Ahklun Mountains of southwest Alaska using  
253  $^{36}\text{Cl}$ . These ages (not recalculated) overlap with the later part of MIS 4 and are part of

254 the 'Arolik Lake' glaciation (Briner et al., 2001). Two  $^{10}\text{Be}$  ages from the Mackintosh  
255 Lake area in the southern Yukon Territory date to MIS 4 and come from a subdued end  
256 moraine relating to the 'Reid' glaciation (Stroeven et al., 2014). Turner et al. (2013)  
257 examined glacial and non-glacial deposits in southwestern Yukon and used radiocarbon  
258 and tephra beds to constrain tills to MIS 4, and MIS 6.

259         There is a notable absence of MIS 4 moraines around and to the south of the  
260 North American ice sheets (except Yukon). This finding has been recognized previously  
261 and had led to hypotheses accounting for different past climates in different parts of  
262 North America (e.g., Tulenko et al., 2018; Laabs et al., 2020). One exception is from  
263 Phillips et al. (1990), who used  $^{36}\text{Cl}$  dating to identify MIS 4 deposits in Bloody Canyon,  
264 California. Specifically, five ages overlap with MIS 4 and provide tantalizing - but not  
265 yet reproduced - evidence of a glacial maximum during MIS 4 in the Sierra Nevada. In  
266 the Western Olympic Peninsula of Washington, minimum radiocarbon ages of 54,000  
267 and 51,000  $^{14}\text{C}$  yr B.P. on wood below till are associated with the 'Lyman Rapids'  
268 advance (Thackray, 2001; 2008), which were used to infer an extensive MIS 4 glaciation.  
269 In southern Jackson Hole, Wyoming, a sequence of loess deposits on an outwash terrace  
270 dated to MIS 6 contains a loess deposit dating to MIS 4 (Pierce et al., 2011).  
271 Paleolimnological studies from Mono Lake reveal a higher water level during MIS 4 than  
272 MIS 2 (Zimmerman et al., 2006) suggestion more glacial-like conditions in the Sierra  
273 Nevada at that time.

274         Whether we should expect to find MIS 4 moraines in the western United States is  
275 debatable. The modeling results of Batchelor et al. (2019) support a more extensive  
276 Laurentide Ice Sheet during MIS 2 than MIS 4 in the central and eastern portions of the

277 northern United States (supported by moraine dating, e.g., Balco and Schaefer, 2006;  
278 Corbett et al., 2017; Hall et al., 2017; Heath et al., 2020), and more extensive ice during  
279 MIS 4 relative to MIS 2 in the west. However, of the available moraine chronologies  
280 from the western United States, MIS 4 ages are rare or absent (e.g., Licciardi and Pierce,  
281 2008; Laabs et al., 2020). Moraines that predate MIS 2 exist throughout the Rocky  
282 Mountains (e.g., Gillespie and Molnar, 1995; Marchetti, 2007; Licciardi and Pierce,  
283 2008), and future research efforts need to target older deposits for dating to confirm the  
284 presence/absence of MIS 4 moraines around much of North America.

285

## 286 *2.2. South America*

287 Six ages from near Estrecho de Magallanes, Chile date from ~68 to ~62 ka  
288 (Peltier et al., 2016; in press). These samples come from boulders on a set of moraine  
289 crests deposited by the relatively large southernmost Patagonian Ice Sheet (Fig. 5). This  
290 older moraine is much larger than and distal to moraines dating to MIS 2, and thus is in  
291 stratigraphic order (Peltier et al., 2016; in press). Two additional ages (samples SM-15-  
292 23 and SM-15-32) in this region date to MIS 4, but they were considered outliers in the  
293 original publication.

294 Five  $^{10}\text{Be}$  ages from the southernmost end of the Cordillera Blanca in Peru range  
295 from 73 to 56 ka (Smith and Rodbell, 2010; Fig. 4). Samples PE05-JEU-06 and PE05-  
296 JEU-10 come from boulders on a right lateral moraine distal to a ~14 ka moraine ridge.  
297 Samples PE05-JEU-21, PE05-JEU-23, and PE05-JEU-24 date to MIS 4 and are from a  
298 glacial advance that curved to the right and was not destroyed by subsequent advances  
299 due to avulsion of a glacial trough allowing the MIS 2 glacier to flow to the left (Smith

300 and Rodbell, 2010). Although these MIS 4 ages are from moraines that represent a  
301 slightly smaller glacier extent than during MIS 2, we include them here because the  
302 extents were quite similar. The additional three ages in the supplementary data are from  
303 cobbles on an outwash plain and do not designate past ice extent specifically.

304 Additional support for extensive MIS 4 glaciation in Patagonia and the subtropics  
305 comes from various studies, based on inferences and limited chronological constraints.  
306 North of Estrecho de Magallanes (Fig. 3), three  $^{10}\text{Be}$  ages between  $\sim 73$  and  $\sim 57$  ka near  
307 the Puerto Natales area suggest possible MIS 4 moraines (García et al., 2018). García et  
308 al. (2018) described these ages as outliers because the samples are from the 'Río Turbio'  
309 and 'Arauco' moraine ridges where the majority of ages fall within MIS 3. García et al.  
310 (2018) acknowledge that these ages may hint at an MIS 4 expansion of the Última  
311 Esperanza ice lobe. One nearby age of  $\sim 60$  ka (sample PN-04-11) comes from a moraine  
312 crest adjacent to the southeast side of Lago Dorothea, Chile and rests near or possibly just  
313 outside of MIS 2 and MIS 3 deposits (Sagredo et al., 2011; Garcia et al., 2018). In  
314 central Patagonia,  $^{10}\text{Be}$  ages from the 'Klementek outwash' yield ages of 86 to 67 ka  
315 (Mendelova et al., 2020) but do not relate to a specific glacier extent. In mid-latitude  
316 Chile ( $\sim 40^\circ\text{S}$ ), Denton et al. (1999) and Andersen et al. (1999) identified several moraine  
317 sets, locally known as the 'early Llanquihue' moraines. They associated the moraines  
318 with an MIS 4 glaciation based on cores from bogs and age extrapolation to the base of  
319 the cores (Huesser et al., 1999). Cosmogenic ages in NW Argentina could suggest  
320 extensive glaciation during MIS 4, but ages are considered to be outliers on an older  
321 moraine (Zech et al., 2009).  $^3\text{He}$  ages from glacial landforms on Uturuncu volcano in  
322 Bolivia (Blard et al., 2014) overlap with MIS 4 suggesting more MIS 4 moraines could

323 be found in South America using alternative cosmogenic isotopes when quartz for  
324  $^{10}\text{Be}$  is not available.

325

### 326 2.3. *Asia*

327 Asia contains the highest number of studies with MIS 4 ages, and they span the  
328 length of the Himalaya and beyond (Fig. 3). Due to the abundance of MIS 4 ages from  
329 Asia, we only show on Fig. 4, for the sake of discussion, studies that have at least six  
330  $^{10}\text{Be}$  ages, except for the Urals, which are located in a different region.

331 In the Polar Ural Mountains of northern Russia ( $67^\circ\text{N}$ ,  $65^\circ\text{E}$ ; on the border  
332 between Asia and Europe), four  $^{10}\text{Be}$  samples date to between  $\sim 66$  and  $\sim 56$  ka (Mangerud  
333 et al., 2008). These ages come from deposits associated with complex glacier systems  
334 flowing out of the Ural Mountains.

335 Thirteen ages from Gurla Mandhata in southwestern Tibet range from  $\sim 75$  to  $\sim 55$   
336 ka (Owen et al., 2010). Two ages are from a right lateral moraine ridge designated to the  
337 local 'Namorangre' glaciation in the Muguru Valley, two ages are from the Namarodi  
338 Valley, four ages are from a right lateral moraine in the Ronggua Gorge Foreland and  
339 five ages are from composite moraines in the Ronggua Gorge Foreland (Owen et al.,  
340 2010).

341 Thirteen ages from central Tibet date to MIS 4, locally known as the 'Bashico  
342 Glacial Stage'. This includes ten from the youngest moraine in the Tanggula Shan and  
343 three from the oldest moraine in the Nyainqentangulha Shan (Owen et al., 2005). These  
344 moraines are located in stratigraphic order with younger moraines up valley dating to



345 MIS 2 (Nyainqentangulha Shan site) and older, down valley moraines dating to MIS 6  
346 (Tanggula Shan site) (Owen et al., 2005).

347 Twelve ages from four parts of southeast Pamir in China range from ~77 to ~57  
348 ka (Owen et al., 2012). One age comes from ground moraine in the mouth of Kuzigun  
349 Valley, one age from the mouth of Jialongquiete Valley, four ages from Hangdi-  
350 Dabudaer, four ages from the southern Tashkurgan Valley, and two ages from Alpine  
351 Meadow (Owen et al., 2012). All of these ages relate to deposits representing a more  
352 extensive or thicker glacier during MIS 4 relative to MIS 3 or MIS 2.

353 From the NW sector of the Himalayas, five ages from the East, Middle, and West  
354 Gissar Valleys in Tajikistan date from ~73 to ~63 ka (Zech et al., 2013). Three of the  
355 ages come from a moraine in the Gissar Valley, and are down valley of moraines dating  
356 to MIS 2. The other two ages come from a moraine in the West Gissar Valley, also down  
357 valley of a moraine dating to MIS 2 (Zech et al., 2013).

358 Seven ages from Tajikistan and Kyrgyzstan date from ~79 to ~57 ka  
359 (Abramowski et al., 2006). Sample TK12 may be an outlier as it is among ages between  
360 91 and 84 ka in the Takhtakorum River Valley. Samples UK28, UK31, UK33 and UK34  
361 are from the Kol-Uchkol Valley and samples KK1, KK2 and KK3 are from the Koksu  
362 Valley in the Alay Range. Five ages from Ala Bash and one age from At Bashi in  
363 Kyrgyz Tien Shan span MIS 4 (Koppes et al., 2008).

364 Three ages from the Pangong lower inner moraine and one age from the lower  
365 outer moraine date to MIS 4 (Dortch et al., 2013). Two ages from the Diger La lower  
366 deposit date to MIS 4 (LDK-35 and LDK-208A), but are among a range of ages, as is  
367 sample LDK-52 on the North Pulu lower deposit (Dortch et al., 2013). One age from a

368 moraine in northernmost Ladakh, India dates to MIS 4 (NU-26) and two ages from  
369 nearby deposits within the Nubra Valley were considered outliers, but also date to MIS 4  
370 (NU-2 and NU-7; Dortch et al., 2010b).

371 Thirteen  $^{10}\text{Be}$  ages from boulders on glacial deposits in Bayan Har Shan in the  
372 northeastern Tibetan Plateau overlap with MIS 4 (Heyman et al., 2011). Three of these  
373 ages are from boulders on a single moraine in area 'D', and the rest of the ages individual  
374 deposits in multiple valleys suggesting large glacier extents across the Bayan Har Shan  
375 during this time (Heyman et al., 2011).

376 Several additional studies support that MIS 4 deposits are well preserved  
377 throughout the Himalaya and much of Asia. Thirteen  $^{10}\text{Be}$  ages from cobbles on  
378 moraines and outwash on the south slope of Sulamu Tagh date to MIS 4 (Mériaux et al.,  
379 2004), but the moraines have been offset from the glacial valley, so these ages might not  
380 represent a more extensive glacier during MIS 4.

381 Three  $^{10}\text{Be}$  ages from moraines associated with an ice cap that filled the valleys of  
382 the Ural Mountains date to MIS 4 (Svendsen et al., 2019). Eleven OSL ages in the same  
383 area support extensive ice during MIS 4 in the Ural Mountains (Svendsen et al., 2019).  
384 Ice-rafted debris in marine cores (Kneis et al., 2000) and stratigraphic evidence in  
385 northern Russia also suggest a retreat of the eastern margin of the Barents/Kara Ice Sheet  
386 from east to west from MIS 4 to MIS 2 (Svendsen et al., 2004; 2014). A combination of  
387 OSL and radiocarbon ages suggest MIS 4 moraines in the Verkhoyansk Mountains and  
388 Chukchi Peninsula in northeast Russia (e.g., Stauch et al., 2007; Barr and Clark, 2012),  
389 but a focused effort to date these deposits using cosmogenics could help clarify the  
390 glacial history in this region.

391 Four  $^{10}\text{Be}$  ages from Mount Jaggang, Tibet date to MIS 4 (Dong et al., 2018;  
392 Table 3). Two ages from M6 in the Kitschi-Kurumdu Valley in Kyrgyzstan date to MIS  
393 4 (Zech, 2012). Two ages from the Turgan Valley in the Karlik Range ( $43^\circ\text{N}$ ,  $94^\circ\text{E}$ ) fall  
394 within MIS 4 (Chen et al., 2015), but nearby ages are chronologically scattered and we  
395 found it difficult to assess their geomorphic context. Three ages from erratics on till  
396 remnants in Ala Valley in Tian Shan date to MIS 4 (Li et al., 2014). Two ages, one from  
397 the Raikot Valley and one from Indus Valley in Nanga Parbat in northwestern Himalaya  
398 ( $35^\circ\text{N}$ ,  $75^\circ\text{E}$ ), date to MIS 4 (Phillips et al., 2000). Three ages from northeastern Turkey  
399 (Basyayla Village area;  $41^\circ\text{N}$ ,  $41^\circ\text{E}$ ) date to the latest part of MIS 4 (Reber et al., 2014)  
400 and suggest that a focused effort to date pre-MIS 2 moraines in this region could reveal  
401 more MIS 4 moraines. Additional support for extensive MIS 4 glaciation comes from  
402 northwestern Tanggula Shan (one  $^{10}\text{Be}$  age; Colgan et al., 2006) and southern and  
403 western Tibet (three  $^{10}\text{Be}$  ages from different valleys; Chevalier et al., 2011). OSL ages  
404 of  $58 \pm 9.1$  ka (silt) and  $86 \pm 10$  ka (clay) are morphostratigraphically associated with a  
405 moraine ( $M_{1C}$ ) in Khurgan nuur in the western Mongolian Altai, and indicate that the  
406 moraine formed during MIS 4 (Lehmkuhl et al., 2016). Similarly, an OSL age of  $73 \pm$   
407  $6.6$  ka from deposits in the Kanas River Valley in the Altai Mountains of China also  
408 support MIS 4 glaciation being larger than MIS 2 (Zhao et al., 2013).

409

#### 410 *2.4. Oceania*

411 Forty-six  $^{10}\text{Be}$  ages from the South Island, New Zealand date to MIS 4, and  
412 comprise the most comprehensive record reviewed here (Schaefer et al., 2015). Samples  
413 come from boulders on the left lateral 'Balmoral' moraines near Lake Pukaki and right

414 lateral 'Balmoral' moraines of Lake Tekapo as part of the 'Otira' glaciation (Barrell,  
415 2014), and are in stratigraphic order beyond moraines dating to MIS 3 and MIS 2  
416 (Doughty et al., 2015; Denton et al., 2021). While this location contains the highest  
417 number of MIS 4 ages in the world, it is important to note that the moraines in the  
418 neighboring Lake Ohau valley do not contain MIS 4 ages (Putnam et al., 2013). Hence,  
419 MIS 4 ages exist for two of the three sub-lobes (Pukaki and Tekapo, and not Ohau). This  
420 difference in moraine preservation highlights the importance of dating multiple moraines  
421 in multiple valleys to understand the full MIS 4 glacial and climatic history of a region.

422 Four samples from the Snowy Mountains of southeastern Australia date to late  
423 MIS 4 (Barrows et al., 2001; supplementary data). Three ages are from a blockfield  
424 down valley of the 'BL-1' moraine and the fourth age is from a boulder on the BL-1  
425 moraine. The boulder ages are in sequential order with moraines dating to MIS 2 up  
426 valley.

427 Additional support for MIS 4 glaciation in the western Pacific Ocean comes from  
428 Papua New Guinea, where Barrows et al., (2011) used  $^{36}\text{Cl}$  to obtain three ages  
429 corresponding to MIS 4 for the local 'Komia Glaciation'. Cascade Plateau in New  
430 Zealand revealed two  $^{10}\text{Be}$  boulder ages from moraines dating to MIS 4 (Sutherland et al.,  
431 2007), but these moraines have been shifted by the strike-slip Alpine Fault and do not  
432 necessarily represent a more extensive glacier position. Additional MIS 4 deposits in  
433 New Zealand include one  $^3\text{He}$  boulder exposure age on Mt. Ruapehu, North Island (57  
434 ka; Eaves et al., 2016), three OSL ages from fine lacustrine sediments in Boulder Creek,  
435 northern South Island (ranging from 65 to 55 ka; McCarthy et al., 2008) and three OSL  
436 ages in west-central South Island (~80 to 63 ka; Preusser et al., 2005).

437

438 *2.5. Europe*

439 MIS 4-aged moraines have not yet been confirmed in Europe. Hence, we only  
440 mention 'supporting evidence' of MIS 4 glaciations, which do not necessarily provide  
441 information on relative extent, and thus, they may document MIS 4 glaciers smaller than  
442 or similar to those during MIS 2. One of the issues is that ice sheets that covered Great  
443 Britain and Scandinavia advanced onto the continental shelf, and  $^{10}\text{Be}$  dating is not  
444 possible for submarine moraines. Bathymetric and marine core analyses indicate that the  
445 western margin of the Fennoscandinavian Ice Sheet reached similar extents on the  
446 continental shelf off of Norway during MIS 4 and MIS 2 (Mangerud et al., 2011; Hughes  
447 et al., 2013).

448 Extensive MIS 4 glaciation, locally known as the 'Early Weichselian Glaciation',  
449 is supported by two  $^{10}\text{Be}$  ages from erratics on a bedrock step on the northwestern Iberian  
450 Peninsula (Rodriguez-Rodriguez et al., 2016). These ages are down valley of moraines  
451 dating to early MIS 2. OSL dates of a glacio-fluvio-lacustrine sequence support a  
452 maximum extent of several glaciers in the south-central Pyrenees during MIS 4 (e.g.,  
453 Lewis et al., 2009; Garcia-Ruiz et al., 2013; Sancho et al., 2003; 2018).

454 Records from the European Alps relating to MIS 4 mainly come from OSL dates  
455 of proglacial sediments (outwash or lacustrine) rather than glacial sediments (till or  
456 moraines) (Preusser, 2004). OSL ages from buried proglacial outwash in the Rhône  
457 Glacier Valley indicate the presence of the glacier in the Lake Neuchâtel area during MIS  
458 4 (Preusser et al., 2007). In contrast,  $^{14}\text{C}$ ,  $^{230}\text{Th}/\text{U}$ , and OSL ages from the Gossau section

459 in the Swiss Alps suggest glacial advances during MIS 5d, MIS 3, and MIS 2, but not  
460 MIS 4 (Preusser et al., 2003).

461 Reuther et al. (2007) mapped moraines down valley of moraines that date to MIS  
462 2 in the Carpathian Mountains, Romania. Although they did not date these deposits, they  
463 associate the moraines to MIS 4 (locally named the 'early Würmian') because local  
464 speleothem and micromammal records suggest severe conditions during MIS 4  
465 (Radulescu and Samson, 1992; Onac and Lauritzen, 1996; Tamas and Causse, 2000/01;  
466 Petculescu and Samson, 2001).

467

#### 468 *2.6. Africa*

469 MIS 4-aged moraines have not yet been identified in Africa. Multiple locations  
470 have undated moraines down valley from MIS 2 moraines, such as in the Rwenzori  
471 Mountains of tropical East Africa (Osmaston, 1989; Kelly et al., 2014; Jackson et al.,  
472 2019). MIS 4-aged moraines also exist on Mt. Kenya in the Teleki Valley (two  $^{36}\text{Cl}$  ages  
473 from Liki II moraine) and Gorges Valley (three  $^{36}\text{Cl}$  ages Naro Moru till) (Shanahan and  
474 Zreda, 2000), but these ages are among a spread of ages (e.g., ~135 to ~23 ka).

475

#### 476 *2.7. Antarctica*

477 MIS 4-aged moraines have not yet been identified in Antarctica to our knowledge.  
478 Cosmogenic dating of pre-Holocene moraines can be challenging in Antarctica due to  
479 possible inheritance from prior exposure that was not reset by glacial erosion during the  
480 last Glaciation. We note that two  $^{10}\text{Be}$  ages from erratics on Mt. Dewe in the southern  
481 Antarctica Peninsula (Bentley et al., 2006) date to 59.1 and 76.6 ka but neighboring

482 erratics yielded dates of 30.6 and 44.5 ka and so the glacial history is unclear. One  $^{10}\text{Be}$   
483 age from an erratic in the Darwin Mountains has the potential to relate the 'Danum drift'  
484 to MIS 4 (Storey et al., 2010). Given such issues as inheritance and the scope of this  
485 review, we do not include Antarctic data in the summary figures.

486

### 487 **3. Discussion**

488         The available ages from moraines suggest that mountain glaciers in a range of  
489 environments and latitudes were more extensive – or at least of a similar extent - during  
490 MIS 4 than during MIS 2. We discuss the geographic pattern of MIS 4 moraines and the  
491 possible role of precipitation, significance of the  $\delta^{18}\text{O}$  benthic stack, and inferred  
492 connections between insolation and world-wide glacial cycles.

493

#### 494 *3.1. Geographic pattern of MIS 4 sites*

495         The geographic extent of MIS 4 moraine ages shows that glaciers from a broad  
496 range of latitudes, longitudes, and altitudes were larger relative to MIS 2 (Fig. 3). MIS 4  
497 moraines have been found in low-, middle, and higher-latitude regions. This indicates a  
498 global temperature and climate signal similar in magnitude to MIS 2, rather than only a  
499 local climate particular to one study area. Similarly, this global occurrence of MIS 4  
500 glaciation suggests an insolation forcing – if causal – that would have had a global rather  
501 than local impact. Direct summer insolation intensity is opposite between the Northern  
502 and southern hemispheres, making it unlikely that  $65^\circ\text{N}$  or  $65^\circ\text{S}$  summer insolation drove  
503 MIS 4 glaciation. MIS 4 moraines exist in both maritime (e.g., New Zealand) and  
504 continental (e.g., central Asia) locations, also suggesting that the cause is probably related

505 to regional or hemispheric-scale atmospheric and oceanic circulation and not only local  
506 conditions.

507 MIS 4 moraines were deposited both by portions of ice sheets (e.g. Cordilleran  
508 and Patagonian) and by relatively large and small mountain glacier systems (e.g., Alaska  
509 Range, Southern Alps in New Zealand), and thus, glacier size and response time cannot  
510 explain all of the MIS 4 moraines. If, for example, MIS 4 was a short-duration cooling  
511 and only mountain glaciers could respond fast enough to register the cooling, then we  
512 would expect to find a correlation between the presence of MIS 4 moraines and glacier  
513 size. Such a correlation is absent in the data; for example, most mountain glaciers the  
514 western United States and European Alps did not appear to leave dateable MIS 4  
515 moraines (e.g., Fig. 3). We note that Peltier et al. (in press) hypothesize that MIS 4  
516 glacier expansion in southern South America lasted at least several thousands of years  
517 (Fig. 5).

518 In addition to similar magnitudes of cooling during MIS 4 and MIS 2 (e.g., those  
519 shown in Fig. 2), several records indicate that locations were wetter during MIS 4 relative  
520 to MIS 2. Relatively drier conditions during MIS 2 may be attributed to the larger area of  
521 exposed continental shelf (e.g., Briner et al., 2005), changes in atmospheric circulation  
522 (e.g., Mangerud et al., 1998; De Decker et al., 2019; Tulenko et al., 2020), increased sea  
523 ice extent (Gildor and Tziperman, 2000), and changes in monsoons (e.g., Wang et al.,  
524 2001; Owen et al., 2012). Alaska, for example, was likely more arid during MIS 2  
525 because of the exposed Bering continental shelf (Ward et al., 2007; Briner and Kaufman,  
526 2008; Thackray et al., 2008) and possibly the change in atmospheric circulation caused  
527 by a larger Laurentide Ice Sheet during MIS 2 (Tulenko et al., 2020). The lack of MIS 4



528 moraines south of the Laurentide could be due to these circulation changes caused by a  
529 larger Laurentide during MIS 2, bringing colder and/or wetter conditions to the Rocky  
530 Mountains during MIS 2 (Tulenko et al., 2020). Higher shorelines of Mono Lake during  
531 MIS 4 supported by stratigraphic relative paleointensity (Zimmerman et al., 2006) may  
532 counter the hypothesis proposed in Tulenko et al. (2020), and suggest wet conditions in  
533 the Sierra Nevada of California during MIS 4 (e.g., Phillips et al., 1990). If precipitation  
534 (in addition to temperature) caused more extensive glaciation during MIS 4, then indeed  
535 we would anticipate finding MIS 4 moraines in more locations that are generally thought  
536 to have been wetter during MIS 4 than MIS 2. Such locations include monsoonal regions  
537 (e.g., Owen et al., 2006), and regions that were drier during MIS 2 due to more extensive  
538 sea ice, such as northern Asia (Mangerud et al., 2011) or Alaska (Fig. 5). In addition,  
539 perhaps some sites between 40°S and 55°S associated with the westerly winds during  
540 glacial conditions in Patagonia (e.g., Peltier et al., in press) and in western North America  
541 (e.g., Phillips et al., 1990; Zimmerman et al., 2006) may have experienced shifts in  
542 precipitation due to changes in atmospheric circulation.

543         Of importance, our review also highlights several regions where MIS 4 moraines  
544 are notably absent. These include around the Laurentide Ice Sheet, the western U.S.  
545 (except maybe the Sierra Nevada; Phillips et al., 1990; Gillespie and Molnar, 1995) and  
546 the European Alps. A lack of evidence for MIS 4 moraines could be because not all pre-  
547 MIS 2 moraines have been dated, many glaciers were marine terminating and we cannot  
548 yet map or date their past extents, or because glaciers were more extensive in these areas  
549 during MIS 2 or MIS 3 than during MIS 4. Regardless, future studies need to question

550 the absence of MIS 4-aged moraines in some regions (Fig. 3) (e.g., Gillespie and Molnar,  
551 1995; Tulenko et al., 2018; Laabs et al., 2020).

552

### 553 3.2. How pervasive is the 'sawtooth' pattern of glacial cycles?

554 In contrast with the stacked benthic  $\delta^{18}\text{O}$  signal, the MIS 4 moraine chronologies  
555 show no reflection of a 'sawtooth' pattern in glacial extent over the last glacial cycle.  
556 This divergence suggests that the  $\delta^{18}\text{O}$  record is not a good indication of global glacial  
557 *extent*. The 'sawtooth' pattern of glacial/interglacial cycles likely reflects the step-wise  
558 growth and sudden demise of northern hemisphere (North American in particular) ice  
559 sheets (Dyke et al., 2002; Bintanja and van de Wal, 2008; Batchelor et al., 2019). Large  
560 ice sheets require both moisture and large-scale cooling to initiate, but can also respond  
561 to mechanical and dynamical changes in isostasy, height-mass balance-climate  
562 feedbacks, and calving especially along extensive margins (e.g., Hudson Strait/Bay). Ice  
563 sheets also form an active component of the climate system by altering atmospheric  
564 circulation due to ice sheet thickness and altering ocean circulation by changing sea level,  
565 salinity, and ocean temperature (e.g., Oerlemans, 1991; Clark et al., 1999; Berger and  
566 Loutre, 2004; Margold et al., 2018). These other factors could give rise to divergence  
567 between the ice *volume* signal found in sea level records and world-wide atmospheric  
568 temperature and climate changes during the last glacial cycle (e.g., Schaefer et al., 2015).  
569 Collectively, these feedbacks could cause many records to show a 'sawtooth' pattern that  
570 is ultimately a response to changes in ice *volume* and not necessarily reflecting more  
571 global-wide atmospheric temperature and climatic conditions (e.g., Gong et al., 2015).

572 Several studies suggest that northern hemisphere high latitude summer insolation  
573 drives northern hemisphere ice volume, which then alters Earth's energy balance through  
574 albedo and subsequently cools the planet (e.g., Denton and Hughes, 1983; Clark et al.,  
575 1999; Clark et al., 2009). Records that show a 'sawtooth' pattern similar to the  $\delta^{18}\text{O}$  stack  
576 (e.g., Fig. 1) include atmospheric  $\text{CO}_2$  (was ~85% of its MIS 2 minimum; Bereiter et al.,  
577 2012), eustatic sea level (was only 75% of its full glacial lowstand; Grant et al., 2012),  
578 and dust flux to EPICA Dome C (was only ~75% of its MIS 2 value; Lambert et al.,  
579 2008). However, it is difficult to explain the prevalence of MIS 4 glacier extents, or any  
580 of the records in Figs. 2 and 4, if one assumes that global mean temperature followed a  
581 'sawtooth' pattern.

582 The moraine record is not alone in its departure from the 'sawtooth' pattern of  
583 global ice volume; variations in regional insolation represent the dominant control on  
584 monsoon variability as reconstructed from cave speleothems (e.g. Cheng et al., 2016) and  
585 ice core temperature reconstructions from both polar regions suggest that MIS 4 may  
586 have been just as cold as MIS 2 (e.g., Dansgaard et al., 1993; Johnsen et al., 1997; GRIP  
587 Members, 1993; Vinther et al., 2011; Shackleton et al., 2021; Fig. 2). For example,  
588 Kindler (2014) used the NGRIP record to reconstruct temperature, suggesting a minimum  
589 temperature during MIS 4 of  $-53^\circ\text{C}$  and MIS 2 of  $-52^\circ\text{C}$  (although we note that that study  
590 was mainly focused on the magnitude of abrupt warming events, rather than equilibrium  
591 temperatures). Similarly, temperature reconstructions based on ice core records from  
592 Antarctica (Vostock  $\delta\text{D}$ ) suggest an abrupt shift into glacial conditions following MIS 5  
593 and prolonged periods of very cold conditions during MIS 4 and MIS 2 (Petit et al., 1999;  
594 Fig. 2).

595           Records of sea surface temperature vary by region but several indicate colder  
596 temperatures during MIS 4 compared with MIS 2, e.g., the Chilean Margin (Kaiser et al.,  
597 2005), Benguela upwelling zone (Kirst et al., 1999), SE Atlantic (Barker and Diz, 2014),  
598 and Iberian Margin (Martrat et al., 2007) (Fig. 2). Below the surface ocean, indicators  
599 sensitive to changes in ocean circulation also hint at conditions during MIS 4 that may  
600 have been more extreme than (or at least similar to) MIS 2. For example, benthic carbon  
601 isotopes suggest that deep water in the Atlantic Ocean were less well ventilated during  
602 MIS 4 than MIS 2 (Curry, 1996), which is also supported by carbonate system proxies  
603 including preservation indices (e.g., Barker and Diz, 2014) and B/Ca ratios in benthic  
604 foraminifera - a proxy for bottom water carbonate saturation state (Yu et al., 2014; Yu et  
605 al., 2016). Evidence from the NW Atlantic suggests that the deep western boundary  
606 current had a similar structure during MIS 4 and MIS 2 (e.g. Thornalley et al., 2013) and  
607 sedimentary Pa/Th ratios also suggest similar rates of deep water export from the Atlantic  
608 during MIS 4 and MIS 2 (Böhm et al., 2015). On the other hand, Nd isotopes, which  
609 have been used to trace deep water mass mixing, suggest that the dominance of (poorly  
610 ventilated) southern- versus northern-sourced deep waters in the Atlantic may have been  
611 greater during MIS 2 than MIS 4 (Piotrowski et al., 2005; Böhm et al., 2015). Finally,  
612 sub-surface indicators of Southern Ocean surface processes (e.g., denitrification in the SE  
613 Pacific) also suggest conditions at least as extreme (in this case in terms of ventilation  
614 and preformed nutrient content of Sub-Antarctic mode water) during MIS 4 as during  
615 MIS 2 (Robinson et al., 2007).

616           We therefore infer that the 'sawtooth' pattern thought to be characteristic of  
617 glacial/interglacial variability might not be so pervasive as a global climate signal.

618 Consequently, we suggest that a reevaluation of climate evolution during the last glacial  
619 cycle is required. Global ice volume was undoubtedly at its maximum during MIS 2 but  
620 this was mainly a function of the massive northern hemisphere ice sheets reaching their  
621 maximum size at this time (e.g., Liverman et al., 1989; Balco and Schaefer, 2006;  
622 Bintanja and van de Wal, 2008; Kennedy et al., 2010; Klemen et al., 2013; Corbett et al.,  
623 2017; Hall et al., 2017; Andriashek and Barendregt, 2017; Heath et al., 2020) due to a  
624 combination of climatic and mechanical feedbacks. Accordingly, we suggest that the  
625 importance of other parameters (such as global surface temperatures and their influence  
626 on mountain glaciers) has been underestimated in light of the dominance of the North  
627 American ice sheets in the isotope and sea level records. The connection between 65°N  
628 insolation and records showing the 'sawtooth' pattern might thus be misleading as a way  
629 of understanding the cause of ice ages. If glaciers are not responding to North America  
630 ice sheet volume or carbon dioxide in a linear way, and they are not responding to local  
631 overhead summer insolation intensity, then we need to look for other forcing  
632 mechanisms.

633

### 634 *3.3. Insolation and glacial cycles*

635 The predictable periodicity of ice ages is paced by insolation (e.g., Hays et al.,  
636 1976) but the exact details of the mechanisms involved are unclear. Ice age cycles  
637 recorded in the benthic record once had a dominant periodicity of 41 kyr, similar to the  
638 periodicity of obliquity (e.g., Raymo and Nisancioglu, 2003), but now they last for ~100  
639 kyr, similar to eccentricity (e.g., Abe-Ouchi et al., 2013), or perhaps the average of 2 or 3  
640 obliquity cycles (e.g., Huybers and Wunsch, 2005). Several theories invoke 65°N

641 summer insolation intensity as the driver of northern hemisphere ice sheets, which in turn  
642 influence global climate through feedbacks including changes in ice albedo, calving, and  
643 ocean circulation (and its influence on atmospheric CO<sub>2</sub>) (Milankovitch, 1941; Hays et  
644 al., 1976; Berger and Loutre, 1991; Roe, 2006; Huybers, 2011). Due to these powerful  
645 feedbacks, fluctuations in North American ice volume are not necessarily a direct  
646 reflection of insolation or global mean temperature, and, thus, variations in global ice  
647 volume need not necessarily reflect those in global mean temperature or glacier extent  
648 maxima. Invoking ice sheets as the messenger of global climate is problematic, not only  
649 because several ice sheets were smaller during MIS 4 when many mountain glaciers were  
650 larger, but also because many mountain glaciers began retreating prior to an increase in  
651 CO<sub>2</sub> or a collapse in the ice sheets (e.g., Putnam et al., 2013; Jackson et al., 2019; Denton  
652 et al., 2021). It is not necessary that 65°N summer insolation intensity controls global  
653 mean temperature, a suggestion also made by previous studies (e.g., Rubincam, 2004;  
654 Huybers and Denton, 2008; Timmermann et al., 2009). Insolation drivers must explain  
655 similar magnitudes of cooling during MIS 4 and MIS 2 that impact both hemispheres  
656 synchronously, such as obliquity.

657         Unlike precession, which gives rise to opposite trends in either hemisphere  
658 (Cheng et al., 2013; 2016), variations in obliquity occur symmetrically between the  
659 hemispheres. Prior to the Mid-Pleistocene Transition (MPT) global ice volume varied  
660 dominantly on obliquity time scales (41 kyr) (Raymo et al., 2006) and it seems  
661 reasonable to expect that obliquity should influence the growth and decay of glaciers  
662 through its influence on Earth's energy balance. Low obliquity concentrates solar  
663 radiation at the tropics, so relatively less radiation reaches high latitude regions. This

664 redistribution of insolation has two main effects; (1) it increases the area of the Earth  
665 where incoming radiation is less than outgoing radiation and thus there is a net release of  
666 energy to space and (2) the latitudinal insolation gradient increases the latitudinal  
667 temperature gradient from equator to the poles, causing increased winds and atmospheric  
668 circulation. Multiple studies have highlighted the importance of obliquity in climate  
669 variability (e.g., Paillard, 2001; Huybers and Wunsch, 2005; Caley et al., 2011; Zhang et  
670 al., 2013; Barker and Diz, 2014; Kindler et al., 2014; Peltier et al., 2016; in press). We  
671 speculate that similarly low obliquity during MIS 4 and MIS 2 may explain at least some  
672 of the records we summarize. We acknowledge that extensive glaciers during MIS 3 are  
673 more difficult to explain with obliquity, unless there is a threshold, perhaps between  
674 Earth's tilt at  $23.5^\circ$  and Earth's energy budget. Focusing on the influence of obliquity  
675 provides at least one sensible approach to improving our understanding of glacier  
676 evolution through time. If global mean temperature is responding to obliquity, there  
677 should also be cooling at  $\sim 120$  ka (MIS 5d).

678

#### 679 *3.4. Testable ideas*

680 Our MIS 4 moraine review presents several testable ideas:

- 681 1. If large and small glaciers were at/near a global maximum during MIS 4, then the  
682 'sawtooth' pattern (e.g., benthic  $\delta^{18}\text{O}$ ) is not a clear representation of global glacier  
683 extent or mean climate, including temperature. Likewise, studies are needed to  
684 understand why larger MIS 4 glacier expansions are not evident in some parts of  
685 the globe such as Europe and parts of North America (Fig. 3), if correct.

- 686 2. If the 'sawtooth' pattern does not represent world-wide climate, but instead  
687 represents North American ice sheet volume, perhaps controlled by internal  
688 feedbacks, then this allows better fingerprinting of other records that display the  
689 'sawtooth' pattern (i.e., sea level, CO<sub>2</sub>) and are being influenced, to some degree,  
690 by North American ice volume.
- 691 3. If glaciers were at/near a global maximum during MIS 4, we need to revise the  
692 proposed role of 65°N insolation in driving ice ages (Milankovitch et al., 1941;  
693 Roe et al., 2006). It is possible that obliquity is underappreciated in pacing global  
694 glaciations (and not just terminations).
- 695 4. If MIS 4 glaciers were responding, in part, to higher precipitation during MIS 4  
696 relative to MIS 2, then we need to determine the difference in precipitation and  
697 temperature during these times.

698

#### 699 **4. Conclusions**

700 MIS 4 moraines exist in many locations around the globe indicating that glaciers  
701 were more extensive than during MIS 2. MIS 4 advances are observed at sites with a  
702 range of geologic, topographic, latitudinal, and climatic setting, suggesting a similar  
703 magnitude of climate change (including temperature). Based on paleoclimate records  
704 that show a similar magnitude of cooling, we hypothesize that MIS 4 moraines might be  
705 expected in locations that would have been slightly wetter than during MIS 2. Drier  
706 conditions during MIS 2 in some locations could be linked to more exposed continental  
707 shelves, atmospheric circulation changes, greater sea ice extent, and weaker monsoons.  
708 The classic 'sawtooth' pattern is potentially misleading as a representation of global



709 glacier-climate records, as it is dominated by growth and decay of North American ice  
710 sheets. To understand the cause(s) of ice ages, it will be vital to examine records  
711 reflecting not only global ice volume changes and consider other forcings, such as  
712 obliquity.

713

#### 714 **Author statement**

715 M.R.K. recalculated the  $^{10}\text{Be}$  ages from the literature for the supplement (Fig. 4)  
716 with up-to-date systematics, so that they are all comparable. A.M.D. wrote the paper  
717 with contributions from all authors. All authors have approved the submitted version of  
718 the manuscript.

719

#### 720 **Declaration of Competing Interest**

721 The authors declare that they have no known competing financial interests or  
722 personal relationships that could have appeared to influence the work reported in this  
723 paper.

724

#### 725 **Acknowledgments**

726 We thank QSR for inviting this review, Editor T. Horscroft for his patience, B.  
727 Ward for helpful suggestions and one anonymous reviewer for their valuable insight and  
728 encouragement. We thank numerous colleagues for associated discussions over the  
729 years, including D. Barrell, T. Barrows, S. Birkel, G. Denton, L. Lisiecki, A. Putnam, J.  
730 Schaefer, and J. Severinghaus. In particular, we thank Joerg Schaefer for his significant  
731 contributions on this topic and for helping us to understand the MIS 4 glaciation. We

732 thank Lewis Owen for assistance with Asian records. We thank colleagues who  
733 contributed to our MIS 4 conference sessions and discussions at AGU and INQUA. This  
734 is LDEO publication #.

735

### 736 **Appendix A. Supplementary data**

737 Supplementary data to this article can be found online at

738

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## 1377 **Figures**

1378

1379 **Fig. 1.** Insolation compared with climate records for the past 250,000 years that show a  
 1380 'sawtooth' pattern. Marine Isotope Stages 6, 4, and 2 are designated by the vertical blue  
 1381 bars. The following panels show A)  $65^\circ\text{N}$  summer insolation (black line) and obliquity  
 1382 (orange line; Berger and Loutre, 1991), B) benthic stack  $\delta^{18}\text{O}$  (Lisiecki and Raymo,  
 1383 2005), C) composite atmospheric  $\text{CO}_2$  (Bereiter et al., 2015 and references therein), D)  
 1384 eustatic sea level change (Waelbroeck et al., 2002), D) Vostok dust record (Petit et al.,  
 1385 1999), E) modeled North American ice volume relative to present (Bintanja and van de  
 1386 Wal, 2008). Notice the classic 'sawtooth' pattern in the paleoclimate records, as  
 1387 symbolized by the green arrows.

1388

1389 **Fig. 2.** Stack of paleoclimate records indicating similar conditions during MIS 4 and MIS  
 1390 2. The following panels show A)  $\delta^{18}\text{O}$  from NGRIP adjusted for global ice volume  
 1391 (Huber et al., 2006), B)  $\delta\text{D}$  from Vostok (Petit et al., 1999), C) sea surface temperatures  
 1392 (SST) from the west coast of southern Chile (blue line; ODP Site 1233; Kaiser et al.,  
 1393 2005) and from the Iberian Margin (black line; core MD01-2444; Martrat et al., 2007),  
 1394 D) Mg/Ca ratios from Pacific marine cores (blue line; core TR163-31P; Martin et al.,  
 1395 2002) (black line; ODP Site 181-1123; Elderfield et al., 2012), E) percent polar species  
 1396 from southern Cape Basin (core TN057-21; Barker and Diz, 2014), and F)  $\delta\text{D}_{\text{wax-IV}}$  from  
 1397 the Gulf of Aden (core RC09-166; Tierney et al., 2017). We show these climate records  
 1398 for the past 250,000 years for comparing Marine Isotope Stages 6, 4, and 2 (vertical blue  
 1399 bars).

1400

1401 **Fig. 3.** World map with dark blue dots marking the locations of MIS 4-aged moraines as  
 1402 documented with  $^{10}\text{Be}$  surface exposure ages (see also Table 2 and supplementary data).



1403 Cyan dots mark locations with supporting evidence of maximum MIS 4 glacier extent  
 1404 through alternative methods including other cosmogenic isotopes (e.g.,  $^{10}\text{Be}$  of erratics or  
 1405 cobbles,  $^{10}\text{Be}$  of <3 ages,  $^{36}\text{Cl}$ ,  $^3\text{He}$ ; see Table 3 and end of supplementary data).

1406  
 1407 **Fig. 4.** Probability density plots of sites around the globe where  $^{10}\text{Be}$ -dated glacial  
 1408 deposits (e.g., moraines) are between ~75 and ~55 ka, as shown in the supplementary  
 1409 data. Y-axis is relative probability standardized to 1. Thin curves are Gaussian  
 1410 representations of individual  $^{10}\text{Be}$  ages (highlighted in the supplement), while the thicker  
 1411 black curve represents the summed probability of the total population. For Asia, given  
 1412 the quantity of studies, we only provide plots for those that have >5  $^{10}\text{Be}$  ages, excluding  
 1413 the Urals, which are in a different sector; other studies with  $\leq 3$   $^{10}\text{Be}$  ages are cited in the  
 1414 text. For the other areas around the globe, due to the scarceness of studies, we provide  
 1415 probability density plots for sites where there are at least 3  $^{10}\text{Be}$  ages. Whereas in the  
 1416 supplement we provide ages with different production rates and scaling schemes, for the  
 1417 purpose of this figure and in the text, we use the Lm scaling scheme (Balco et al. 2008);  
 1418 we emphasize that different production rates and schemes do not affect our main findings  
 1419 and conclusions. We plot the 'best' records towards the leftmost-side (except for Asia,  
 1420 which is the top row), based on number of ages and uncertainties (e.g., more recent  
 1421 efforts), coherence among moraine suites, and documentation of geomorphic setting in  
 1422 the publications. All x-axes are identical in scale for ease of comparison.

1423  
 1424 **Fig. 5.** Three examples of adapted geomorphic maps and (recalculated) individual  $^{10}\text{Be}$   
 1425 ages from well-dated records of MIS 4 glacier advances (ages in italics are considered  
 1426 outliers). These maps show the geomorphic context of MIS 4 moraines and how glaciers  
 1427 were more extensive in some locations relative to MIS 2. In addition, two of the maps  
 1428 show multiple moraine crests dating to MIS 4, indicating a rich history of glacier  
 1429 fluctuations during this time. A) Pukaki left lateral and Tekapo right lateral moraine  
 1430 sequence in the Southern Alps, New Zealand (Schaefer et al., 2015). Each sample (red  
 1431 text) is shown with its  $^{10}\text{Be}$  age and  $1\sigma$  analytical error (black text). Red moraines date to  
 1432 MIS 2. B) Estrecho de Magallanes, Chile (Peltier et al., in press). Bi. Glacial  
 1433 geomorphic map from Soteres et al., (2020). Bii. Right lateral MIS 4 moraine sequence.  
 1434 Each sample is shown with its  $^{10}\text{Be}$  age and  $1\sigma$  analytical error (black text). Pink  
 1435 moraines date to MIS 2. C) Revelation Mountains, USA (Tulenko et al., 2018). Ci. Map  
 1436 of glacial moraines in the western Revelation Mountains. Cii. Left lateral moraines and  
 1437 chronology. Red moraines date to MIS 2. We note there are studies in Asia also with  
 1438 well-mapped and dated geomorphic contexts (Fig. 3).

1439  
 1440 **Table 1.** Comparison of MIS 4 versus MIS 2 values relative to the Late Holocene from  
 1441 proxy records. Records include global ice volume (Lisiecki and Raymo, 2005),  $\text{CO}_2$   
 1442 (Bereiter et al., 2015 and references therein), eustatic sea level (Waelbroeck et al., 2002)  
 1443 and Antarctic Deuterium excess (Petit et al., 1999).

Proxy	Late Holocene	MIS 2	MIS 4	Relative to MIS 2 (%)
Global ice volume ( $\delta^{18}\text{O}$ )	3.2	5.0	4.6	78%
$\text{CO}_2$ (ppmv)	280	180	200	80%
Eustatic sea level change (m)	0	-120	-90	75%

Antarctic Deuterium excess	-430	-490	-490	100%
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1444

1445

1446 **Table 2.** Summary of sites with four or more exposure ages between ~75 and ~55 ka.  
 1447 Locations are marked in Fig. 3 as blue dots, ages are highlighted in the supplementary  
 1448 data and shown on Fig. 4. Outliers in original publications are typically excluded (see  
 1449 text).

Lat, Long	Location	Number of ages	Reference
61, -155	Alaska, USA	9	Tulenko et al., 2018
64, -149	Alaska, USA	8	Dortch et al., 2010a
64, -146	Alaska, USA	4	Matmon et al., 2010
61, -155	Alaska, USA	7	Briner et al., 2005
61, -140	Yukon, Canada	4	Ward et al., 2007
-53, -70	Patagonia	6	Peltier et al., 2021
-10, -77	Peru	5	Smith and Rodbell, 2010
67, 65	Russia	4	Mangerud et al., 2008
30, 81	Ronggua Gorge, Tibet	13	Owen et al., 2010
29+33, 92	Tibet	13	Owen et al., 2005
37+38, 75	Pamir	12	Owen et al., 2012
39, 68	Tajikistan	5	Zech et al., 2013
39, 73	Tajikistan, Kyrgyzstan	7	Abramowski et al., 2006
42, 76	Kyrgyzstan	6	Koppes et al., 2008
34, 78	Himalaya	8	Dortch et al., 2010b; 2013
34, 98	Himalaya	13	Heyman et al., 2011
-44, 170	New Zealand	46	Schaefer et al., 2015
-36, 148	Australia	4	Barrows et al., 2001

1450

1451 **Table 3.** Supporting evidence for a large MIS 4 glaciation based on fewer or more sparse  
 1452 surface exposure data between ~75 and ~55 ka, in order of appearance in the main text  
 1453 (cyan dots in Fig. 2).

Lat, Long	Location	Method	Reference
61, -154	Alaska, USA	<sup>36</sup> Cl	Briner et al., 2001
62, -137	Yukon, CA	<sup>10</sup> Be	Stroeven et al., 2014
38, -119	CA, USA	<sup>36</sup> Cl	Phillips et al., 1990
-51, -72	Chile	<sup>10</sup> Be	García et al., 2018
-52, -72	Chile	<sup>10</sup> Be	Sagredo et al., 2011
-22, -67	Bolivia	<sup>3</sup> He	Blard et al., 2014
38, 87	Himalaya	<sup>10</sup> Be	Mériaux et al., 2004
68, 66	Russia	<sup>10</sup> Be	Svendsen et al., 2019
31, 89	Mt. Jaggang, Tibet	<sup>10</sup> Be	Dong et al., 2018
41, 76	Kyrgyzstan	<sup>10</sup> Be	Zech, 2012
43, 94	Tian Shan	<sup>10</sup> Be	Chen et al., 2015
43, 87	Tian Shan	<sup>10</sup> Be	Li et al., 2014
35, 75	Pakistan	<sup>10</sup> Be	Phillips et al., 2000
41, 41	Turkey	<sup>10</sup> Be	Reber et al., 2014

33, 92	Tanggula Shan	$^{10}\text{Be}$	Colgan et al., 2006
28, 87	Tibet	$^{10}\text{Be}$	Chevalier et al., 2011
-5, 144	Papua New Guinea	$^{36}\text{Cl}$	Barrows et al., 2011
-44, 168	New Zealand	$^{10}\text{Be}$	Sutherland et al., 2007
-39, 176	New Zealand	$^3\text{He}$	Eaves et al., 2016
43, -5	Iberia	$^{10}\text{Be}$	Rodriguez-Rodriguez et al., 2016

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