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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 δ^{18}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}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

the growth of the North American ice sheets (and perhaps other northern ice sheets). Glaciers ultimately respond to changes in climate, however, large northern ice sheets also were affected by factors involving topography, isostacy, and glaciologic and mass balance dynamics. Given these feedbacks, the North American ice sheets' dominant role in global ice volume, sea level, and benthic $\delta^{18}O$ signals might therefore result in a skewed picture of global climate. If maximum global ice volume during MIS 2 is mainly a function of North American ice sheet volume and not necessarily directly connected to global temperatures, then other records with extremes during MIS 2, such as dust and CO_2, could be primarily reflecting ice volume change.

1. Introduction

The cause of ice ages is one of the major unresolved mysteries in the Earth sciences. The theory of ice ages began with the study of glacial geology and mapping of past glacial extents, mainly in Europe and North America and correlated them with calculations of the secular changes in Earth's orbit around the sun (e.g., Milankovitch, 1941; Imbrie and Imbrie, 1986). The theory gained momentum with continuous and semi-continuous records of global ice volume changes represented by oxygen isotope variation and sea level change (e.g., Shackleton, 1967; Hays et al., 1976; Yokoyama et al., 2000; Waelbroeck et al., 2002; Raymo and Nisancioglu, 2003; Lisiecki and Raymo, 2005; Arz et al., 2007; Grant et al., 2012). The classic 'sawtooth' pattern (Broecker and van Donk, 1970; Lisiecki and Raymo, 2005; Fig. 1) found in records of benthic foraminiferal $\delta^{18}O$, sea level, and CO_2 reflects a relatively slow or step-wise descent into glacial conditions and a rapid termination toward interglacial conditions. Spectral analysis of benthic $\delta^{18}O$ records revealed peaks at ~23-24 kyr, 40-43 kyr, and 94-106 kyr, with the ~100-kyr cycle constituting a major feature of the record (e.g., Hays et al., 1976). A 100-kyr cycle likely relates to the wavelength of eccentricity but the influence of eccentricity on Earth's climate is thought to be too small to pace ice ages (Imbrie et al., 1993). The seeming ubiquity of the ~100-kyr 'sawtooth' pattern in so many records may lead to the inference that the largest ice volume, which occurred ~21 ka (Mix et al., 2001), must coincide with world-wide maximum glacier extent and the coldest climates of the last ~125,000 years (e.g., Lisiecki and Raymo, 2005; Mix et al., 2001; Bereiter et al., 2012; Fig. 1; Table 1). However, several researchers have pointed out that this correlation is not necessarily correct, at least with respect to glacier extent or temperature depression (e.g., Gillespie and Molnar 1995; Berger et al., 1999; Bintanja and van de Wal, 2008; Schaefer et al., 2015; Tulenko et al., 2018 and references therein). In particular, glacier records do not necessarily follow the asymmetric 'sawtooth' pattern of the large North American ice sheets. Before firm chronological evidence was available, Gillespie and Molnar (1995) concluded that the global ice volume record does not describe the pattern of alpine glacier advances. However, they could not decipher geographic patterns or the timing of glacier behavior prior to the maximum in global ice volume.

Stacked benthic foraminiferal $\delta^{18}O$ stack (LR04; Lisiecki and Raymo, 2005; Fig. 1) represents changes in both land-ice volume and deep-water temperature. The isotopic values of this record have been used to define the structure of the last glacial cycle including Marine Isotope Stage (MIS) 5 (130-71 ka), MIS 4 (71-57 ka), MIS 3 (57-29 ka), MIS 2 (29-14 ka), and MIS 1 (14-0 ka) (Lisiecki and Raymo, 2005), where even-numbered MISs relate to glacial periods (blue bars in Fig. 1). Modeling studies have been used to separate the relative contributions of ice sheet volume and ocean temperature to δ^{18}O, and demonstrated that the North American ice sheets play an important role in the 'sawtooth' pattern, the mechanism of glacial terminations in the last 1 Myr, and the possible switch from ~41-kyr to ~100-kyr glacial cycles during the Middle Pleistocene transition (Berger et al., 1999; Bintanja and van de Wal, 2008). Records of δ^{18}O and sea level, therefore, are skewed by the waxing and waning of North American ice volume (Bintanja and van de Wal, 2008), and it is possible that these large ice sheets vary somewhat independently from global climatic drivers in part due to their internal mechanical and dynamical feedbacks.

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

Moraines are unambiguous and direct evidence of past glacial extents by marking where glaciers terminated on the landscape. Moraine dating reveals that in some places glaciers were larger during the middle of the last ice age cycle (MIS 4) than they were during the global ice volume maximum of MIS 2 (~21ka). The baseline connection between moraine ages and climate is that glacier size depends on changes in local temperature especially during the ablation season, and precipitation to a lesser extent in moist regions (e.g., Oerlemans, 1991; 2001; Mackintosh et al., 2017). Evidence of glacier extents prior to MIS 2 is sparse due to moraine preservation issues such as erosion, burial, or obliteration by younger advances (Gibbons et al., 1984). Thus the preservation of MIS 4 moraines is evidence that all subsequent glacier advances were less extensive because glaciers typically destroy moraines if they readvance over these deposits (excluding cold-based systems). Glaciers at these locations therefore must have been more extensive during MIS 4 relative to MIS 2. Although discontinuous by nature, dated terrestrial glacial geomorphic records are the best proxy to address the issue of glacier extents during the last glacial cycle. With the increased use of cosmogenic exposure dating and our ability to date glacier deposits older than the ^{14}C limit, more moraine chronologies appear to contain remnants of similar or slightly more extensive glaciers during MIS 4. Individual publications of moraines dating to MIS 4 often relate their presence to a local or regional effect of climate (e.g., increased precipitation) or glacier dynamics, or simply overlook these ages altogether if the number of samples is low. While it is not yet possible to reject these possible explanations, the abundance of MIS 4 moraine chronologies found in different locations with different regional climates, latitudes, proximity to bodies of water, geology and topographic settings suggests a possible collective advance of glaciers due to global cooling at that time.

Other paleoclimate proxy records showing similar conditions during MIS 4 and MIS 2 (Fig. 2) include isotope records such as those from Greenland (e.g., adjusted δ^{18}O; Huber et al., 2006) and Antarctica (e.g., δD from Vostok; Petit et al., 1999), and marine records, such as sea surface temperature from the Iberian margin (Martrat et al., 2007) and Southern Chile (Kaiser et al., 2005) and polar species from southern Cape Basin (Barker and Diz, 2014). Pacific Mg/Ca ratios (Martin et al., 2002; Elderfield et al., 2012) reflect changes in temperature and suggest similar temperatures during MIS 4 and MIS 2 (Fig. 2). $\delta D_{wax\text{-}IV}$ from Gulf of Aden (core RC09-166; Tierney et al., 2017) suggests a cold and dry climate in East Africa during MIS 4 and MIS 2.

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

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

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

2. MIS 4 moraine chronologies

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

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

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

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

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

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

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

2.1. North America

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

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

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

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

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

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

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

Additional support for more extensive glaciers in North America comes from studies with other geochronometers or smaller ^{10}Be datasets. Briner et al. (2001) dated four boulders on ground moraine in the Ahklun Mountains of southwest Alaska using ^{36}Cl. These ages (not recalculated) overlap with the later part of MIS 4 and are part of the 'Arolik Lake' glaciation (Briner et al., 2001). Two ^{10}Be ages from the Mackintosh Lake area in the southern Yukon Territory date to MIS 4 and come from a subdued end moraine relating to the 'Reid' glaciation (Stroeven et al., 2014). Turner et al. (2013) examined glacial and non-glacial deposits in southwestern Yukon and used radiocarbon and tephra beds to constrain tills to MIS 4, and MIS 6.

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

Whether we should expect to find MIS 4 moraines in the western United States is debatable. The modeling results of Batchelor et al. (2019) support a more extensive Laurentide Ice Sheet during MIS 2 than MIS 4 in the central and eastern portions of the northern United States (supported by moraine dating, e.g., Balco and Schaefer, 2006; Corbett et al., 2017; Hall et al., 2017; Heath et al., 2020), and more extensive ice during MIS 4 relative to MIS 2 in the west. However, of the available moraine chronologies from the western United States, MIS 4 ages are rare or absent (e.g., Licciardi and Pierce, 2008; Laabs et al., 2020). Moraines that predate MIS 2 exist throughout the Rocky Mountains (e.g., Gillespie and Molnar, 1995; Marchetti, 2007; Licciardi and Pierce, 2008), and future research efforts need to target older deposits for dating to confirm the presence/absence of MIS 4 moraines around much of North America.

2.2. South America

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

Five ^{10}Be ages from the southernmost end of the Cordillera Blanca in Peru range from 73 to 56 ka (Smith and Rodbell, 2010; Fig. 4). Samples PE05-JEU-06 and PE05-JEU-10 come from boulders on a right lateral moraine distal to a ~14 ka moraine ridge. Samples PE05-JEU-21, PE05-JEU-23, and PE05-JEU-24 date to MIS 4 and are from a glacial advance that curved to the right and was not destroyed by subsequent advances due to avulsion of a glacial trough allowing the MIS 2 glacier to flow to the left (Smith and Rodbell, 2010). Although these MIS 4 ages are from moraines that represent a slightly smaller glacier extent than during MIS 2, we include them here because the extents were quite similar. The additional three ages in the supplementary data are from cobbles on an outwash plain and do not designate past ice extent specifically.

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

2.3. Asia

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

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

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

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

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

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

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

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

Three ages from the Pangong lower inner moraine and one age from the lower outer moraine date to MIS 4 (Dortch et al., 2013). Two ages from the Diger La lower deposit date to MIS 4 (LDK-35 and LDK-208A), but are among a range of ages, as is sample LDK-52 on the North Pulu lower deposit (Dortch et al., 2013). One age from a moraine in northernmost Ladakh, India dates to MIS 4 (NU-26) and two ages from nearby deposits within the Nubra Valley were considered outliers, but also date to MIS 4 (NU-2 and NU-7; Dortch et al., 2010b).

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

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

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

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

2.4. Oceania

Forty-six ^{10}Be ages from the South Island, New Zealand date to MIS 4, and comprise the most comprehensive record reviewed here (Schaefer et al., 2015). Samples come from boulders on the left lateral 'Balmoral' moraines near Lake Pukaki and right lateral 'Balmoral' moraines of Lake Tekapo as part of the 'Otira' glaciation (Barrell, 2014), and are in stratigraphic order beyond moraines dating to MIS 3 and MIS 2 (Doughty et al., 2015; Denton et al., 2021). While this location contains the highest number of MIS 4 ages in the world, it is important to note that the moraines in the neighboring Lake Ohau valley do not contain MIS 4 ages (Putnam et al., 2013). Hence, MIS 4 ages exist for two of the three sub-lobes (Pukaki and Tekapo, and not Ohau). This difference in moraine preservation highlights the importance of dating multiple moraines in multiple valleys to understand the full MIS 4 glacial and climatic history of a region.

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

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

2.5. Europe

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

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

Records from the European Alps relating to MIS 4 mainly come from OSL dates of proglacial sediments (outwash or lacustrine) rather than glacial sediments (till or moraines) (Preusser, 2004). OSL ages from buried proglacial outwash in the Rhône Glacier Valley indicate the presence of the glacier in the Lake Neuchâtel area during MIS 4 (Preusser et al., 2007). In contrast, ^{14}C, ^{230}Th/U, and OSL ages from the Gossau section in the Swiss Alps suggest glacial advances during MIS 5d, MIS 3, and MIS 2, but not MIS 4 (Preusser et al., 2003).

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

2.6. Africa

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

2.7. Antarctica

MIS 4-aged moraines have not yet been identified in Antarctica to our knowledge. Cosmogenic dating of pre-Holocene moraines can be challenging in Antarctica due to possible inheritance from prior exposure that was not reset by glacial erosion during the last Glaciation. We note that two ^{10}Be ages from erratics on Mt. Dewe in the southern Antarctica Peninsula (Bentley et al., 2006) date to 59.1 and 76.6 ka but neighboring erratics yielded dates of 30.6 and 44.5 ka and so the glacial history is unclear. One ^{10}Be age from an erratic in the Darwin Mountains has the potential to relate the 'Danum drift' to MIS 4 (Storey et al., 2010). Given such issues as inheritance and the scope of this review, we do not include Antarctic data in the summary figures.

3. Discussion

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

3.1. Geographic pattern of MIS 4 sites

The geographic extent of MIS 4 moraine ages shows that glaciers from a broad range of latitudes, longitudes, and altitudes were larger relative to MIS 2 (Fig. 3). MIS 4 moraines have been found in low-, middle, and higher-latitude regions. This indicates a global temperature and climate signal similar in magnitude to MIS 2, rather than only a local climate particular to one study area. Similarly, this global occurrence of MIS 4 glaciation suggests an insolation forcing – if causal – that would have had a global rather than local impact. Direct summer insolation intensity is opposite between the Northern and southern hemispheres, making it unlikely that 65°N or 65°S summer insolation drove MIS 4 glaciation. MIS 4 moraines exist in both maritime (e.g., New Zealand) and continental (e.g., central Asia) locations, also suggesting that the cause is probably related to regional or hemispheric-scale atmospheric and oceanic circulation and not only local conditions.

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

In addition to similar magnitudes of cooling during MIS 4 and MIS 2 (e.g., those shown in Fig. 2), several records indicate that locations were wetter during MIS 4 relative to MIS 2. Relatively drier conditions during MIS 2 may be attributed to the larger area of exposed continental shelf (e.g., Briner et al., 2005), changes in atmospheric circulation (e.g., Mangerud et al., 1998; De Decker et al., 2019; Tulenko et al., 2020), increased sea ice extent (Gildor and Tziperman, 2000), and changes in monsoons (e.g., Wang et al., 2001; Owen et al., 2012). Alaska, for example, was likely more arid during MIS 2 because of the exposed Bering continental shelf (Ward et al., 2007; Briner and Kaufman, 2008; Thackray et al., 2008) and possibly the change in atmospheric circulation caused by a larger Laurentide Ice Sheet during MIS 2 (Tulenko et al., 2020). The lack of MIS 4 moraines south of the Laurentide could be due to these circulation changes caused by a larger Laurentide during MIS 2, bringing colder and/or wetter conditions to the Rocky Mountains during MIS 2 (Tulenko et al., 2020). Higher shorelines of Mono Lake during MIS 4 supported by stratigraphic relative paleointensity (Zimmerman et al., 2006) may counter the hypothesis proposed in Tulenko et al. (2020), and suggest wet conditions in the Sierra Nevada of California during MIS 4 (e.g., Phillips et al., 1990). If precipitation (in addition to temperature) caused more extensive glaciation during MIS 4, then indeed we would anticipate finding MIS 4 moraines in more locations that are generally thought to have been wetter during MIS 4 than MIS 2. Such locations include monsoonal regions (e.g., Owen et al., 2006), and regions that were drier during MIS 2 due to more extensive sea ice, such as northern Asia (Mangerud et al., 2011) or Alaska (Fig. 5). In addition, perhaps some sites between 40°S and 55°S associated with the westerly winds during glacial conditions in Patagonia (e.g., Peltier et al., in press) and in western North America (e.g., Phillips et al., 1990; Zimmerman et al., 2006) may have experiences shifts in precipitation due to changes in atmospheric circulation.

Of importance, our review also highlights several regions where MIS 4 moraines are notably absent. These include around the Laurentide Ice Sheet, the western U.S. (except maybe the Sierra Nevada; Phillips et al., 1990; Gillespie and Molnar, 1995) and the European Alps. A lack of evidence for MIS 4 moraines could be because not all pre-MIS 2 moraines have been dated, many glaciers were marine terminating and we cannot yet map or date their past extents, or because glaciers were more extensive in these areas during MIS 2 or MIS 3 than during MIS 4. Regardless, future studies need to question the absence of MIS 4-aged moraines in some regions (Fig. 3) (e.g., Gillespie and Molnar, 1995; Tulenko et al., 2018; Laabs et al., 2020).

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

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

Several studies suggest that northern hemisphere high latitude summer insolation drives northern hemisphere ice volume, which then alters Earth's energy balance through albedo and subsequently cools the planet (e.g., Denton and Hughes, 1983; Clark et al., 1999; Clark et al., 2009). Records that show a 'sawtooth' pattern similar to the $\delta^{18}O$ stack (e.g., Fig. 1) include atmospheric CO_2 (was ~85% of its MIS 2 minimum; Bereiter et al., 2012), eustatic sea level (was only 75% of its full glacial lowstand; Grant et al., 2012), and dust flux to EPICA Dome C (was only ~75% of its MIS 2 value; Lambert et al., 2008). However, it is difficult to explain the prevalence of MIS 4 glacier extents, or any of the records in Figs. 2 and 4, if one assumes that global mean temperature followed a 'sawtooth' pattern.

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

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

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

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

3.3. Insolation and glacial cycles

The predictable periodicity of ice ages is paced by insolation (e.g., Hays et al., 1976) but the exact details of the mechanisms involved are unclear. Ice age cycles recorded in the benthic record once had a dominant periodicity of 41 kyr, similar to the periodicity of obliquity (e.g., Raymo and Nisancioglu, 2003), but now they last for ~100 kyr, similar to eccentricity (e.g., Abe-Ouchi et al., 2013), or perhaps the average of 2 or 3 obliquity cycles (e.g., Huybers and Wunsch, 2005). Several theories invoke 65°N summer insolation intensity as the driver of northern hemisphere ice sheets, which in turn influence global climate through feedbacks including changes in ice albedo, calving, and ocean circulation (and its influence on atmospheric CO_2) (Milankovitch, 1941; Hays et al., 1976; Berger and Loutre, 1991; Roe, 2006; Huybers, 2011). Due to these powerful feedbacks, fluctuations in North American ice volume are not necessarily a direct reflection of insolation or global mean temperature, and, thus, variations in global ice volume need not necessarily reflect those in global mean temperature or glacier extent maxima. Invoking ice sheets as the messenger of global climate is problematic, not only because several ice sheets were smaller during MIS 4 when many mountain glaciers were larger, but also because many mountain glaciers began retreating prior to an increase in CO_2 or a collapse in the ice sheets (e.g., Putnam et al., 2013; Jackson et al., 2019; Denton et al., 2021). It is not necessary that 65°N summer insolation intensity controls global mean temperature, a suggestion also made by previous studies (e.g., Rubincam, 2004; Huybers and Denton, 2008; Timmermann et al., 2009). Insolation drivers must explain similar magnitudes of cooling during MIS 4 and MIS 2 that impact both hemispheres synchronously, such as obliquity.

Unlike precession, which gives rise to opposite trends in either hemisphere (Cheng et al., 2013; 2016), variations in obliquity occur symmetrically between the hemispheres. Prior to the Mid-Pleistocene Transition (MPT) global ice volume varied dominantly on obliquity time scales (41 kyr) (Raymo et al., 2006) and it seems reasonable to expect that obliquity should influence the growth and decay of glaciers through its influence on Earth's energy balance. Low obliquity concentrates solar radiation at the tropics, so relatively less radiation reaches high latitude regions. This redistribution of insolation has two main effects; (1) it increases the area of the Earth where incoming radiation is less than outgoing radiation and thus there is a net release of energy to space and (2) the latitudinal insolation gradient increases the latitudinal temperature gradient from equator to the poles, causing increased winds and atmospheric circulation. Multiple studies have highlighted the importance of obliquity in climate variability (e.g., Paillard, 2001; Huybers and Wunsch, 2005; Caley et al., 2011; Zhang et al., 2013; Barker and Diz, 2014; Kindler et al., 2014; Peltier et al., 2016; in press). We speculate that similarly low obliquity during MIS 4 and MIS 2 may explain at least some of the records we summarize. We acknowledge that extensive glaciers during MIS 3 are more difficult to explain with obliquity, unless there is a threshold, perhaps between Earth's tilt at 23.5° and Earth's energy budget. Focusing on the influence of obliquity provides at least one sensible approach to improving our understanding of glacier evolution through time. If global mean temperature is responding to obliquity, there should also be cooling at ~120 ka (MIS 5d).

3.4. Testable ideas

Our MIS 4 moraine review presents several testable ideas:

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

2. If the 'sawtooth' pattern does not represent world-wide climate, but instead represents North American ice sheet volume, perhaps controlled by internal feedbacks, then this allows better fingerprinting of other records that display the 'sawtooth' pattern (i.e., sea level, CO_2) and are being influenced, to some degree, by North American ice volume.
3. If glaciers were at/near a global maximum during MIS 4, we need to revise the proposed role of 65°N insolation in driving ice ages (Milankovitch et al., 1941; Roe et al., 2006). It is possible that obliquity is underappreciated in pacing global glaciations (and not just terminations).
4. If MIS 4 glaciers were responding, in part, to higher precipitation during MIS 4 relative to MIS 2, then we need to determine the difference in precipitation and temperature during these times.

4. Conclusions

MIS 4 moraines exist in many locations around the globe indicating that glaciers were more extensive than during MIS 2. MIS 4 advances are observed at sites with a range of geologic, topographic, latitudinal, and climatic setting, suggesting a similar magnitude of climate change (including temperature). Based on paleoclimate records that show a similar magnitude of cooling, we hypothesize that MIS 4 moraines might be expected in locations that would have been slightly wetter than during MIS 2. Drier conditions during MIS 2 in some locations could be linked to more exposed continental shelves, atmospheric circulation changes, greater sea ice extent, and weaker monsoons. The classic 'sawtooth' pattern is potentially misleading as a representation of global glacier-climate records, as it is dominated by growth and decay of North American ice sheets. To understand the cause(s) of ice ages, it will be vital to examine records reflecting not only global ice volume changes and consider other forcings, such as obliquity.

Author statement

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

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at

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Figures

Fig. 1. Insolation compared with climate records for the past 250,000 years that show a 'sawtooth' pattern. Marine Isotope Stages 6, 4, and 2 are designated by the vertical blue bars. The following panels show A) 65°N summer insolation (black line) and obliquity (orange line; Berger and Loutre, 1991), B) benthic stack δ^{18}O (Lisiecki and Raymo, 2005), C) composite atmospheric CO_2 (Bereiter et al., 2015 and references therein), D) eustatic sea level change (Waelbroeck et al., 2002), D) Vostok dust record (Petit et al., 1999), E) modeled North American ice volume relative to present (Bintanja and van de Wal, 2008). Notice the classic 'sawtooth' pattern in the paleoclimate records, as symbolized by the green arrows.

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

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

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

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

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

Table 1. Comparison of MIS 4 versus MIS 2 values relative to the Late Holocene from proxy records. Records include global ice volume (Lisiecki and Raymo, 2005), CO_2 (Bereiter et al., 2015 and references therein), eustatic sea level (Waelbroeck et al., 2002) and Antarctic Deuterium excess (Petit et al., 1999).

Proxy	Late Holocene	MIS 2	MIS 4	Relative to MIS 2 (%)
Global ice volume ($\delta^{18}O$)	3.2	5.0	4.6	78%
CO_2 (ppmv)	280	180	200	80%
Eustatic sea level change (m)	0	-120	-90	75%

Antarctic Deuterium excess	-430	-490	-490	100%

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

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

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

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