



Glacial and interglacial intensities across the Mid-Pleistocene Transition from a new 1.5 Myr long compilation of marine and terrestrial records

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Abstract. The Mid-Pleistocene Transition (MPT), between 1.2 and 0.8 Ma, altered the amplitude and frequency of Quaternary glacial–interglacial cycles with varying regional and proxy-dependent effects. Efforts to characterize these differences are constrained by the scarcity of continuous, high-resolution terrestrial archives, in contrast to the relative abundance of marine sediment cores. Previous compilations have focused on only the last 800 kyr or solely on marine records, and thus have not captured the full expression of the MPT across different proxies and for the pre- and post-MPT world. In this study, we present a new compilation of 29 paleoclimatic records spanning the last 1.5 Myr with equal contributions from marine and terrestrial archives. Interglacial and glacial strength is assessed for each record. This reveals a glacial amplification in strength from Marine Isotope Stage (MIS) 22 onwards, around 930 ka, which is evident in both the marine and terrestrial archives. For the past 1.5 Myr, there is no consistent temporal trend in interglacial strength visible in the terrestrial records. In contrast, the interglacial patterns of the marine records agree with previous studies, which are characterized by relatively strong interglacials during early stages (MIS 49–43) and following the Mid-Brunhes Shift (MBS), and more subdued interglacials during MIS 29–13a. A consistently strong global signal is detected during interglacial MIS 31 across most archives. MIS 13a emerges as a particularly interesting stage, as it appears weak in marine archives but strong in several terrestrial records, indicating that the manifestation of the MPT was not homogeneous between the marine and continental climate systems. Moreover, our compilation indicates a strong linear relationship between interglacial strength and the preceding glacial strength in benthic $\delta^{18}\text{O}$ records since the MBS. For other archive types, we identify notably strong post-MBS interglacials during MIS 5e, 9e, and 11c, each of which follows a strong glacial interval. However, there is no consistent linear relationship in intensity evident across these archives. Furthermore, most records indicate distinct interglacial and glacial states, separated by their value ranges. To facilitate the exploration of the presented archives, we provide an interactive web-based dashboard that allows users to investigate the compiled records and their associated glacial and interglacial intensities. The compiled archives, especially



the newly compiled terrestrial records, will be essential for future efforts to derive chronologies synchronised across different archives and as targets for model-data comparisons across the MPT.

1 Introduction

The Quaternary period spans the last 2.6 Myr and is linked to the onset of major glaciations in the Northern Hemisphere (NH) (Shackleton and Opdyke, 1977; Shackleton et al., 1984; Hodell et al., 2026). The alternating warmer interglacial and colder glacial states led to the waxing and waning of these large ice sheets (Raymo and Huybers, 2008). Milankovitch (1941) proposed the idea that variations in Earth's orbital parameters, leading to changes in solar radiation, drive these glacial cycles. Hays et al. (1976) were the first to provide geological evidence supporting this theory by identifying spectral peaks in a deep-sea sediment core coinciding with the orbital periods of precession ($\sim 19/23$ kyr), obliquity (~ 41 kyr) and eccentricity (~ 100 kyr). Nevertheless, this astronomical theory cannot explain the occurrence of the Mid-Pleistocene Transition (MPT) around 1.2-0.8 Ma, when the frequency of glacial cycles increased from ~ 41 kyr to ~ 100 kyr, accompanied by an increase in amplitude, since there was no apparent change in insolation during this period (Berends et al., 2021).

Natural archives such as marine sediments, ice cores or loess sequences provide a crucial source of information on how the Quaternary climate has evolved. Indeed, their use is twofold: (i) they provide sequences of climatic changes over time and space, and (ii) they can be used as benchmarks to evaluate climate models. Collaborative efforts like the Deep Sea Drilling Project (DSDP) and its successors, the Ocean Drilling Program (ODP), the Integrated Ocean Drilling Program (IODP), and the International Ocean Discovery Program (IODP), retrieved invaluable high-resolution paleoclimatic archives in the form of deep-sea sediment cores, covering the MPT. Isotopic signals such as benthic or planktonic $\delta^{18}\text{O}$, Sea Surface Temperature (SST) reconstructions, as well as many other paleoclimatic time series, can be retrieved from these marine sediment cores. While an abundance of long, high-resolution marine sediment cores are available from all ocean basins, their terrestrial counterparts are much less readily available. The majority stem from some long loess sequences from the Chinese Loess Plateau (CLP) (Sun et al., 2019; Ding et al., 2002), various paleo lake records (Prokopenko et al., 2006; Melles et al., 2012), and some long pollen sequences (Tzedakis et al., 2006; Torres et al., 2013), which are geographically very confined.

Available paleoclimatic time series covering diverse proxy archives and time periods document spatially and temporally heterogeneous responses within the climate system. For example, reconstructions of regional SSTs indicate differences in the timing of deglacial warming between the hemispheres (Stevenard et al., 2025; Hoffman et al., 2017). Furthermore, analyses by Lu et al. (2022) and Wang et al. (2025) reveal a long-term warming trend in terrestrial surface temperatures over the Asian monsoon region, in contrast to the global SST cooling trend between 1.5 and 0.9 Ma (Clark et al., 2024). This highlights that responses in the Earth-Climate system are not homogeneous, and global events like the MPT can have contrasting expressions among different archives.

A large focus has been directed toward the study of the past 800 kyr, as this interval corresponds to the age of the oldest continuous ice core records retrieved from Antarctica (Parrenin et al., 2007; Jouzel et al., 2007; Lüthi et al., 2008). Being the most recent interval in the Quaternary, it is covered by numerous high-resolution archives with relatively well-constrained



chronologies. Compilation studies, which take a selection from these available paleoarchives, make it possible to infer common spatial and temporal patterns among the records as well as the characterization of systematic differences. Lang and Wolff (2011) created a compilation of 37 marine, ice and terrestrial paleoclimatic records, covering the last 800 kyr and investigated the glacial and interglacial intensities over this period. Their analysis mainly includes marine isotopic $\delta^{18}\text{O}$ records and is limited to four terrestrial records. The Past Interglacials Working Group of PAGES (2016) conducted a similar synthesis study in which they investigated interglacial intensities of the past 800 kyr and included eight terrestrial records.

However, one of the challenges in understanding Quaternary climate is to look further back in time at the MPT, as this major transition marks a fundamental change in the Quaternary climate and in its glacial-interglacial cycles. A recent compilation of SST records over the past 1.5 Myr (Watson et al., 2026) takes on this challenge by assessing changes in glacial and interglacial intensities, but it does not include any terrestrial archives. With new data emerging from deep ice core drilling projects in Antarctica (e.g. Beyond EPICA-Oldest Ice, Million Year Ice Core Project), shifting the oldest continuous ice core records beyond 1 Ma and shedding new light on the evolution of greenhouse gas concentrations across the MPT, it is timely to develop a new synthesis including terrestrial records covering the MPT. Such a compilation is particularly valuable for placing the upcoming ice core records within a broader global context.

In this study, we build upon and extend the work of Lang and Wolff (2011), the Past Interglacials Working Group of PAGES (2016), and Watson et al. (2026). To this end, we compile a dataset of 29 high-resolution marine and terrestrial paleoclimate records spanning the last 1.5 Myr, including the MPT. With this new compilation, we aim to examine the manifestation of the MPT globally and to provide useful targets for the evaluation of climate models. We place specific emphasis on terrestrial records, given their relative scarcity and the over-representation of the marine realm in previous work. We quantify the glacial and interglacial intensities in each record and evaluate whether there are any global, regional, or proxy-specific patterns visible. For each Marine Isotope Stage (MIS), we identify outstandingly strong or weak glacials and interglacials. We also explore the value range and distribution of these extreme values. In addition, we look into a selection of terrestrial pre- and post-MPT glacial and interglacial periods to investigate the temporal morphologies of these specific MIS. Finally, we assess whether interglacial strength might depend on the previous glacial strength for any of the included paleoarchives. Along with this study, we provide a web-based interface that enables interactive visualization of the various records in this study and easy exploration of their glacial and interglacial characteristics (intensity, structure, duration, spectral characteristics).

2 Methods

2.1 Data compilation

This study builds upon a meta database¹ of marine and terrestrial records covering both 41-kyr and 100-kyr glacial cycles and the MPT period, developed within the framework of the EU Horizon 2020 project *Beyond EPICA-Oldest Ice*. The database comprises a variety of marine and terrestrial archives spanning the last 1.5 Myr, characterized by high temporal resolution and

¹ Can be downloaded here: <https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e50ea5b5f2&appId=PPGMS>



85 geographical coverage. From this meta database, we select a subset of records for this study using two main criteria: (i) high temporal resolution up to a maximum of 3 kyr², and (ii) continuous records that allow the identification of individual MIS. Within these constraints, we aim to maximize global spatial coverage and to include a wide range of proxy types and climatic variables, with particular emphasis on terrestrial records. The high temporal resolution and continuity ensure that the different MIS are identifiable in the records. The global coverage and the variety of included proxies ensure a more comprehensive
 90 characterization of the MPT. While the majority of the marine records have small data gaps of a maximum of 3 kyr, several terrestrial archives exhibit larger gaps with up to 23.3 kyr in the temperature record from the Heqing Basin. Due to the scarcity of terrestrial records, such records are included as long as individual MIS stages are identifiable, even if they contain larger gaps. Since the recently published temperature reconstruction from Lake Baikal (Novak et al., 2026) and the annual lake surface temperature record from Lake Malawi (Johnson et al., 2016) both exhibit too low temporal resolution to identify meaningful
 95 strength patterns over individual MIS, they are not included in the final compilation. An overview of the included records in this study can be found in Table 1. The majority of records exhibit a temporal resolution of 1 kyr or higher. Three records (AP % from Tenaghi Philippon, AP % and Log Ca/K from Lake Ohrid) cover shorter periods than 1.5 Myr, but are included due to the geographical scarcity of the terrestrial records. For the same reason, the Heqing Basin temperature reconstruction is also included, except for its upper ~250 kyr interval, which is excluded because its temporal resolution is insufficient to
 100 reliably resolve the younger MIS intervals. Overall, marine records are much more readily available than terrestrial records. Hence, we include most of the available terrestrial records from the meta database to give the most complete picture of the terrestrial MPT imprint. Figure 1 shows the location of the included terrestrial records in this study. The majority come from Asia and the Chinese Loess Plateau. Only two European records (Lake Ohrid and Tenaghi Philippon) and one South American record (Paleolake at Bogota Basin) meet the criteria. To allow comparison with previous work (Lang and Wolff, 2011; Past
 105 Interglacials Working Group of PAGES, 2016; Watson et al., 2026), we include benthic $\delta^{18}\text{O}$ and SST records as marine records in this study.

For the benthic $\delta^{18}\text{O}$, we incorporate the recently published BIGSTACK_{mixed} global stack together with its two associated regional stacks from the Pacific (BIGSTACK_{mixedP}) and the Atlantic (BIGSTACK_{mixedA}) (Zhou et al., 2026). BIGSTACK_{mixed} represents the most recent global $\delta^{18}\text{O}$ stack and contains approximately 45% more data than its precursor Prob-stack (Zhou
 110 et al., 2026). In view of the widespread use of the LR04 (Lisiecki, 2014) and Prob-stack (Ahn et al., 2017) global stacks in the literature, these two reference stacks are also included in our analysis.

For the SST archives, we do not include individual SST records as the work of Watson et al. (2026) has already addressed this. Instead, we use the global and regional SST stacks compiled by Clark et al. (2024), which integrate a large number of individual SST records. In addition, we include the tropical SST stack from Herbert et al. (2017).

115 The selected terrestrial archives comprise a variety of eight different metrics and proxy types. Apart from the Mean Annual Precipitation and Temperature reconstructions, all terrestrial records represent indirect proxies for some environmental parameters. Loess sequences from the CLP are interpreted as archives of paleomonsoon variability across glacial–interglacial cycles (Sun et al., 2019, 2021). Within these sequences, mean grain size serves as an indicator of the intensity of the East Asian Winter

²Due to the scarcity of terrestrial records, the record from Heqing Basin is included with temporal resolution of 5.3 kyr.



Table 1. Overview of records used in this study. ^aAverage resolution for period 0-1.5 Ma; ^bExcluding Gramineae and aquatic/semi-aquatic taxa; ^cexcluding *Pinus*; ^dexcluding *Quercus* & *Alnus*.

Record/Site	Proxy/Variable	Location	Coordinates	Resolution ^a	Temporal length	Reference
Benthic $\delta^{18}\text{O}$ records						
LR04 stack	Benthic $\delta^{18}\text{O}$	Global stack (57 records)	NA	1.4 kyr	5.32 Ma	Lisiecki and Raymo (2005)
Prob-stack	Benthic $\delta^{18}\text{O}$	Global stack (180 records)	NA	1.4 kyr	5 Ma	Ahn et al. (2017)
BIGSTACK _{mixed}	Benthic $\delta^{18}\text{O}$	Global stack (221 records)	NA	1 kyr	2.7 Ma	Zhou et al. (2026)
BIGSTACK _{mixedA}	Benthic $\delta^{18}\text{O}$	Atlantic stack (125 records)	NA	1 kyr	2.7 Ma	Zhou et al. (2026)
BIGSTACK _{mixedP}	Benthic $\delta^{18}\text{O}$	Pacific stack (81 records)	NA	1 kyr	2.7 Ma	Zhou et al. (2026)
SST records						
Global ΔSST stack	ΔSST	Global stack	NA	1 kyr	4.5 Ma	Clark et al. (2024)
Regional ΔSST stack	ΔSST	North Atlantic	NA	1 kyr	4 Ma	Clark et al. (2024)
Regional ΔSST stack	ΔSST	Tropical Atlantic	NA	1 kyr	4 Ma	Clark et al. (2024)
Regional ΔSST stack	ΔSST	South Atlantic	NA	1 kyr	4 Ma	Clark et al. (2024)
Regional ΔSST stack	ΔSST	North Pacific	NA	1 kyr	4 Ma	Clark et al. (2024)
Regional ΔSST stack	ΔSST	Tropical Pacific	NA	1 kyr	4 Ma	Clark et al. (2024)
Regional ΔSST stack	ΔSST	South Pacific	NA	1 kyr	4 Ma	Clark et al. (2024)
Regional ΔSST stack	ΔSST	Tropics	NA	1 kyr	4 Ma	Clark et al. (2024)
Regional SST stack	SST	Tropics	NA	3 kyr	5 Ma	Herbert et al. (2017)
Terrestrial records						
Chiloparts stack	Loess size	Chinese Loess Plateau (CLP)	Mean: 35.36°N, 107.93°W	1 kyr	2.6 Ma	Ding et al. (2002)
Gulang Loess	Loess size	Gulang Loess (NW CLP)	37.5°N, 102.88°E	0.1 kyr	1.488 Ma	Sun et al. (2021)
Jingyuan Loess	Loess size	Jingyuan Loess (NW CLP)	36.35°N, 104.6°E	0.4 kyr	1.74 Ma	Sun et al. (2019)
Jingyuan Loess	Inorganic Loess carbonates $\delta^{13}\text{C}_{\text{IC}}$	Jingyuan Loess (NW CLP)	36.35°N, 104.6°E	0.4 kyr	1.74 Ma	Sun et al. (2019)
Jingyuan Loess	Mean Annual Precipitation (MAP)	Jingyuan Loess (NW CLP)	36.35°N, 104.6°E	1 kyr	1.7 Ma	Sun et al. (2019)
Jingyuan Loess	Mean Annual Temperature (MAT)	Jingyuan Loess (NW CLP)	36.35°N, 104.6°E	1 kyr	1.7 Ma	Sun et al. (2019)
Zoige Basin (Core ZB13-C2)	Mean Annual Temperature (MAT)	Paleolake at Zoige Basin (Eastern Tibetan Plateau)	33.97°N, 102.33°E	0.63 kyr	1.74 Ma	Zhao et al. (2021)
Heqing Basin	Mean Annual Temperature (MAT)	Paleolake at Heqing Basin (SE Tibetan Plateau)	26.57°N, 100.17°E	5.3 kyr	2 Ma	Wang et al. (2025)
Tenaghi Philippon	Arboreal Pollen ^b (AP %)	NE Greece	41.17°N, 24.33°E	1.6 kyr	1.35 Ma	Tzedakis et al. (2006)
Lake Ohrid (DEEP core 5045-1)	Arboreal Pollen ^c (AP %)	Lake Ohrid (Balkan Peninsula)	41.04°N, 20.71°E	2.0 kyr	1.36 Ma	Donders et al. (2021)
Zoige Basin (Core ZB13-C2)	Arboreal Pollen (AP %)	Paleolake at Zoige Basin (Eastern Tibetan Plateau)	33.97°N, 102.33°E	0.6 kyr	1.74 Ma	Zhao et al. (2020)
Bogota Basin (Funza09)	Arboreal Pollen ^d (AP %)	Paleolake at Basin of Bogota (Colombia)	4.83°N, 74.2°W	1.3 kyr	2.25 Ma	Torres et al. (2013)
Lake El'gygytgyn (ICDP 5011-1)	Si/Ti	Lake El'gygytgyn (Siberia, NE Russia)	67.5°N, 172.1°E	0.5 kyr	2.8 Ma	Melles et al. (2012)
Lake Baikal (Composite BDP-96)	Biogenic Silica (BioSi %)	Lake Baikal (Siberia, Russia)	53.7°N, 108.35°E	0.5 kyr	1.84 Ma	Prokopenko et al. (2006)
Lake Ohrid (DEEP core 5045-1)	Log Ca/K	Lake Ohrid (Balkan Peninsula)	41.04°N, 20.71°E	0.1 kyr	1.36 Ma	Sun et al. (2021)

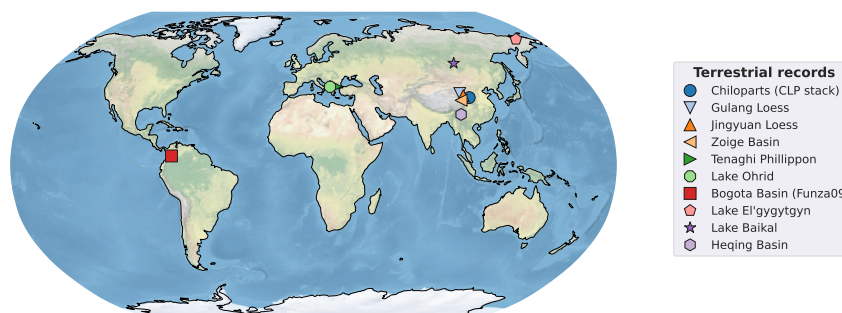


Figure 1. Location of terrestrial record sites used in this study.

Monsoon (Ding et al., 2002; Sun et al., 2019), whereas inorganic carbonate $\delta^{13}\text{C}_{\text{IC}}$ values act as a proxy for monsoon-induced changes in vegetation density (Sun et al., 2019). Arboreal pollen (AP %) records reflect the dynamics of local vegetation history and forest diversity (Donders et al., 2021; Torres et al., 2013). Over long timescales, variations in tree taxa can reflect changes in environmental conditions such as summer temperature and drought stress (Zhou et al., 2018). Biogenic silica concentrations in Lake Baikal primarily reflect variations in the lake's diatom productivity (Prokopenko et al., 2006), with higher values being associated with warmer mean annual temperatures over continental Siberia (Prokopenko et al., 2009). Similarly, Si/Ti ratios measured in sediments from Lake El'gygytgyn serve as an indicator of biogenic silica content (Melles et al., 2012). So, enhanced continental temperatures lead to reduced periods of ice cover over the lake, thereby increasing diatom productivity and leading to higher biogenic silica and Si/Ti values. However, it appears that at higher resolutions, sediment input and erosion rates play an important role that can lead to a mismatch between these two indicators (Cunningham et al., 2013). At Lake Ohrid, Ca/K ratios are used as a proxy for local hydrological variability. Elevated Ca/K values predominantly reflect an increased supply of Ca ions derived from karst aquifers, which is particularly sensitive to variations in winter precipitation amounts (Sun et al., 2021).

In total, we include 29 records in this study, consisting of five benthic $\delta^{18}\text{O}$ stacks (Fig. 2), nine global and regional SST stacks (Fig. 3) and fifteen terrestrial records (Fig. 4).

2.2 Glacial, interglacial and termination strength

This study aims to assess the intensity or strength of glacials, interglacials, and terminations over the last 1.5 Myr, including the pre- and post-MPT world. To assess the strength of glacials and interglacials, we need to consider the following three main points in our analysis:

- (i) Definition of MIS boundaries
- (ii) Method to obtain interglacial/glacial extrema

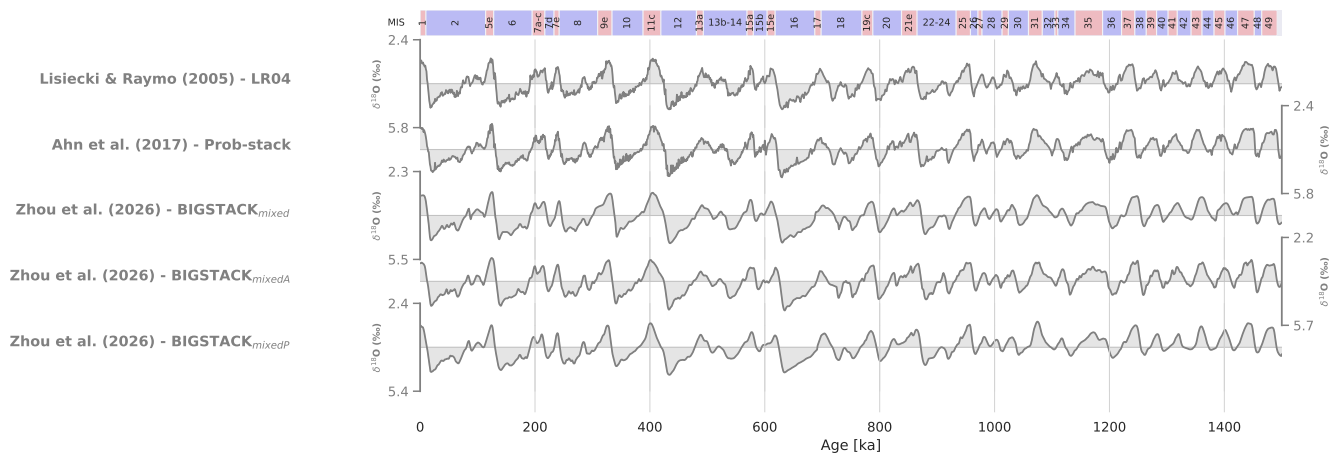


Figure 2. Benthic $\delta^{18}\text{O}$ records used in this study. Marine Isotope Stages (MIS) are given as in Table 2.

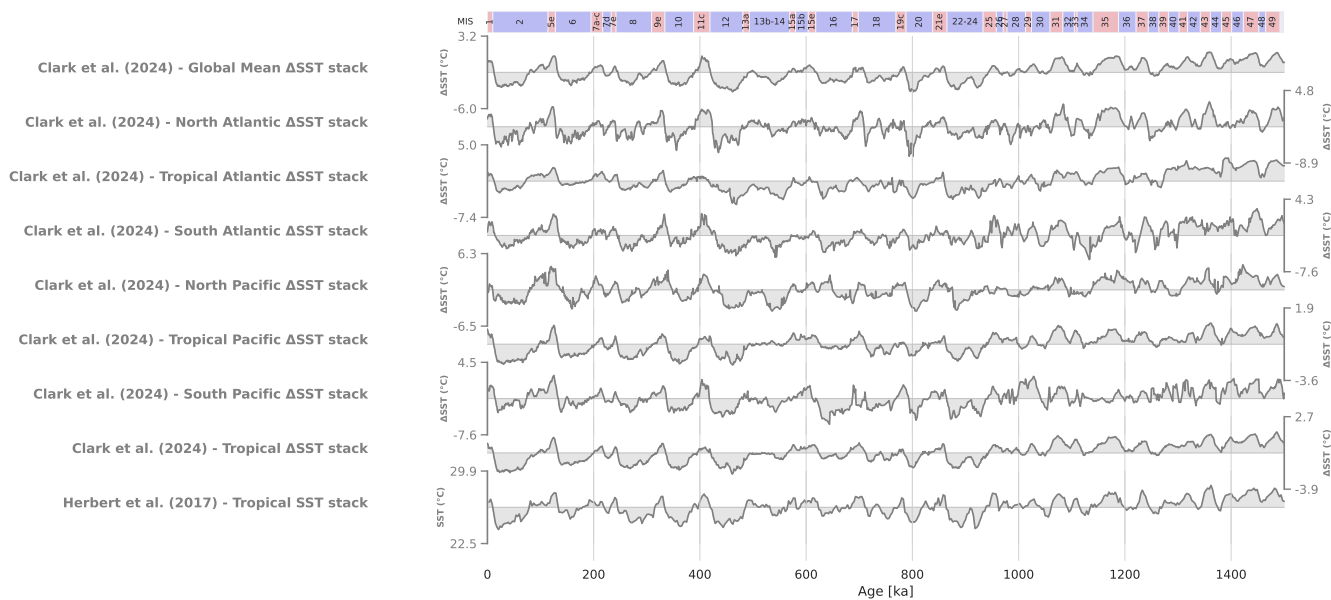


Figure 3. Sea surface temperature (SST) records used in this study. Marine Isotope Stages (MIS) are given as in Table 2.

140 (iii) Age models of records

2.2.1 Marine Isotope Stages

In order to quantify interglacial and glacial strength, it is necessary to set age boundaries to separate adjacent MIS. Lang and Wolff (2011) adopted the LR04 MIS boundaries (Lisiecki and Raymo, 2005), whereas Watson et al. (2026) employed the

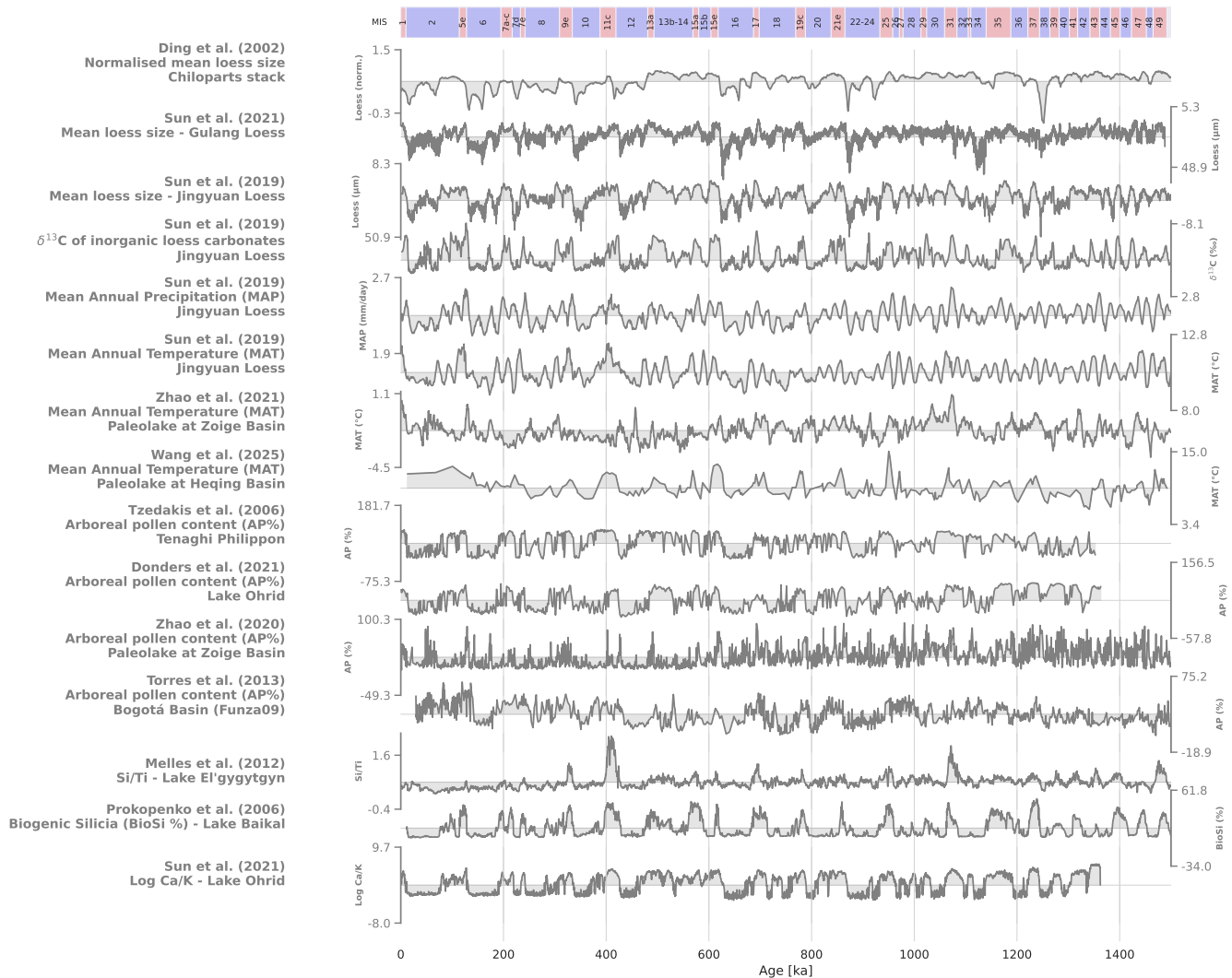


Figure 4. Terrestrial records of various proxy types used in this study. Marine Isotope Stages (MIS) are given as in Table 2.

definition of interglacials by Tzedakis et al. (2017), but therefore, they only defined the glacial terminations rather than both
145 terminations and glacial inceptions. Furthermore, the Past Interglacials Working Group of PAGES (2016) defined interglacials
as intervals with ice volumes comparable to the present day (0 ± 20 m), characterized by the absence of substantial Northern
Hemisphere ice outside of Greenland, which are separated by glacial periods associated with significantly reduced sea level,
falling below a prescribed threshold.

Here, we follow the definition of interglacials by Tzedakis et al. (2017), based on thresholds in the benthic $\delta^{18}\text{O}$ record of
150 LR04: values falling below a threshold of 3.68‰ mark the onset of an interglacial, and $\delta^{18}\text{O}$ must rise back above a threshold
of 3.92‰ between two intervals for them to be counted as two separate interglacials. Since Tzedakis et al. (2017) did not

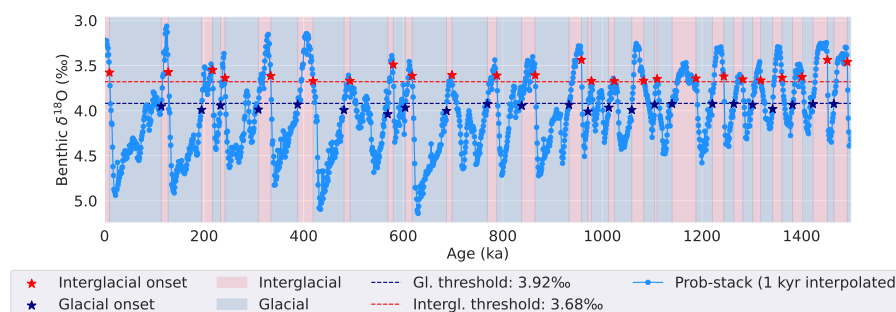


Figure 5. Definition of glacial and interglacial onsets in this study. The boundaries are based on the interglacial definition by Tzedakis et al. (2017), where thresholds in benthic $\delta^{18}\text{O}$ are applied to Prob-stack (Ahn et al., 2017). Interglacial onset is defined by crossing a threshold of 3.68 ‰ in benthic $\delta^{18}\text{O}$. Glacial inception is defined by exceeding a threshold of 3.92 ‰.

explicitly define a glacial inception, we adopt the 3.92‰ threshold for this purpose, meaning that a glacial inception is defined at the time when $\delta^{18}\text{O}$ exceeds this value. Furthermore, we apply this method to the Prob-stack benthic $\delta^{18}\text{O}$ record rather than to LR04. Figure 5 illustrates how these two boundaries define the MIS stages in Prob-stack. The associated MIS boundaries over the last 1.5 Myr are given in Table 2.

2.2.2 Interglacial and glacial extrema

Previous work adopted different methods in order to assess the interglacial and glacial strength. Lang and Wolff (2011) tested three methods - taking the extrema from (i) the raw data, (ii) the 1 kyr averaged data, and (iii) after applying a ramp fit through the data points. Since the authors did not identify a significant difference in the results for these three methods, they adhered to the raw data points. They selected the extrema closest to either side of a glacial termination as an indicator for glacial/interglacial strength, which does not necessarily correspond to the absolute extrema during a stage. Moreover, they did not define what they meant by *closest* and which distances to the glacial terminations they were considering. The Past Interglacials Working Group of PAGES (2016) discussed the advantages and disadvantages of various approaches, e.g. taking the average value over the entire interglacial could be problematic for records with varying resolutions or when data gaps are present. To reduce subjectivity (e.g. what distance to consider for closest extrema) and since it is the simplest method, which enhances reproducibility of the results, the authors defined interglacial strength as the absolute maxima/minima during interglacial periods. Prior to this, they applied a 1 kyr smoothing to records with higher resolutions in order to reduce noisy outliers. Watson et al. (2026) smoothed high-resolution records to 1 kyr and then calculated the extrema closest to a glacial termination as well as the absolute extrema. They presented results for both methods, but did not identify large differences, except for some specific MIS with delayed secondary peaks.

In this study, we define interglacial and glacial strength as the absolute extrema during each MIS. This approach is the most objective, since it only depends on the MIS boundaries and it is the easiest to reproduce. Using the closest extrema to a glacial termination introduces the subjective choice of which interval to include, which may differ between records and proxy types.



Table 2. Marine Isotope Stages (MIS) and their time intervals. The boundaries were calculated with the interglacial definition by Tzedakis et al. (2017), where thresholds in benthic $\delta^{18}\text{O}$ are applied to Prob-stack (Ahn et al., 2017). Interglacial onset is defined by crossing a threshold of 3.68 ‰ in benthic $\delta^{18}\text{O}$. Glacial inception is defined by exceeding a threshold of 3.92 ‰.

MIS	Time Interval (ka)	MIS	Time Interval (ka)
1	0–10	26	958–971
2	10–114	27	971–978
5e	114–128	28	978–1013
6	128–195	29	1013–1024
7a-c	195–217	30	1024–1059
7d	217–233	31	1059–1083
7e	233–242	32	1083–1105
8	242–309	33	1105–1110
9e	309–334	34	1110–1140
10	334–388	35	1140–1188
11c	388–419	36	1188–1221
12	419–481	37	1221–1244
13a	481–493	38	1244–1264
13b-14	493–569	39	1264–1282
15a	569–580	40	1282–1302
15b	580–604	41	1302–1318
15e	604–618	42	1318–1342
16	618–687	43	1342–1361
17	687–698	44	1361–1382
18	698–769	45	1382–1401
19c	769–788	46	1401–1423
20	788–838	47	1423–1452
21e	838–865	48	1452–1465
22-24	865–933	49	1465–1492
25	933–958		

Figure 6 shows an example of interglacial strength depending on these two methods. When examining absolute extrema, it is important to note that these may not occur simultaneously for different records. Therefore, glacial and interglacial strengths cannot be associated with a specific date, only a time interval. An exception is made when assessing the influence of the glacial strength on the subsequent interglacial period (Sect. 3.7). In this case, we consider the glacial extrema nearest to the termination, because they are immediately followed by the glacial terminations that initiate the next interglacial, in contrast to

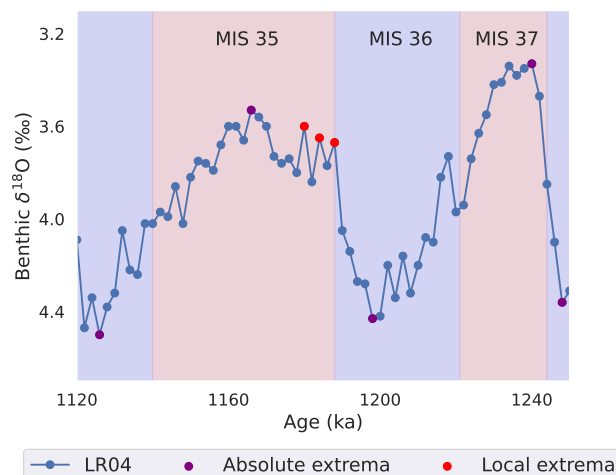


Figure 6. Difference between the absolute interglacial extremum (purple dot) during MIS 35 and the local extrema (red dots) closest to the glacial termination. The example shown is from the LR04 record (blue line). Red-shaded areas indicate interglacial periods, and blue-shaded areas indicate glacial periods. MIS boundaries are defined as in Table 2.

absolute extrema, which may occur several tens of thousands of years prior to the subsequent interglacial peak. Furthermore, we
 180 define the termination strength as the absolute difference between the interglacial strength and the preceding glacial strength.

2.2.3 Age models - Peak adjustment procedure

Numerous studies have shown evidence that climate and environmental changes are not synchronous across the globe. For instance, local variations in the deep-water hydrography influence the benthic $\delta^{18}\text{O}$ signals and can lead to phase lags between different record sites. Skinner and Shackleton (2005) identified a ~ 4 kyr phase lag between the occurrence of termination I in
 185 the deep equatorial Pacific and the deep Northeast Atlantic. Leads and lags between marine and terrestrial records also exist, e.g. Xu et al. (2013) found that the terrestrial warming over East Asia lagged around 3–4 ka behind the SST warming in the East China Sea and the tropical western Pacific during the last glacial termination. Although lead-lag relations exist between various proxies and geographical locations, this study aims to investigate the glacial/interglacial strengths rather than exact timings and phase relations. Therefore, phase lags between different proxies do not matter for this study, as long as records
 190 identify the same MIS stages and the extrema are located within the correct MIS boundaries.

Lang and Wolff (2011) aligned their $\delta^{18}\text{O}$ and SST records to the LR04 stack, while leaving the terrestrial records on their individual timescales. In contrast, Watson et al. (2026) did not perform any age alignment since most of their SST records are already tuned to LR04 or similar orbital targets and the MIS stages are clearly identifiable for all records. Both studies emphasize that the focus is on the interglacial/glacial strength rather than existing leads and lags.

195 Here, we also do not perform an age alignment between the records, since we are not interested in leads and lags. However, our set of records is much more diverse compared to previous studies, with the terrestrial records alone comprising eight

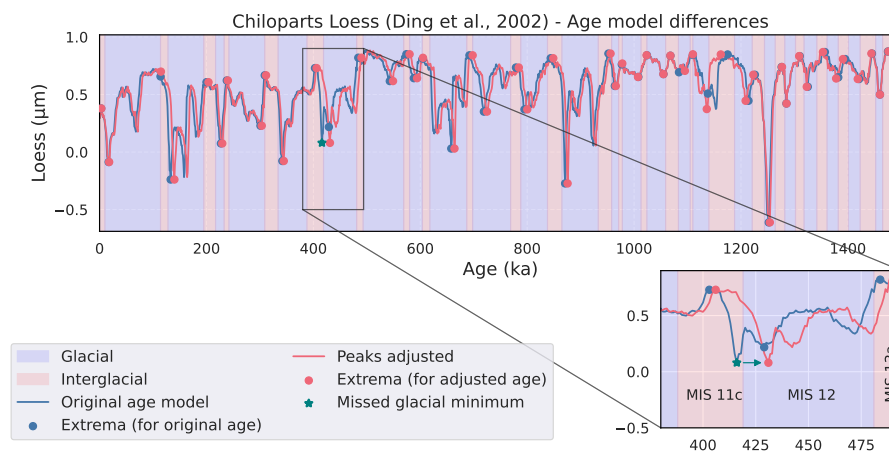


Figure 7. Example of the peak-adjustment procedure applied to the Chiloparts loess sequence of Ding et al. (2002). The original age model (blue line) is shown together with the adjusted one (red line). Blue and red dots indicate the extrema assigned to each MIS. The inset highlights the interval of MIS 11c to MIS 13a. For the original age scale, the absolute minimum in loess size (teal star) falls just outside the glacial MIS 12 boundary. Consequently, a preceding local minimum is assigned as the glacial minimum for MIS 12. For the adjusted age scale, this absolute minimum is shifted into the MIS 12 interval (teal arrow), allowing it to be assigned as the glacial strength for MIS 12.

different types of proxies/variables. Furthermore, the MIS boundaries defined above (Table 2) are based on thresholds applied to Prob-stack, a benthic $\delta^{18}\text{O}$ stack. Therefore, other proxy records containing phase shifts with respect to Prob-stack may be misaligned in such a way that some extrema fall just outside their corresponding MIS interval and may not be assigned to the correct interglacial or glacial period. Figure 7 depicts an example of such a situation: The Chiloparts loess sequence (Ding et al., 2002) is shown on its original timescale (blue line). Between the interglacial maxima of MIS 11c and MIS 13a (blue dots), the loess reaches its absolute minimum (teal star), which falls just outside the glacial MIS 12 boundary. Consequently, on the original timescale, a preceding local minimum is selected as the glacial minimum for MIS 12, which does not correspond to the absolute minimum between the two interglacials. To prevent this, we adjust the record by moving the absolute minimum (teal star) into the MIS 12 boundaries (teal arrow). This adjusted record (red line) now identifies this absolute minimum as the glacial peak for MIS 12. We apply this adjustment procedure to all records where absolute maxima or minima fall within a few kyr of their closest MIS boundary, while keeping the other extrema within their current MIS intervals. This adjustment is performed using the PyAnalyzeSeries software (Brockmann, 2025). This procedure distorts and shifts parts of the original age model and leads to incorrect age scales (as visible in Fig. 7). However, when analysing glacial and interglacial intensities, it is only important to assess the values of the extrema during each MIS, not their exact dates. Hence, this procedure seems reasonable. Moreover, we only apply this method to analyze interglacial/glacial strength, not to investigate the differences in interglacial/glacial morphologies (Sect. 3.8), for which undistorted ages are required. Reported ages are always given on the original age models.



2.3 Interactive visualization tool

215 In parallel with this study, we provide a web-based application that enables interactive exploration of the compiled datasets and their interglacial and glacial patterns. The application is hosted on *Hugging Face* and is accessible at:
<https://huggingface.co/spaces/felix04/meta-database-dashboard>.

The interface allows users to select individual records and generate interactive visualizations for the past 1.5 Myr, with glacial and interglacial intervals and their extrema explicitly highlighted. It includes all records analyzed in this study, as well
 220 as additional archives that were not selected for this study, such as the Annual Lake Surface Temperature record from Lake Malawi (Johnson et al., 2016), and alternative proxy records like planktonic $\delta^{18}\text{O}$ and magnetic susceptibility. For each record incorporated in the present analysis, both the data on the original age model and on the corresponding peak-adjusted age scale are provided.

The MIS boundaries can be changed by the user between those defined by Lisiecki and Raymo (2005) and those reported in
 225 Table 2. Furthermore, noisy data can be smoothed using the *Whittaker-Eilers* Python package (Eilers, 2003). The selected time series is then plotted with all MIS intervals and their glacial and interglacial extrema highlighted. In addition, the application displays a heatmap showing interglacial, glacial, and termination intensities, as well as wavelet scalograms (computed with the *Pyleoclim* package; Khider et al. (2022, 2026)) that illustrate temporal variations in the periodicity of glacial–interglacial cycles.

230 3 Results

3.1 Interglacial strength

The interglacial strength patterns over the past 1.5 Myr derived from the five benthic $\delta^{18}\text{O}$ stacks are highly homogeneous (Tab. 3), which is not surprising as BIGSTACK is based on Prob-stack and Prob-stack, in turn, is based on LR04. Although the regional ΔSST and SST stacks exhibit more variability, they still present a rather homogeneous pattern that corresponds
 235 closely to that observed in the benthic $\delta^{18}\text{O}$ stacks. Both groups exhibit an increase in intensity after the Mid-Bruhnes Shift (MBS; Transition between MIS 12 and 11c around 450ka), except for MIS 7a-c and 7e, which are consistently weaker than their adjacent interglacials. This post-MBS strengthening follows an interval of generally weaker interglacial strength spanning MIS 29–13a, although this trend is interrupted by relatively strong interglacials during MIS 21e and MIS 25, particularly in the benthic $\delta^{18}\text{O}$ stacks and MIS 29 being exceptionally strong in the South Pacific SST signal. The early interval is again
 240 characterized by comparatively strong interglacials, especially MIS 43, 47 and 49. In the SST records, these early interglacials are of equal strength or even exceed those of late-Quaternary interglacials, followed by an almost linear decrease in intensity until MIS 13a. While still strong, these early stages are less pronounced in the benthic $\delta^{18}\text{O}$ records.

In contrast, the terrestrial records exhibit large variations, with no discernible common pattern (Tab. 3). The recorded interglacial strength pattern highly depends on the proxy type or climate variable considered, as well as on the specific archive. The
 245 trend towards stronger interglacials after the MBS observed in the marine records is apparent in some of the terrestrial datasets,

Table 3. Interglacial strength for the proxy records included in this study. Strength is defined as the global extremum within a given MIS, it does not necessarily correspond to the local extremum closest to a glacial termination. Colour-coding reflects interglacial strength, ranging from weakest (pale red) to strongest (deep red) for each record. Grey cells indicate missing values, or deprecated ones, where MIS stages are incompletely resolved (less than 3 kyr).

	Proxy/Variable	Record	Reference	MIS 1	MIS 5e	MIS 7a-c	MIS 7e	MIS 9e	MIS 11c	MIS 13a	MIS 15a	MIS 15e	MIS 17	MIS 19c	MIS 21e	MIS 25	MIS 27	MIS 29	MIS 31	MIS 33	MIS 35	MIS 37	MIS 39	MIS 41	MIS 43	MIS 45	MIS 47	MIS 49
Marine archives	Benthic $\delta^{18}\text{O}$ (‰)	LIR04	Lisiecki & Raymo (2005)	3.18	3.10	3.48	3.44	3.19	3.11	3.47	3.39	3.49	3.50	3.48	3.42	3.30	3.72	3.57	3.21	3.67	3.53	3.33	3.56	3.59	3.41	3.49	3.24	3.31
		Prob-stack	Alm et al. (2017)	3.22	3.06	3.48	3.37	3.15	3.15	3.61	3.39	3.46	3.61	3.44	3.40	3.28	3.67	3.64	3.26	3.65	3.47	3.29	3.60	3.46	3.29	3.49	3.25	3.30
		BIGSTACK _{mineral}	Zhou et al. (2026)	3.14	3.02	3.38	3.35	3.08	3.05	3.50	3.31	3.37	3.52	3.38	3.32	3.19	3.62	3.49	3.14	3.63	3.39	3.17	3.50	3.43	3.21	3.43	3.20	3.27
		BIGSTACK _{mineralX}	Zhou et al. (2026)	3.16	2.98	3.29	3.24	3.06	3.05	3.51	3.36	3.36	3.50	3.27	3.20	3.16	3.57	3.47	3.15	3.42	3.32	3.08	3.47	3.33	3.15	3.37	3.05	3.21
		BIGSTACK _{mineralB}	Zhou et al. (2026)	3.14	3.14	3.45	3.41	3.15	3.07	3.47	3.37	3.49	3.42	3.33	3.29	3.12	3.54	3.55	3.02	3.59	3.38	3.14	3.45	3.44	3.18	3.30	3.07	3.22
	ΔSST (°C)	Global Mean stack	Clark et al. (2024)	0.14	0.64	-0.48	-0.63	0.06	0.64	-1.17	-0.92	-0.50	-0.78	-0.71	-0.62	-0.57	-1.37	-0.38	0.52	-0.26	0.65	0.44	-0.30	0.53	1.14	0.29	1.06	1.08
		North Atlantic stack	Clark et al. (2024)	0.37	1.78	-0.91	-0.78	1.06	1.28	-0.78	-1.00	-0.28	0.99	-0.87	-0.14	-0.70	-1.40	-1.79	2.27	-0.46	1.65	0.57	-0.74	1.31	2.69	-1.06	1.15	1.71
		Tropical Atlantic stack	Clark et al. (2024)	0.31	1.13	0.45	-0.05	0.63	-0.34	-1.72	-0.60	-0.46	-0.59	-1.02	0.33	-0.96	-1.67	-0.05	0.69	0.41	1.23	0.14	0.90	2.32	1.15	2.80	2.34	2.42
		South Atlantic stack	Clark et al. (2024)	0.63	1.86	-0.54	-0.21	1.84	1.93	-1.75	-1.57	-0.87	-0.66	-0.66	-0.13	1.63	-0.22	0.54	0.85	-1.20	1.43	1.39	0.72	1.36	0.90	1.38	2.77	1.60
		North Pacific stack	Clark et al. (2024)	0.94	4.02	2.34	1.39	3.36	2.64	-0.24	0.91	1.26	1.21	1.19	1.62	0.62	0.16	0.57	2.11	-0.42	3.33	1.94	1.52	2.16	3.74	2.29	4.33	2.61
SST (°C)	Tropical Pacific stack	Clark et al. (2024)	0.28	0.56	-0.41	-0.25	-0.09	-0.26	-0.82	-0.03	-0.16	0.10	-0.73	-0.25	0.03	-0.38	-0.24	0.54	0.18	0.26	0.07	-0.30	0.01	0.73	0.34	0.51	0.68	
	South Pacific stack	Clark et al. (2024)	0.67	2.35	0.19	-0.39	0.58	1.64	-0.28	-1.12	0.63	0.70	0.76	-0.04	0.31	-0.05	2.17	0.51	-0.08	-0.01	-0.30	1.13	1.60	1.56	1.81	1.71	1.70	
Terrestrial archives	Mean loess size (normalized)	Tropical stack	Herbert et al. (2017)	27.66	26.96	27.18	27.30	27.53	26.94	27.13	27.13	27.28	27.15	27.45	27.62	26.85		27.82		27.74	27.92		27.60	28.41	27.57	28.12	28.13	
		Chioparts stack	Ding et al. (2002)	0.38	0.70	0.61	0.62	0.67	0.73	0.82	0.85	0.82	0.84	0.73	0.82	0.86	0.77	0.84	0.84	0.85	0.85	0.67	0.74	0.83	0.87	0.81	0.86	0.87
	Mean loess size (μm)	Gulang Loess	Sun et al. (2021)	16.95	16.77	16.80	16.66	18.21	17.23	14.74	15.72	16.19	14.23	15.95	16.23	18.87	18.52	20.90	15.49	19.67	17.54	20.58	17.44	17.02	13.35	16.99	14.85	16.66
		Jingyuan Loess	Sun et al. (2019)	21.63	21.59	19.78	30.42	20.69	19.20	17.77	20.05	18.16	17.97	30.41	18.96	18.95	21.55	30.07	18.04	21.31	18.26	18.80	21.53	21.23	20.88	30.55	21.43	22.50
	Inorganic loess carbonates $\delta^{13}\text{C}$ (‰)	Jingyuan Loess	Sun et al. (2019)	-6.26	-8.19	-6.31	-6.14	-6.11	-6.35	-6.35	-5.82	-6.46	-7.01	-6.23	-6.32	-5.35	-4.77	-6.53	-6.38	-4.89	-5.80	-6.26	-5.31	-4.85	-5.73	-6.25	-5.94	-4.81
		Jingyuan Loess	Sun et al. (2019)	2.45	2.58	2.50	2.54	2.53	2.53	2.44	2.52	2.45	2.46	2.44	2.47	2.54	2.51	2.40	2.60	2.38	2.49	2.45	2.43	2.43	2.54	2.43	2.50	2.53
	Mean Annual Precipitation (mm/day)	Jingyuan Loess	Sun et al. (2019)	12.07	12.18	11.30	11.87	11.94	12.23	10.99	11.61	11.41	11.22	10.64	11.15	11.70	11.69	10.96	11.74	11.18	11.22	11.31	10.99	10.77	11.42	10.99	11.77	11.60
		Zoige Basin	Zhao et al. (2021)	0.56	0.27	-1.80	-1.61	-1.50	-1.98	-1.00	-1.42	-0.58	-0.35	-0.84	-0.58	0.57	-0.89	0.31	1.02	-1.04	-0.31	-0.34	-1.33	-0.09	-0.46	-0.89	-0.32	-1.08
		Heqing Basin	Wang et al. (2025)					10.54	11.73	10.89	11.97	13.02	11.69	11.96	12.35	15.07	11.84	9.14	12.43	10.56	10.40	11.15	8.52	8.92	10.58	9.53	10.25	12.13
		Arboreal pollen (AP %) (excl. Gramineae and aquatic/semi-aquatic taxa)	Tenaghi Philippon	Tzedakis et al. (2006)	99.48	96.76	95.81	96.70	95.50	100.00	95.78	96.90	95.18	89.08	83.27	93.20	95.67	54.63	72.77	95.00	84.98	85.84	90.38	75.88	76.64	91.89		
Arboreal pollen (AP %) (excl. Pinus)			Lake Ohrid	80.73	92.78	95.95	85.02	91.46	81.20	93.46	92.37	88.17	65.73	82.96	87.50	88.36	67.88	74.79	93.43	87.20	97.01	98.52	96.62	93.21	90.52			
Arboreal pollen (AP %)	Zoige Basin		51.26	86.21	43.83	50.33	64.57	79.31	75.33	54.55	76.19	91.93	65.91	92.12	69.38	93.36	89.46	83.58	83.35	76.44	89.55	85.90	65.16	64.27	78.99	86.72	71.40	
Arboreal pollen (AP %)	Funza09		68.04	52.43	53.30	53.01	47.02	40.15	34.66	35.47	54.35	45.98	46.32	48.33	49.73	41.87	44.90	48.72	42.83	50.14	37.01	36.75	30.48	28.74	36.58	44.67		
Si/Ti	Lake El'gygytyn		Melles et al. (2012)	0.63	0.69	0.71	0.80	1.31	2.35	0.89	1.04	1.04	1.31	1.12	0.94	1.22	0.84	0.92	1.99	0.86	0.92	0.97	1.07	1.05	1.16	0.99	0.65	1.44
	Biogenic Silica (BioSi %)	Lake Baikal	43.10	40.10	32.30	43.00	46.20	37.30	47.40	44.00	42.10	37.20	47.00	44.30	16.80	36.48	46.10	9.10	39.10	51.00	19.90	31.10	19.10	40.30	37.00	34.00		
	Log Ca/K	Lake Ohrid	4.10	4.81	3.89	3.69	3.71	4.58	4.09	4.24	4.46	4.33	4.28	4.28	4.03	2.49	3.72	4.61	3.44	4.35	4.98	3.52	4.27	5.75				

whereas other records show opposing trends. For instance, the Funza09 pollen record indicates an almost linear increase in interglacial intensity since MIS 15e, and Mean Annual Precipitation (MAP) and Mean Annual Temperature (MAT) reconstructions from the Jingyuan loess sequence also document stronger interglacials after the MBS. By contrast, the Chiloparts loess sequence, the Jingyuan and Gulang loess sequences, and the Si/Ti record from Lake El'gygytyn reveal an opposing trend, with reduced interglacial intensities following the MBS. Furthermore, the observed marine pattern of reduced interglacial intensity between MIS 29-13a is not generally visible in the terrestrial archives. For example, the Chiloparts loess sequence records relatively strong interglacials between MIS 49-13a and the Gulang and Jingyuan loess sequences show high interglacial loess concentrations between MIS 25-13a. Finally, the recorded pattern of stronger interglacials during the early stages of the marine records is likewise not a common trend for the terrestrial archives. Although the Chiloparts and Gulang loess records document several strong interglacials in this interval, especially MIS 43 and MIS 47, other archives such as the Jingyuan loess sequence and the Funza09 pollen record indicate comparatively reduced interglacial intensities over the same period.

3.2 Glacial strength

The evolution of glacial strength displays a much more consistent pattern over the past 1.5 Myr (Tab. 4). Records of $\delta^{18}\text{O}$ and SST show a clear intensification of glacial intensity from MIS 22 onwards, except for MIS 7d and 15b. One exception is the South Atlantic ΔSST stack, which experiences the strongest glacial during MIS 34 with strong adjacent glacial periods.



The early glacials between MIS 48-40 are particularly weak in the $\delta^{18}\text{O}$ records. This pattern is not observed in the SST reconstructions, however, MIS 46 consistently appears as a notably weak glacial stage in nearly all marine archives.

While the terrestrial archives exhibit larger inter-record variability, a general tendency toward enhanced glacial intensity from MIS 22 onwards is evident in many records. For example, the Chiloparts and Gulang loess sequences both indicate an increase from MIS 22 onwards, while also documenting pronounced glacial intervals at earlier stages, notably MIS 34 and 38. In contrast, the Log Ca/K record from Lake Ohrid and the Funza09 pollen record reveal an opposing pattern, with a gradual decrease in glacial intensity from MIS 16 onwards and stronger intensities before. Reconstructed MAT from the Heqing Basin exhibits a decline in glacial strength between MIS 48-30, followed by relatively stable glacial values afterwards. Notably, this record is missing the last three glacial cycles. While several marine records display particularly weak glacials during MIS 48–40, with MIS 46 being especially weak, this pattern is only partially observed in the terrestrial datasets. The Chiloparts and Gulang loess sequences broadly follow this trend, however, it does not hold for the mean loess size and the $\delta^{13}\text{C}$ measured at the Jingyuan loess sequence, both of which indicate a notably strong MIS 46. In contrast, MIS 46 is the weakest glacial of the past 1.5 Myr in the reconstructed MAP from the Jingyuan loess sequence, but with relatively strong adjacent MIS 44 and 48. The observed lower glacial intensity during MIS 15b in the marine archives is also apparent in most terrestrial archives, but its amplitude varies widely between the records. The weakening is very pronounced for all the loess records from the CLP and their derived quantities, as well as in the Log Ca/K record from Lake Ohrid. Although less pronounced than the decrease during MIS 15b, the glacial period of MIS 7d shows another consistent period of lower glacial intensity in all marine archives relative to the strong adjacent glacials. This observation is not apparent for most terrestrial archives. For instance, reconstructed MAT from the Jingyuan loess sequence and the Zoige Basin indicate that MIS 7d is stronger than its adjacent glacials and the Log Ca/K record from Lake Ohrid, biogenic silica from Lake Baikal, and Si/Ti from Lake El'gygytgyn all show comparably strong glacial conditions during MIS 7d relative to MIS 6 and 8. On the other hand, the Funza09 pollen record indicates MIS 7d as the weakest glacial interval of the past 1.5 Myr.

3.3 Termination strength

Since the strength in termination is calculated as the absolute difference in interglacial and glacial strength, it is not surprising that the observed trends reflect the ones from the underlying glacials and interglacials (Tab. 5). The termination strengths of the $\delta^{18}\text{O}$ and SST records mostly reflect their glacial patterns, since they show larger variations and absolute values compared to their interglacial periods. Accordingly, stronger terminations mostly prevail from TX onwards, with notably weaker ones during TVIIa, TVI and TIIIa. Moreover, a further enhancement of termination strength after the MBS, i.e. from TV onwards, is visible for the marine archives.

Although the terrestrial archives exhibit larger variations among the different records and proxy types, regarding their termination strength over the last 1.5 Myr, numerous records do show stronger terminations after TX. This is particularly evident in most loess records, which document an exceptionally strong TX, especially in comparison with the preceding termination TXII. Before this interval, terminations generally appear weaker, with the notable exceptions of a very strong TXVII in the Chiloparts and Jingyuan loess sequences and a pronounced TXV in the Gulang loess. In contrast, the pollen records display a



Table 4. Glacial strength for the proxy records included in this study. Strength is defined as the global extremum within a given MIS, it does not necessarily correspond to the local extremum closest to a glacial termination. Colour-coding reflects glacial strength, ranging from weakest (pale blue) to strongest (deep blue) for each record. Grey cells indicate missing values, or deprecated ones, where MIS stages are incompletely resolved (less than 3 kyr).

	Proxy/Variable	Record	Reference	MIS 2	MIS 6	MIS 7d	MIS 8	MIS 10	MIS 12	MIS 13b-14	MIS 15b	MIS 16	MIS 18	MIS 20	MIS 22-24	MIS 26	MIS 28	MIS 30	MIS 32	MIS 34	MIS 36	MIS 38	MIS 40	MIS 42	MIS 44	MIS 46	MIS 48	
Marine archives	Benthic $\delta^{18}\text{O}$ (‰)	LR04	Lisiecki & Raymo (2005)	5.02	4.98	4.44	4.63	4.84	5.08	4.55	4.33	5.08	4.75	4.74	4.69	4.58	4.28	4.54	4.29	4.50	4.43	4.36	4.35	4.19	4.26	4.40	4.31	
		Prob-stack	Ahn et al. (2017)	4.94	4.91	4.43	4.63	4.83	5.09	4.68	4.35	5.14	4.64	4.72	4.72	4.51	4.35	4.43	4.30	4.48	4.58	4.40	4.31	4.20	4.28	4.26	4.35	
		BIGSTACK _{mined}	Zhou et al. (2026)	4.79	4.76	4.27	4.47	4.66	4.90	4.39	4.09	4.88	4.42	4.50	4.57	4.26	4.11	4.24	3.95	4.25	4.35	4.28	4.12	4.03	4.07	3.85	4.18	
		BIGSTACK _{minedA}	Zhou et al. (2026)	4.88	4.88	4.30	4.52	4.79	5.03	4.58	4.22	5.06	4.56	4.61	4.62	4.28	4.17	4.36	4.08	4.44	4.44	4.45	4.16	4.11	4.16	4.17	4.35	
		BIGSTACK _{minedB}	Zhou et al. (2026)	4.74	4.68	4.27	4.46	4.55	4.84	4.29	4.03	4.76	4.34	4.37	4.51	4.13	4.04	4.16	3.97	4.19	4.26	4.16	4.02	3.97	3.99	4.00	4.08	
		Global Mean stack	Clark et al. (2024)	-3.29	-3.07	-1.85	-3.05	-3.12	-3.83	-3.02	-1.41	-2.79	-2.72	-3.87	-3.58	-1.73	-1.87	-1.61	-1.35	-1.83	-1.10	-1.86	-0.98	-0.65	-0.95	-0.37	-0.72	
	ΔSST (°C)	North Atlantic stack	Clark et al. (2024)	-5.81	-5.21	-3.60	-4.73	-6.46	-6.88	-3.91	-1.95	-4.39	-5.71	-7.59	-4.39	-3.48	-5.37	-3.71	-3.76	-4.20	-2.52	-4.63	-2.63	-2.45	-2.09	-2.15	-3.00	
		Tropical Atlantic stack	Clark et al. (2024)	-3.20	-1.92	-1.36	-2.73	-3.04	-5.20	-4.34	-1.91	-4.25	-3.17	-4.13	-4.32	-2.23	-2.42	-2.90	-0.63	-1.87	-1.79	-2.30	0.70	0.72	-0.48	0.65	-0.60	
		South Atlantic stack	Clark et al. (2024)	-3.85	-3.75	-2.33	-4.26	-3.53	-5.02	-5.26	-2.31	-4.46	-3.80	-4.06	-3.80	-3.68	-2.69	-3.44	-4.07	-5.64	-4.47	-3.98	-3.71	-0.22	-0.97	-1.79	-1.64	
		North Pacific stack	Clark et al. (2024)	-2.65	-3.44	-1.29	-2.38	-2.10	-3.42	-3.82	-0.57	-2.49	-1.61	-3.83	-3.64	-0.79	-1.36	-0.20	-1.31	-1.30	-0.67	-0.55	-1.15	0.92	-0.83	0.89	0.41	
		Tropical Pacific stack	Clark et al. (2024)	-2.39	-1.88	-1.78	-2.03	-2.35	-2.44	-1.01	-0.56	-1.25	-1.83	-1.75	-2.14	-0.75	-1.24	-1.21	-0.82	-1.19	-0.71	-1.11	-0.75	-0.78	-0.93	-0.26	-0.41	
		South Pacific stack	Clark et al. (2024)	-3.89	-3.85	-2.15	-3.88	-3.93	-4.63	-3.81	-1.43	-5.85	-3.62	-5.18	-4.97	-2.51	-2.48	-3.43	-2.79	-2.84	-2.26	-2.16	-2.18	-2.74	-2.49	-1.29	-1.52	
Terrestrial archives	SST (°C)	Tropical stack	Clark et al. (2024)	-2.42	-1.74	-1.11	-2.06	-2.19	-2.56	-1.22	-0.38	-1.16	-1.45	-1.97	-2.03	-0.55	-0.80	-0.88	-0.19	-0.84	-0.50	-0.85	-0.15	-0.14	-0.56	0.30	-0.13	
		Tropical stack	Herbert et al. (2017)	23.94	25.01	25.59	24.57	24.26	24.16	25.34	26.02	25.31	25.03	24.68	24.05	25.84	26.00	25.21	25.72	25.38	25.89	25.54	26.40	26.00	25.83	26.81	26.72	
	Mean loess size (normalized)	Chilaparts stack	Ding et al. (2002)	-0.09	-0.24	0.07	0.23	-0.08	0.08	0.62	0.64	0.03	0.35	0.37	-0.27	0.57	0.65	0.68	0.71	0.37	0.45	-0.61	0.42	0.57	0.64	0.63	0.50	
		Gulang Loess	Sun et al. (2021)	44.02	46.98	40.73	36.22	44.18	41.24	33.16	33.21	57.72	37.37	35.84	52.94	31.25	33.04	30.94	33.89	53.92	30.86	42.02	33.10	28.89	28.66	32.53	31.86	
	Mean loess size (μm)	Jingyuan Loess	Sun et al. (2019)	42.61	43.13	46.70	34.51	47.28	40.84	31.78	31.30	42.63	34.33	37.29	50.64	37.27	34.12	32.61	33.35	42.08	39.89	50.64	37.67	29.36	34.92	38.36	33.17	
		Inorganic loess carbonates $\delta^{13}\text{C}$ (‰)	Jingyuan Loess	Sun et al. (2019)	-0.63	-0.94	-1.21	-1.00	-1.01	-0.89	-1.48	-1.61	-0.89	-0.87	-1.24	-0.93	-1.59	-1.41	-1.62	-2.13	-1.16	-0.82	-1.21	-1.20	-1.69	-1.44	-1.08	-1.67
	Mean Annual Precipitation (mm/day)	Jingyuan Loess	Sun et al. (2019)	2.12	2.10	2.13	2.13	2.15	2.16	2.14	2.21	2.10	2.12	2.12	2.11	2.15	2.20	2.13	2.18	2.21	2.16	2.18	2.22	2.22	2.15	2.24	2.14	
		Jingyuan Loess	Sun et al. (2019)	9.54	8.96	9.06	9.39	9.45	9.47	9.38	9.60	9.04	9.20	9.76	9.63	9.37	9.63	9.70	10.07	9.81	9.79	9.64	9.69	9.75	9.53	9.89	9.44	
	Mean Annual Temperature (°C)	Zoige Basin	Zhao et al. (2021)	-2.87	-2.58	-3.05	-2.55	-2.54	-3.37	-3.37	-2.42	-2.62	-2.78	-2.64	-2.95	-2.66	-2.18	-1.11	-2.11	-2.50	-2.19	-2.36	-2.45	-2.98	-2.16	-3.11	-3.73	
		Heqing Basin	Wang et al. (2025)				7.48	7.43	7.90	7.62	7.45	7.59	7.36	7.60	7.56	7.35	7.64	7.28	8.30	7.00	6.92	6.73	7.79	5.77	6.12	7.03	6.46	
	Terrestrial archives	Arboreal pollen (AP %) (excl. Gramineae and aquatic/semi-aquatic taxa)	Tenaghi Philippon	Tzedakis et al. (2006)	2.09	1.35	4.07	0.44	3.21	0.00	13.44	7.89	1.33	2.19	16.30	4.89	6.02	23.41	18.01	3.89	16.37	26.59	7.23	6.09	9.16			
			Lake Ohrid	Donders et al. (2021)	8.00	9.48	15.93	7.89	11.29	1.89	8.70	21.79	10.22	12.44	9.13	4.12	12.69	20.75	15.32	30.12	13.08	35.50	46.25	36.60	14.83			
Arboreal pollen (AP %) (excl. Pinus)		Zoige Basin	Zhao et al. (2020)	2.39	1.79	2.75	1.99	2.36	1.46	1.44	6.84	2.46	7.29	2.76	5.17	4.98	6.07	18.30	10.05	12.09	2.61	16.36	5.12	9.52	9.09	6.01	4.17	
Arboreal pollen (AP %) (excl. Quercus & Alnus)		Funza09	Torres et al. (2013)	17.54	10.29	34.88	11.48	9.33	9.80	6.67	15.57	3.77	2.56	4.95	6.95	17.92	12.50	17.13	21.65	23.23	15.08	10.36	16.29	12.69	14.36	10.99	1.78	
Si/Ti		Lake El'gygytyn	Melles et al. (2012)	0.21	0.27	0.29	0.32	0.36	0.35	0.43	0.38	0.35	0.36	0.41	0.38	0.40	0.45	0.44	0.50	0.41	0.47	0.30	0.43	0.45	0.41	0.23		
Biogenic Silica (BioSi %) (excl. Quercus & Alnus)		Lake Baikal	Prokopenko et al. (2006)	2.00	1.80	2.50	2.70	3.20	2.50	5.20	3.20	3.00	3.30	3.00	3.00	3.40	3.10	2.40	2.80	3.00	3.10	2.80	2.70	3.10	3.10	4.20	3.00	
Loe Ca/K		Lake Ohrid	Sun et al. (2021)	-1.71	-1.80	-1.58	-1.68	-1.97	-2.12	-1.81	0.51	-2.73	-2.46	-2.45	-2.60	-2.13	-2.15	-2.43	-2.32	-2.56	-2.44	-2.08	-1.87	-1.06				

less homogeneous pattern. Over the past 600 ka, pollen data from Tenaghi Philippon and Lake Ohrid show high termination intensities. The Funza09 pollen record reveals a gradual intensification of terminations up to TVIII, followed by a significant drop in intensity, which leads to a very weak TVIIa, after which the intensity starts to increase almost linearly again. Furthermore, except for a very strong TII, the pollen record from the Zoige Basin indicates a decline in termination intensity after the MBS. Moreover, the Si/Ti record from Lake El'gygytyn identifies two outstandingly strong terminations at TVIIa and TXIV, whereas the remaining terminations are characterized by substantially lower intensities, with particularly weak signals during the last four terminations.

3.4 Outstanding MIS

To identify exceptionally strong or weak glacials and terminations, we determine, for each record, which stages fall within the five strongest and the five weakest over the past 1.5 Myr (Fig. 8). We categorize the records into three groups: (i) benthic $\delta^{18}\text{O}$ records (Fig. 8a), (ii) SST records (Fig. 8b), and (iii) terrestrial records (Fig. 8c). In addition, we present all records combined (Fig. 8d).

Considering all the available records, MIS 5e is consistently within one of the five strongest interglacials (for 18 records out of the 29 records considered), although not unambiguously, as two terrestrial records instead place MIS 5e among the weakest interglacials. In contrast, MIS 31 is unambiguously identified as a strong interglacial across many records, especially



Table 5. Termination strength of each glacial termination for the proxy records included in this study. Colour-coding reflects termination strength, ranging from weakest (pale purple) to strongest (deep purple) for each record. Grey cells indicate missing values, or deprecated ones, where MIS stages are incompletely resolved (less than 3 kyr). The termination strength is defined as the absolute difference between the global extremum of a glacial stage and the global extremum of the subsequent interglacial stage.

Proxy/Variable	Record	Reference	TI	TII	THIa	THI	THV	TV	TVI	TVIIa	TVII	TVIII	TX	TXII	TXIII	TXIV	TXV	TXVI	TXVII	TXVIII	TXIX	TX	TXI	TXII			
			MIS 2/ MIS 7e	MIS 7e/ MIS 7c	MIS 7c/ MIS 7e	MIS 7c/ MIS 7e	MIS 10/ MIS 9c	MIS 12/ MIS 11c	MIS 13b-14/ MIS 13a	MIS 15b/ MIS 15a	MIS 16/ MIS 15e	MIS 17/ MIS 17c	MIS 20/ MIS 19c	MIS 22-24/ MIS 21c	MIS 26/ MIS 25	MIS 28/ MIS 27	MIS 30/ MIS 29	MIS 32/ MIS 31	MIS 34/ MIS 33	MIS 36/ MIS 35	MIS 38/ MIS 37	MIS 40/ MIS 39	MIS 42/ MIS 41	MIS 44/ MIS 43	MIS 46/ MIS 45	MIS 48/ MIS 47	
Marine archives	Benthic $\delta^{18}\text{O}$ (‰)	LR04	1.84	1.88	0.96	1.19	1.65	1.97	1.08	0.94	1.59	1.25	1.55	1.27	1.26	0.56	0.97	1.08	0.83	0.90	1.03	0.79	0.60	0.85	0.91	1.07	
		Prob-stack	1.72	1.85	0.94	1.26	1.67	1.95	1.08	0.96	1.68	1.04	1.26	1.32	1.22	0.68	0.79	1.04	0.83	1.11	1.10	0.71	0.74	0.98	0.77	1.10	
		IRROTACK _{Global}	1.65	1.73	0.89	1.17	1.58	1.85	0.89	0.78	1.51	0.91	1.12	1.34	1.06	0.49	0.74	0.81	0.62	0.97	1.11	0.62	0.61	0.86	0.42	0.98	
		IRROTACK _{Marine}	1.72	1.90	1.01	1.28	1.73	1.98	1.06	0.87	1.70	1.06	1.34	1.42	1.11	0.59	0.89	0.93	1.01	1.12	1.37	0.70	0.78	1.01	0.80	1.10	
		IRROTACK _{Marine}	1.60	1.54	0.82	1.05	1.39	1.77	0.82	0.66	1.27	0.92	1.04	1.22	1.01	0.50	0.60	0.96	0.60	0.88	1.02	0.58	0.53	0.81	0.70	1.00	
	ASST (°C)	Global Mean stack	3.43	3.71	1.37	2.42	3.18	4.47	1.85	0.49	2.29	1.94	3.16	2.96	1.16	0.50	1.23	1.87	1.57	1.75	2.30	0.68	1.18	2.09	0.66	1.78	
		North Atlantic stack	6.18	6.99	2.69	3.95	7.52	8.16	3.13	0.95	4.11	6.70	6.72	6.35	2.78	3.97	1.92	6.03	3.74	4.17	5.20	1.89	3.76	4.36	1.09	4.15	
		Tropical Atlantic stack	3.51	3.05	1.81	2.67	3.67	4.86	2.62	1.31	3.79	2.58	3.11	4.65	1.27	0.75	2.85	1.32	2.28	3.02	2.84	0.20	1.60	1.63	2.15	2.54	
		South Atlantic stack	4.48	5.61	1.79	1.65	5.37	6.95	3.51	0.74	3.50	3.14	3.40	3.07	5.31	2.47	3.86	4.92	4.44	5.90	5.37	4.41	1.58	1.87	3.17	4.41	
		North Pacific stack	3.59	7.46	3.63	3.77	5.46	6.06	3.58	1.48	3.75	2.82	5.02	5.36	1.41	1.52	0.77	3.42	0.88	4.00	2.49	2.70	1.24	4.57	1.40	3.92	
SST (°C)	Tropical Pacific stack	2.67	2.44	0.87	1.78	2.26	2.18	0.19	0.53	1.09	1.93	1.02	1.89	0.78	0.86	0.97	1.36	1.31	0.97	1.18	0.45	0.79	1.66	0.60	0.92		
	South Pacific stack	4.56	6.30	2.34	3.39	2.93	6.27	0.31	6.48	4.32	5.94	4.93	3.62	2.43	2.69	3.30	2.76	2.25	1.86	1.86	1.86	1.86	1.86	1.86	1.86		
	Tropical stack	2.69	2.54	1.12	2.61	2.45	2.47	0.58	0.52	1.28	1.76	1.79	2.24	0.70	0.57	1.11	1.14	1.14	1.36	1.32	0.35	0.57	1.03	0.54	1.26		
	Tropical stack	3.07	2.65	1.36	2.61	3.04	3.37	1.60	1.12	1.83	2.25	2.46	3.40	1.77	0.77	1.82	1.79	1.70	1.36	1.36	0.50	1.60	2.57	0.76	1.41		
	Mean less size (normalized)	0.47	0.94	0.53	0.39	0.51	0.65	0.20	0.21	0.79	0.49	0.36	1.09	0.28	0.12	0.16	0.13	0.48	0.40	1.24	0.32	0.27	0.23	0.17	0.36		
Terrestrial archives	Mean less size (μm)	Galaxy Loess	37.07	30.31	23.93	19.56	35.93	24.02	18.42	17.50	41.53	23.13	19.89	36.71	12.38	14.52	10.05	18.40	34.55	13.32	21.44	15.67	11.28	15.30	15.55	17.00	
		Jingyuan Loess	36.97	31.54	26.93	14.09	26.60	31.64	14.01	11.25	34.47	16.37	16.88	31.68	18.33	12.57	12.54	15.31	30.73	31.63	11.84	16.13	8.13	14.05	17.81	11.75	
		Inorganic loess carbonates $\delta^{18}\text{O}$ (‰)	Jingyuan Loess	5.63	7.25	5.10	5.11	5.10	5.46	4.87	4.21	5.57	6.14	5.00	5.39	3.76	3.36	4.91	4.25	3.73	4.98	3.03	4.11	3.16	4.29	5.11	4.27
		Mean Annual Precipitation (mm/day)	Jingyuan Loess	0.33	0.48	0.32	0.41	0.38	0.37	0.30	0.31	0.35	0.34	0.31	0.36	0.39	0.31	0.27	0.42	0.17	0.31	0.27	0.21	0.21	0.39	0.19	0.36
		Mean Annual Temperature (°C)	Jingyuan Loess	3.33	3.22	3.24	2.47	2.46	2.36	1.61	2.77	3.07	0.88	1.53	2.33	1.11	1.26	1.67	1.37	1.43	1.67	1.30	1.02	1.10	1.10	1.31	
	Zaige Basin	Zaige Basin	1.43	3.85	1.25	0.93	1.04	1.29	1.71	1.00	2.04	2.14	1.79	2.71	1.69	1.29	1.42	1.12	1.46	1.88	1.02	1.13	1.74	1.70	1.52	1.41	
		Houjiao Basin	Wang et al. (2015)																								
		Tenaghi Philippon	Tzedakis et al. (2006)	97.39	95.41	91.74	96.26	92.29	100.00	82.34	89.01	93.85	86.89	66.97	88.31	89.65	31.22	54.76	91.11	68.61	59.25	83.15	69.79	67.48			
		Arboreal pollen (AP %) (excl. Gramineae and aquatic/semi-aquatic taxa)	Lake Ohrid	72.73	83.30	80.02	77.13	80.17	79.31	84.77	70.58	77.96	83.29	73.83	83.38	75.67	47.12	59.48	63.31	74.11	61.51	52.27	60.01	78.38			
		Arboreal pollen (AP %) (excl. Pinus)	Zaige Basin	48.87	84.42	41.08	48.34	62.31	77.63	73.89	47.71	73.73	84.64	83.16	66.95	64.48	87.29	71.16	71.53	71.36	73.63	73.18	80.74	55.64	55.18	72.98	82.55
Lake Baikal	Arboreal pollen (AP %) (excl. Quercus & Alnus)	Fumaz09	57.75	17.55	41.82	43.68	37.22	33.48	19.09	31.70	51.79	41.03	39.37	30.41	37.23	24.74	23.25	25.49	27.75	59.78	20.72	24.06	16.12	17.75	34.80		
	Silt	Torres et al. (2013)																									
	Lake El'gygytgyn	Meltes et al. (2012)	0.42	0.42	0.42	0.48	0.98	2.00	0.46	0.66	0.69	0.95	0.71	0.56	0.82	0.39	0.48	1.40	0.45	0.45	0.67	0.64	0.60	0.75	0.58	0.42	
	Biogenic Silica (BioSi %)	Lake Baikal	41.30	37.60	39.60	39.80	43.70	35.10	44.20	38.80	34.20	44.00	40.90	13.70	24.00	43.30	6.10	36.00	48.20	17.20	33.30	16.00	36.10	34.00			
	Log Ca/K	Lake Ohrid	5.82	6.63	5.49	5.98	5.92	6.70	5.90	5.73	7.19	6.79	6.73	6.58	6.17	4.64	6.15	6.93	5.99	6.79	7.06	5.30	5.52				

pronounced for the terrestrial records (9/15). In $\delta^{18}\text{O}$ records, MIS 5e and MIS 11c dominate (5/5 for both), while MIS 47 emerges as the strongest in most SST records (8/9). Across all records, MIS 27 is particularly weak (19/29), ranking among the weakest interglacials for $\delta^{18}\text{O}$ (5/5) and terrestrial records (7/15), whereas SST records are dominated by a particularly weak MIS 13a (8/9). MIS 33 is unambiguously weak for all records. A notable difference between the terrestrial and the marine archives is apparent during MIS 13a. While it presents a particularly weak interglacial for many marine archives, it is for three terrestrial records (the three loess records from the CLP) within the five strongest interglacials over the past 1.5 Myr.

Across all records, several glacials emerge as unambiguously strong, in particular MIS 6, MIS 16, and MIS 22-24. Nonetheless, notable differences are evident among the different record categories. A prominent example concerns the classification of MIS 22-24, which differs between the $\delta^{18}\text{O}$ records on the one side and the SST and terrestrial records on the other side. While MIS 22-24 is unambiguously identified as one of the strongest glacials in the majority of the SST records (7/9) and in a substantial fraction of the terrestrial records (6/15), it is not featured among the five strongest glacials in any of the $\delta^{18}\text{O}$ records. Another example is MIS 6, which is much less pronounced for SST records compared to the $\delta^{18}\text{O}$ and terrestrial records. Consistently and unambiguously weak glacials are MIS 15b, 32 and 40. While MIS 32 is one of the weakest terrestrial interglacials (9/15) and also for the $\delta^{18}\text{O}$ records (5/5), it is less pronounced for the SST records (1/9), which are characterized by particularly weak early glacials, especially MIS 46 (9/9).

As previously noted, the relative strength of terminations mainly reflects the glacial patterns. Termination TII is classified among the strongest terminations across nearly all records (23/29), whereas TXIIIa and TXVIII both belong to the weakest terminations (both 20/29). Terminations TI, TII, TIV and TV consistently rank among the strongest terminations in both the



$\delta^{18}\text{O}$ records and the SST records. In contrast, for terrestrial records, TII, TVII and TX are particularly strong. While TVII is consistently among the strongest terminations in the $\delta^{18}\text{O}$ records, it is less prominent in the SST records. Furthermore, TX is never ranked within the five strongest terminations in the $\delta^{18}\text{O}$ records, yet it is more dominant in the SST and terrestrial records. While TVIIa is among the weakest terminations for SST records (8/9), it is less evident in the $\delta^{18}\text{O}$ and the terrestrial records. In these latter archives, pre-MPT terminations like TXIIIa, TXIII, TXVIII and TXIX are among the weakest terminations.

Overall, the strength of interglacial stages is more ambiguous than that of glacial stages in terrestrial records. Almost every interglacial interval appears, in at least one record, among the five strongest and once within the five weakest interglacials. Certain stages, such as MIS 1 and 17, fall into the top five strongest and weakest categories with equal frequency, making it challenging to classify any of them as either a strong or weak interglacial. By contrast, although the strength of glacials is still ambiguous, they are generally less ambiguous than the interglacials, and most glacials can be more consistently characterized as predominantly strong or predominantly weak. Furthermore, Figure 8 shows that the majority of the five strongest glacials occur after MIS 22, whereas the five weakest glacials are concentrated largely in the interval before MIS 22-24.

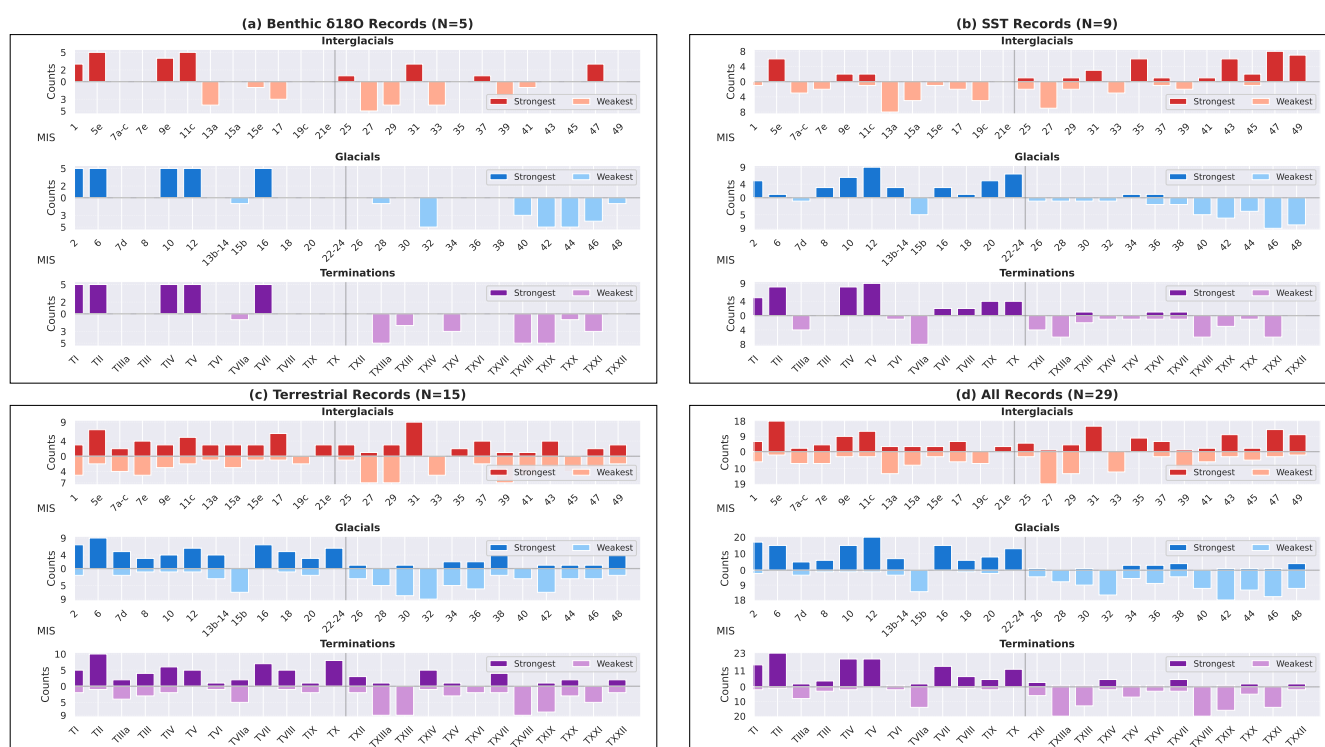


Figure 8. Top 5 strongest (bright colors/upper y-axis) and weakest (pale colors/lower y-axis) interglacials (red), glacials (blue) and terminations (purple) during the Quaternary for (a) 5 benthic $\delta^{18}\text{O}$ stacks, (b) 9 SST stacks, (c) 15 terrestrial records, and (d) all 29 records combined. The counts indicate how often each MIS or termination was ranked among the top 5 strongest (bright colors/upper y-axis) or top 5 weakest (pale colors/lower y-axis) across all records in each category.



3.5 Distribution of interglacial and glacial extrema

In this section, we explore the range of glacial and interglacial strength values. Specifically, we address the following questions: Do glacial and interglacial periods constitute distinct states in terms of their strength values, or do their value ranges overlap? Furthermore, how are their distributions shaped — are they narrowly concentrated around specific values, or do they exhibit large variations across different stages?

At first, we separate the data into three categories: (i) benthic $\delta^{18}\text{O}$ records, (ii) SST records, and (iii) terrestrial records. For each record, we then extract the glacial and interglacial extreme values and estimate their probability density functions using a Gaussian kernel density estimator (Python function *scipy.stats.gaussian_kde*; Virtanen et al. (2020); Scott (1992)). For the benthic $\delta^{18}\text{O}$ records, this procedure is straightforward, as all records have the same units. The same applies to the SST records. Consequently, the distributions of both groups can be displayed on their absolute values. In contrast, the terrestrial archives comprise a wide range of proxy types and climatic variables, and hence they do not share the same units. We therefore first perform a joint normalization of the interglacial and glacial strength values for each terrestrial record such that more positive values correspond to stronger (weaker) interglacials (glacials), and more negative values correspond to weaker (stronger) glacials (interglacials). The kernel density estimator is then applied to these normalized values. The resulting probability density functions for all records are shown in Figure 9.

All five benthic $\delta^{18}\text{O}$ stacks depict highly similar distributions of their interglacial and glacial extrema. They show distinct interglacial and glacial states with a clear separation of both distributions. The interglacial extrema are predominantly characterized by values in the range of around 3 – 3.5 ‰, whereas the glacials have wider distributions, mostly spanning values between 4 – 5 ‰.

In contrast, the SST records reveal a different pattern, as most of the corresponding distributions of glacial and interglacial extrema either overlap (6/9) or are in very close proximity. Moreover, they differ quite a bit in their value ranges, their shapes and how narrow or wide they are. The two tropical stacks, as well as the stack from the tropical Pacific, display the narrowest distributions for both glacial ($\sim [-2.5^\circ\text{C}$ to $-0.3^\circ\text{C}]$) and interglacial extrema ($\sim [-0.8^\circ\text{C}$ to $2.0^\circ\text{C}]$). In contrast, Atlantic and non-tropical Pacific stacks exhibit the widest distributions. For example, the North Atlantic stack records glacial extrema ranging from -7.7°C to -1.9°C , whereas interglacial extrema span from -1.8°C to 2.7°C . The overlap between glacial and interglacial extrema can be attributed to the long-term cooling trend in SSTs between 1.5 and 0.9 Ma (Clark et al., 2024). As a consequence of this general cooling, glacials and interglacials simultaneously cooled down, such that an interglacial around 0.9 Ma can be cooler than an earlier glacial state around 1.5 Ma. For instance, the warmest glacial in the global mean ΔSST stack occurred during MIS 46 (-0.37°C), whereas the coldest interglacial occurred during MIS 27 (-1.37°C), implying that this particular interglacial was approximately 1°C colder than the warmest glacial. However, this only affects the extreme values of the distributions. Specifically, when only considering glacial minima and interglacial maxima within the upper and lower quartiles (SI Fig. S2), there is no overlap observed and distinct glacial and interglacial states are visible. This finding is consistent with the SST compilation of Watson et al. (2026).

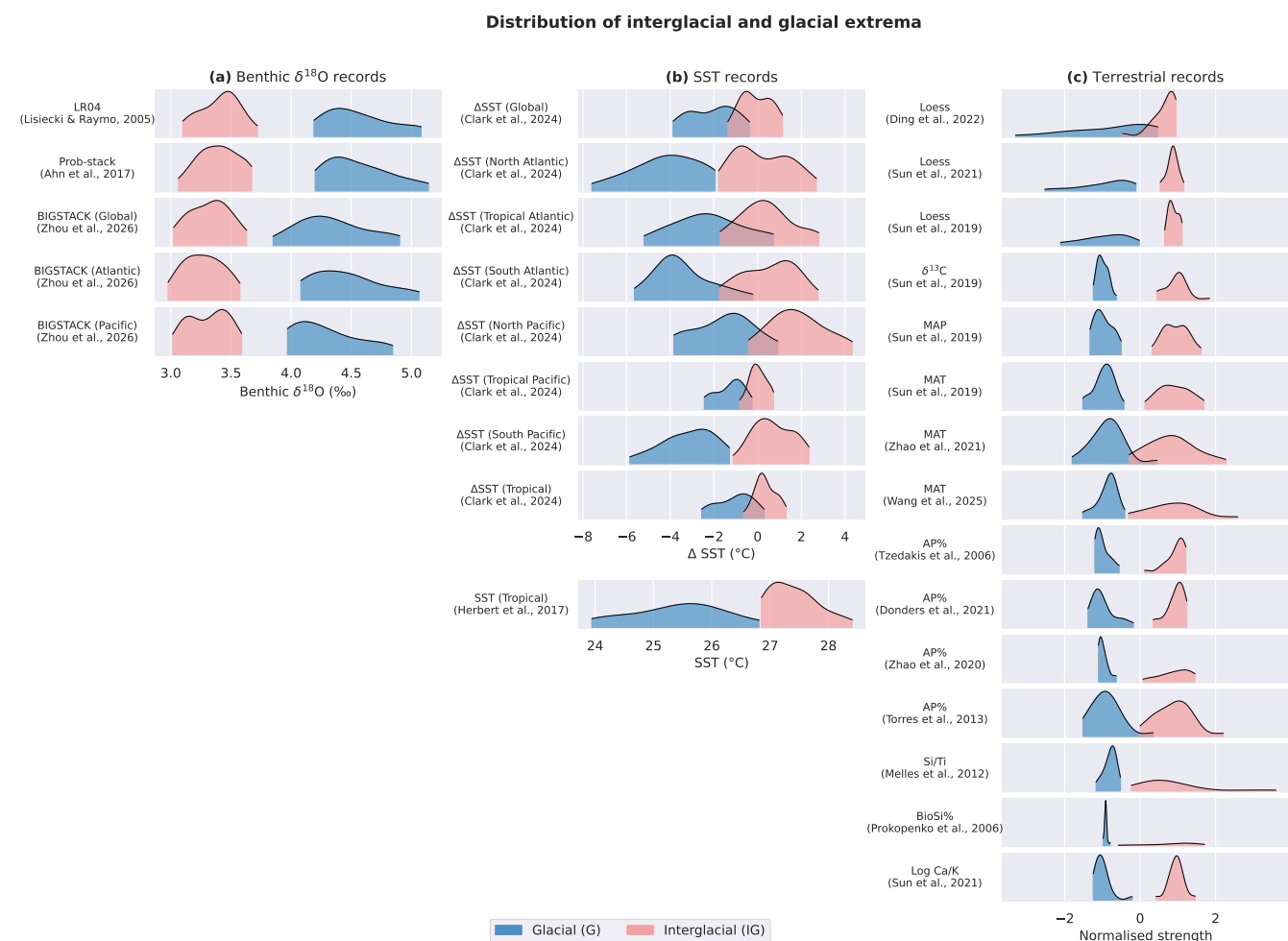


Figure 9. Probability density functions of glacial and interglacial extreme values for (a) benthic $\delta^{18}\text{O}$ records, (b) SST records, and (c) terrestrial records. $\delta^{18}\text{O}$ and SST records are shown on their absolute values, while terrestrial records are normalized in order to display different proxies and climatic values on the same x-scale. Here, more positive values refer to stronger (weaker) interglacials (glacials), and more negative values refer to weaker (stronger) interglacials (glacials). Red-shaded areas show interglacial distributions and blue-shaded areas show glacial distributions. Probability densities are calculated using a Gaussian kernel density estimator, and bandwidth is determined by Scott's rule of thumb (Scott, 1992).

For the terrestrial archives, only three out of the 15 records exhibit overlapping distributions between their interglacial and glacial extrema, whereas the remaining records display a clear distinction between interglacial and glacial states based on their extreme values. Overlapping distributions are observed in the Chiloparts loess sequence, the MAT reconstructions from the Zoige Basin, and the Funza09 pollen record. Although the archives differ substantially in the shapes of their distributions, records reflecting the same proxy or climate variable present a more consistent pattern. Some archives indicate symmetric



distributions for their interglacial and glacial extrema, such as the pollen records from Tenaghi Philippon and Lake Ohrid.
 380 Other archives display relatively narrow distributions during glacial intervals, but very wide distributions during interglacials, for example, Si/Ti measured at Lake El'gygytgyn and biogenic silica from Lake Baikal. In contrast, the loess records generally show narrower interglacial distributions and wider glacial ones. The biogenic silica record is particularly interesting, as the glacial distribution is extremely narrow, ranging between 1.8 and 5.2 %, forming a baseline. Most variability in biogenic silica percentages occurs during interglacial states, when extrema range between 9.1 and 51 %, from which these elevated values
 385 decay back toward the glacial baseline.

Overall, glacial and interglacial extrema are mostly two distinct states over the past 1.5 Myr for the majority of marine and terrestrial archives. General trends, such as the long-term cooling of SSTs, can lead to overlapping distributions.

3.6 Average strength index - Glacial amplification

To facilitate the identification of any large-scale patterns, we follow the approach by Watson et al. (2026) and calculate average
 390 strength indices for the glacials, interglacials and terminations. To do so, we normalize the respective strength values across all MIS for each record (i.e. the values shown in Tab. 3, 4, 5). Next, we group the records into three proxy-based categories: (i) benthic $\delta^{18}\text{O}$ records, (ii) SST records and (iii) terrestrial records. For each category, we average the normalized strength across all included records to obtain an average strength index for each MIS or termination. Figure 10 displays the resulting indices plotted against their corresponding glacial, interglacial, or termination stage. In this regard, it condenses the information stored
 395 in the heatmaps shown in the previous sections into a single plot and can highlight any consistent patterns between the records.

Due to the homogeneous pattern across the $\delta^{18}\text{O}$ records and across the SST records, their respective averaged indices mostly underscore the highlighted observations in the previous sections. Overall, the interglacial strength index shows a similar pattern for the $\delta^{18}\text{O}$ and the SST records with few small differences (Fig. 10a). The enhanced intensity after the MBS, with consistent dilutions in intensity during MIS 7e and 7a-c, is visible for both categories, although much stronger for the $\delta^{18}\text{O}$ index, as
 400 MIS 9e and 11c appear much weaker for SSTs. Furthermore, the period of weaker interglacial intensities between MIS 29-13a is apparent in both indices. However, MIS 21e and 25 are above-average strength for the $\delta^{18}\text{O}$ records. The particular strength of some early interglacials is visible in the indices, as the averaged SST index shows strong interglacials from MIS 49-41, while $\delta^{18}\text{O}$ values are subdued and only MIS 43, 47 and 49 are above average strength. On the other hand, the average strength index of the terrestrial records does not indicate any general trend and due to averaging the varying strength patterns across
 405 the individual records, the index results in a much flatter profile with a larger standard deviation. Only a few peaks stand out, namely the strong MIS 5e and 31. Furthermore, the interval between MIS 33-27 looks fairly similar between the three proxy groups, as these interglacials show consistently low index values, interrupted by a strong MIS 31. While the marine indices indicate a particularly weak signal during MIS 13a, this pattern is not observed for the terrestrial index.

The three glacial strength indices yield a more uniform picture (Fig. 10b). All three curves indicate a clear amplification
 410 of glacial strength from MIS 22 onwards. This pattern is most evident in the $\delta^{18}\text{O}$ index, as all glacial stages before MIS 22-24 exhibit below-average strength, whereas after MIS 22 all glacials are of above-average strength, except for MIS 7d and MIS 15b. The SST index displays a very similar behaviour. Before MIS 22-24, all glacials are of below-average strength, except



for MIS 34, which is slightly above. And after MIS 22, all glacial stages exhibit above-average strength, except for MIS 7d and MIS 15b, mirroring the pattern observed in the $\delta^{18}\text{O}$ records. While MIS 2, 6, and especially MIS 16 are particularly strong for $\delta^{18}\text{O}$, they are less pronounced in the SST records. Conversely, MIS 20 and 22 are stronger for SSTs. MIS 12 is strong for both groups. Due to the heterogeneous responses across the terrestrial archives, it is considerably more difficult to identify a coherent pattern in the glacial strength heatmap. The averaged glacial strength index condenses this information into a single metric and reveals a clear overall trend, namely a glacial amplification from MIS 22 onward. Before MIS 22-24, only MIS 38 and 48 exceed average strength, while all other glacials remain below it. After MIS 22, all glacials are above-average strength, except for MIS 13b-14 and 15b. Notably, the lower intensity of MIS 7d in marine archives is less pronounced in the terrestrial index, which in fact classifies MIS 7d as above-average strength.

Calculating and comparing the mean values of the average glacial strength index before MIS 22-24 and from MIS 22 onward highlights the above observation of glacial amplification in strength. For the benthic $\delta^{18}\text{O}$ index, the mean glacial strength increases from $\mu = -0.73$ to $\mu = +0.73$. For the SST index, the corresponding mean increases from $\mu = -0.66$ to $\mu = +0.66$. Finally, for the terrestrial index, the mean increases from $\mu = -0.34$ to $\mu = +0.35$.

Overall, the average termination strength indices closely reflect their corresponding glacial strength indices (Fig. 10c). All three groups exhibit pronounced maxima at terminations TII and TV, as well as persistently weak terminations at TVIIa and TXIIIa. In general, the terrestrial termination strength index displays a flatter overall profile and greater variability relative to the marine indices.

3.7 Correlation between interglacial and glacial strength

Based on their study of the past 800 ka, Lang and Wolff (2011) concluded the apparent rule that a strong glacial may lead to a strong subsequent interglacial. This was in particular the case for their isotopic records (benthic and planktonic $\delta^{18}\text{O}$) and for the period after the MBS. The follow-up study by Watson et al. (2026) extended the study period to the past 1.5 Myr and focused on SST records. Although they found that strong interglacials since the MBS followed strong glacials, they did not find such a relationship before the MPT when considering the entire 1.5 Myr period. The authors suggest a threshold effect that ice sheets need to exceed a particular size before they can affect the subsequent interglacial strength. In addition to benthic $\delta^{18}\text{O}$ and SST records, this study incorporates a range of terrestrial proxies and climatic variables. To assess whether glacial strength is correlated with the strength of its subsequent interglacial, we use the average glacial and interglacial strength indices derived in the previous section and build data pairs from them. For this purpose, we use the glacial extremum closest to the corresponding termination, rather than the absolute glacial extremum. This choice is motivated by the objective of assessing potential influence on the following interglacial, given that the absolute glacial extremum may occur tens of thousands of years before the subsequent interglacial peak. The resulting paired values are shown in Figure 11, again separated into the three proxy-type categories from above. We then fit a linear regression model and report the corresponding correlation coefficient (r) and significance level (p).

Figure 11 indicates that, among the proxy records examined, only the benthic $\delta^{18}\text{O}$ records exhibit a strong linear relationship between interglacial strength and preceding glacial strength after the MBS ($r = 0.92$, $p < 0.01$; Fig. 11a). Data points in

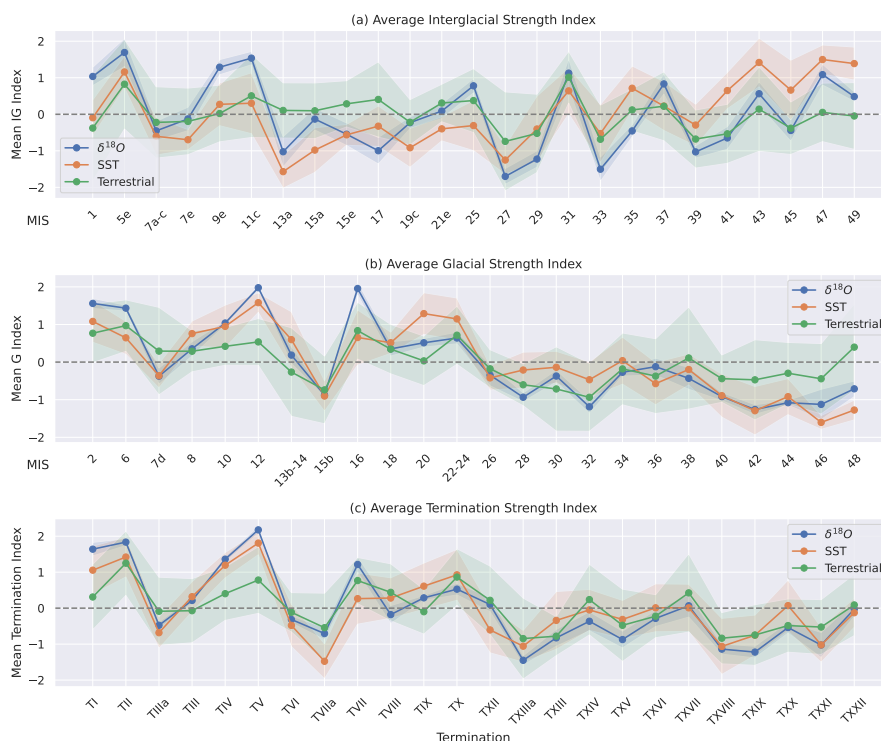


Figure 10. Average strength indices of (a) interglacials, (b) glacial, and (c) terminations over the last 1.5 Myr. All records were normalized and categorized into three groups: benthic $\delta^{18}\text{O}$ records (blue), SST records (orange), and terrestrial records (green). For each category, the average strength is calculated over the included records and plotted against the corresponding MIS or termination. The shaded areas denote ± 1 standard deviation (σ).

quadrant I (upper right) correspond to cases in which relatively strong glacial are succeeded by relatively strong interglacials. In the $\delta^{18}\text{O}$ records, these are all post-MBS terminations, except for the transition MIS 22/21e.

By contrast, the SST records do not indicate such a linear relationship in strength. Nevertheless, the only termination pairs
 450 that fall in quadrant I are exclusively post-MBS terminations, namely MIS 12/11c, MIS 10/9e, and MIS 6/5e, which is consistent with the findings of Watson et al. (2026). In both compilations, termination MIS 2/1 does not fall within quadrant I because the subsequent interglacial MIS 1 is weaker than average, despite the preceding glacial MIS 2 being exceptionally strong. This pattern may also reflect incomplete records near the top of the sediment cores. For example, the SST record reported by Herbert et al. (2017) lacks data for the interval 0–3 ka. Additionally, termination MIS 8/7e represents a further exception, as it corre-
 455 sponds to a strong post-MBS glacial followed by a comparatively weak interglacial, a feature also identified in the compilation of Watson et al. (2026).

Finally, the terrestrial archives likewise do not show any linear relationship between glacial and interglacial strength over the past 1.5 Myr, nor when considering the post-MBS interval exclusively. However, they agree with the $\delta^{18}\text{O}$ and SST records in



assigning the terminations MIS 10/9e, MIS 12/11c, and MIS 6/5e to quadrant I. In the terrestrial records, however, quadrant
 460 I contains not only post-MBS terminations but also earlier transitions, including MIS 22/21e or MIS 48/47. As for the SST
 records, MIS 2/1 and MIS 8/7e are placed in quadrant IV (lower right).

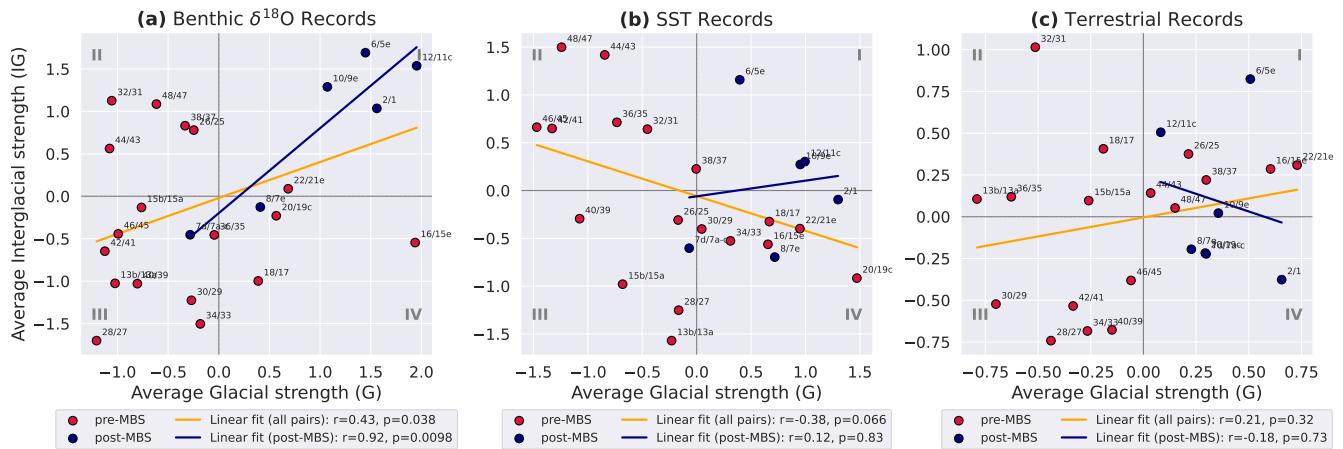


Figure 11. Correlation between glacial and subsequent interglacial strength. The average interglacial strength (y-axis) is plotted against the preceding average glacial strength immediately before a termination (x-axis). Rows show results for: (a) benthic $\delta^{18}\text{O}$ records, (b) SST records, and (c) terrestrial records. Black lines indicate the mean strength, separating the plots into quadrants of stronger-than-average and weaker-than-average glacials and interglacials. Each subplot includes a linear regression for the entire 1.5 Myr window (orange line), or only the post-MBS terminations (blue line). The corresponding r and p values are given. Quadrants are marked with Roman numerals.

3.8 Morphology of selected glacial and interglacial stages

This section focuses on the morphology of glacial and interglacial cycles over the past 1.5 Myr. Given the overall similarity in the patterns of the benthic $\delta^{18}\text{O}$ stacks (Fig. 2) and the SST stacks (Fig. 3) in this study, we exclusively focus on the terrestrial
 465 archives to display the large range of possible MIS morphologies. In total, we select six MIS, namely three interglacials and three glacials. To display both the pre- and post-MPT world, we include MIS from both periods. As particularly strong post-MPT interglacials, we include MIS 5e and MIS 11c, and MIS 31 as an outstandingly strong pre-MPT interglacial. For the glacials, we select MIS 12 and MIS 16 in the late Pleistocene, due to their strength and MIS 30 as a pre-MPT glacial.

The morphology of glacial and interglacial cycles is not symmetrical and largely varies between different stages and records.
 470 The variety in the morphologies of the terrestrial records can be seen in Fig. 12 for the selected pre- and post-MPT glacial and interglacial cycles. Here, we normalized each of the 15 terrestrial records to a range of 0 and 1 to allow a comparison of the different proxy types. As apparent from Fig. 12 (grey lines, first row), the different terrestrial records largely vary in their shapes for the selected MIS. Although the spread appears large, we can take the mean curve over the 14 individual curves and compare it with the corresponding morphology of the benthic $\delta^{18}\text{O}$ Prob-stack (second row Fig. 12). The averaged curves agree within
 475 one standard deviation with Prob-stack, and their general shapes follow that of Prob-stack. As evident from Fig. 12, interglacial



and glacial periods are characterized by a variety of different shapes. While MIS 31 looks more symmetrical in shape and is characterized by similar deglaciation and glaciation periods, MIS 5e exhibits a very quick and sharp deglaciation, followed by declining intensity with superimposed second-order oscillations. MIS 11c is also characterized by a sharp deglacial transition, followed by a prolonged deglaciation phase. While some interglacials are characterized by a sudden and quick transition, the glacial periods constitute more prolonged and steady periods, although still differing in their shapes. The relatively strong glacials of MIS 16 and 22 show long glaciation periods, interrupted by interstadials. In contrast, MIS 30 reaches peak glacial conditions faster and returns more quickly to the next interglacial.

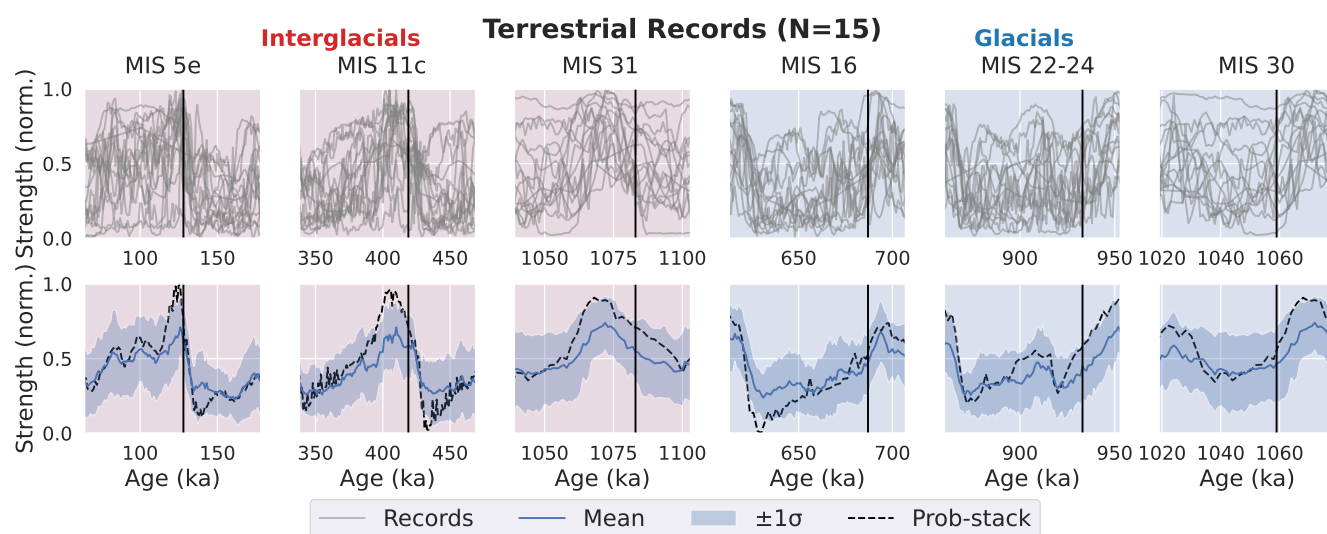


Figure 12. Normalized morphology of selected interglacial and glacial MIS stages from 15 terrestrial records. All records were normalized to a range between 0 and 1 to allow different proxy types to be displayed in a single plot. The first row shows individual records (grey lines), while the second row shows the mean (blue line) across all records. The vertical black lines indicate MIS boundaries as given in Table 2. The morphology of Prob-stack is shown for comparison for each stage (black dotted line).

4 Discussion

4.1 Limitations

Firstly, our analysis is constrained by the availability of records that satisfy our selection criteria. The marine realm is well represented by continuous, high-resolution, and geographically diverse sediment cores. For SST records, we mostly include regional SST stacks, each composed of multiple local records. A compilation of individual SST records has already been covered by Watson et al. (2026). The selected benthic $\delta^{18}\text{O}$ records consist of global and regional stacks. Although we have increased the number of terrestrial records compared to previous studies, these records remain sparse and geographically confined, with no terrestrial coverage from North America, Africa, or Oceania.



Secondly, the quantified intensities of interglacial and glacial intervals depend on the specific methodology used to infer the strength. Compared to previous studies, the approach of using absolute extrema within a given stage is arguably more objective. Nevertheless, relying on absolute extrema may fail to capture the true strength of a stage when the temporal resolution is insufficient, when data gaps are present, or when the record contains outliers. Since an absolute extremum of a glacial can occur multiple kyr before a termination, we use the extremum closest to a glacial termination in our analysis to assess the relationship between glacial and subsequent interglacial strength. Moreover, the MIS boundaries reported in Table 2 are based on the benthic $\delta^{18}\text{O}$ Prob-stack and the defined thresholds to distinguish interglacials and glacials. Because events in paleoclimatic time series, such as deglaciations, do not necessarily occur synchronously and phase relations exist among different proxies and archives (Ganopolski and Roche, 2009), it is difficult to directly transfer benthic $\delta^{18}\text{O}$ -based MIS boundaries to other records like terrestrial archives. Hence, this shortcoming stresses the need to intensify efforts to construct coherent chronologies for different climatic archives and proxies, analogous to the work of Auriol et al. (2025), who constructed such a chronology for the past 640 kyr by integrating ice core, marine sediment, and speleothem records. In order to minimize the impact of these rigid boundaries in our analysis, we implemented the peak alignment procedure (Sect. 2.2.3), which allows extrema that fall slightly outside a given MIS to be shifted into the correct interval.

Finally, the interpretation of interglacial and glacial strength is limited by the characteristic structure of interglacial and glacial variations. Some records exhibit relatively flat profiles during interglacials (or glacials), with most of the main variations occurring during glacial (or interglacial) periods. This can be attributed to some records saturating, for example, arboreal pollen records reaching minima during glacial maxima. Consequently, small fluctuations around a baseline value may provide only limited information about interglacial (or glacial) intensity. One example is the Si/Ti record from Lake El'gygytgyn, which exhibits relatively constant glacial minima and two exceptionally strong "*super interglacials*" during MIS 11c and MIS 31 that dominate the entire record.

4.2 Strength analysis - Comparison with previous compilations

Overall, the previously published compilations of Lang and Wolff (2011), of the Past Interglacials Working Group of PAGES (2016), and of Watson et al. (2026), and the results of this study are broadly consistent when comparing glacial-interglacial intensities of the past 800 kyr, although some differences exist. All compilations agree on the finding that there is an increase in interglacial intensity after the MBS, with consistently weaker interglacials during MIS 7a-c and 7e in the marine archives (noting that the notation of MIS 7 differs among the compilations). In contrast, the terrestrial records in this compilation do not indicate such a trend. Over the last 800 kyr, MIS 5e emerges as the strongest interglacial in most records across all compilations. This pattern is also observed in the marine and terrestrial records, suggesting that MIS 5e represents an event of global strength across various climate archives. Consistent with the observations by Lang and Wolff (2011) and Watson et al. (2026), our results show that MIS 1 is less pronounced in SSTs compared to benthic $\delta^{18}\text{O}$ records. Moreover, in agreement with Lang and Wolff (2011) and the Past Interglacials Working Group of PAGES (2016), we identify an exceptionally strong MIS 13a in the loess records from the CLP, suggesting that the terrestrial response of MIS 13a differs substantially from the marine trend during this stage. All compilations indicate weaker glacials during MIS 7d, 13b-14 and 15b (noting that not all compilations resolve the



525 same set of MIS). However, they do not agree on their relative magnitudes. The patterns of glacial intensity over the past 800 kyr mostly agree between the various marine archives presented in the previous compilations and those presented in this study. These records indicate that MIS 12 and 16 are particularly strong in benthic $\delta^{18}\text{O}$ records, while MIS 16 is less strong for SST records. Although we also find that MIS 16 is indeed weaker in SST records compared to $\delta^{18}\text{O}$ records in our compilation, it ranks among the strongest glacials in most of the terrestrial records and is one of the few glacials that is unambiguously strong. 530 Our compilation, therefore, suggests that MIS 16 reflects not only an ice-volume signal, as hypothesized by Lang and Wolff (2011), but also a pronounced global climate signal.

When extending the period to the last 1.5 Myr, the only other compilation that covers this interval is the recent study by Watson et al. (2026), focusing on SST records. By extending the temporal interval, Watson et al. (2026) identified several particularly strong early interglacials - namely MIS 43, 47, and 49 - and concluded that MIS 5e and MIS 49 are the two 535 strongest interglacials over this entire interval. In our compilation, MIS 5e is slightly weaker, while the earlier stages are more pronounced, with MIS 47 being the most intense. With regard to glacial stages, they found a long-term trend towards progressively colder glacials over the last 1.5 Myr, with some of the coldest glacials appearing since MIS 12, but also MIS 20 and 22 were of particular strength, whereas early glacials between MIS 50-40 were comparatively weak. This agrees with our finding of glacial amplification from MIS 22 onwards. While the period from MIS 48-40 is also particularly weak in marine 540 archives in our compilation, MIS 48 emerges as relatively strong in several of the terrestrial archives. Furthermore, we identify MIS 31 as an interglacial of exceptional strength, particularly in the terrestrial records. Although less strong in SST records, it is ranked as the second strongest interglacial in our compilation when all 29 records are considered (SI Fig. S3).

4.3 Relationship between interglacial and preceding glacial strength

Previous studies have suggested a link between the strength of interglacials and the strength of the preceding glacials. Berger 545 and Wefer (2003) related the strength of MIS 11 to the strength of the preceding glacial MIS 12. Parrenin and Paillard (2003) suggested a threshold mechanism depending on insolation and ice volume size, which triggers a deglaciation. Hence, the strength of a glacial can influence the subsequent interglacial state in their conceptual model. Lang and Wolff (2011, p. 361) hypothesised the *apparent rule* that "strong interglacials, particularly in the marine isotopic records, tend to follow strong glacials". However, their analysis was confined to only the past 800 kyr. Watson et al. (2026) extended the period to the past 550 1.5 Myr, but only for SSTs. They did not find a general relationship between interglacials and pre-termination glacial strength throughout their entire records, only for the last 450 kyr when strong interglacials followed strong glacials. Our study extends these previous efforts by including terrestrial archives which cover the last 1.5 Myr.

Our analysis demonstrates no general linear relationship between glacial strength and succeeding interglacial strength over the last 1.5 Myr. A distinct transition occurs from MIS 11c onwards, when the strength patterns of glacial and interglacial stages 555 become more symmetric (Tab. 3, 4). This interval corresponds to the post-MBS period (0–450 ka), during which we detect a pronounced positive correlation between glacial and interglacial strength in the benthic $\delta^{18}\text{O}$ records. However, no comparable linear relationship is evident in the SST or terrestrial proxy records. Nevertheless, in agreement with Watson et al. (2026), we



identify that the only pairs of strong interglacials that follow a strong glacial all appear after the MBS for our compiled SST records, namely MIS 12/11c, MIS 10/9e, and MIS 6/5e.

560 Overall, our findings do not support the hypothesis that interglacial strength is, in general, determined by the strength of the preceding glacial, although there exists a strong positive correlation in the benthic $\delta^{18}\text{O}$ records after the MBS. Given that the late Pleistocene is characterized by larger global ice volumes, and that $\delta^{18}\text{O}$ primarily reflects ice-volume changes, this may explain why strong glacials after the MBS seem to influence the strength of the following interglacials, whereas the SST and terrestrial proxies do not exhibit such a relationship. As previously suggested, this could be linked to a critical threshold in ice
 565 sheet size which enables a glacial period to influence its subsequent interglacial stage (Berger and Wefer, 2003; Parrenin and Paillard, 2003). Watson et al. (2026) proposed that meltwater forcing and its influence on ocean circulation during a glacial termination may provide an explanation for modulating the subsequent interglacial state.

4.4 Various manifestations

The manifestation of the climatic signals across the records included in this compilation exhibits considerable variability.
 570 Most prominent is the glacial amplification from MIS 22 onwards, which is evident in the majority of records, especially for the marine ones, but also in the terrestrial records, albeit less pronounced (Fig. 8). While the glacial intervals display a relatively coherent pattern, the interglacial periods show a different picture. In the marine records, strong interglacials (particularly for SSTs) dominate the early phase (MIS 43-49), while during the MPT a prolonged interval of weak interglacials follows (MIS 13a-29), before the interglacial intensity sharply increases after the MBS (except for MIS 7a-c and 7e). This pattern is
 575 not evident in our compiled terrestrial records, nor is there any general trend visible, except for MIS 27 being consistently among the weakest interglacials in many records. The other exception is MIS 31, which constitutes one of the only unambiguously strong interglacials. It particularly stands out for the terrestrial datasets, as MIS 31 is consistently strong for all terrestrial records. When all records in this compilation are taken into account, its average strength index ranks immediately behind MIS 5e (SI Fig. S3). Along with MIS 11c, MIS 31 is identified as one of two “*super interglacials*” in the Si/Ti record
 580 reported by Melles et al. (2012). Collectively, these observations suggest that MIS 31 represents one of the most intense interglacials of the past 1.5 Myr, exhibiting strong expressions across numerous records, especially in terrestrial archives, whereas corresponding signals in SST records are less strong.

The MPT can also affect the value range and distribution of glacial and interglacial extrema. The majority of the included records indicate distinct glacial and interglacial states with regard to the distribution of their extreme values. However, the
 585 gradual cooling trend in SSTs during the MPT led to overlapping distributions of glacial and interglacial strength, as it simultaneously cooled glacials and interglacials.

Finally, our compilation suggests that the climate responses of the marine and terrestrial realms differ in their expressions during several time intervals. One example is the above-mentioned difference in interglacials throughout the Quaternary in marine and terrestrial archives. For instance, the stacked loess sequence of Ding et al. (2002) shows consistently strong inter-
 590 glacials over the Quaternary, until they weaken after MIS 11c, in contrast to the marine records, which show an intensification of interglacials following MIS 11c. Another example is MIS 13a, which was particularly weak in marine records, but in loess



archives from the CLP and in arboreal pollen records from Tenaghi Philippon and Lake Ohrid, it was particularly strong. The strength of MIS 13a in loess records from the CLP has already been documented by Lang and Wolff (2011) and the Past Interglacials Working Group of PAGES (2016) and has been attributed to a strong East Asian summer monsoon. These different climatic responses to the MPT are also evident in recent literature. Studies by Lu et al. (2022) and Wang et al. (2025) reconstructed land surface temperatures (LST) over the East Asian summer monsoon region, based on lipid proxies from the CLP and the Heqing paleolake in East Asia, respectively. Both records revealed a surprising long-term warming trend during the Pleistocene (2.6–0.6 Ma and 1.8–0.6 Ma, respectively), which contrasts with the observed long-term cooling trend in SSTs (Herbert et al., 2010; Clark et al., 2024). Both studies attributed this decoupling of marine and terrestrial temperatures to regional climate phenomena, which led to an intensified East Asian summer monsoon. These findings underscore the complexity of the coupled marine and terrestrial climate system and challenge the idea that Pleistocene terrestrial LSTs simply mirror marine temperature evolution. Consequently, the manifestation of the MPT cannot be regarded as a synchronised and homogeneous event, but highly depends on the geographical location and proxy type.

5 Conclusions

Exploring the manifestation of the MPT across various paleoclimatic archives is limited due to the scarcity and the geographical confinement of continuous, long-term terrestrial records. In this study, we compiled a new dataset comprising 29 marine and terrestrial archives spanning the last 1.5 Myr and incorporating multiple proxy types, with nearly half of the records stemming from continental archives. We analyzed the intensities and shapes of past interglacial and glacial intervals, their distributions of extreme values and identified any apparent patterns within and among these records, thereby extending previous efforts of this kind (Watson et al., 2026; Lang and Wolff, 2011; Past Interglacials Working Group of PAGES, 2016). In addition to the compilation, we provide an intuitive web-based dashboard that enables interactive exploration of these records and their associated intensity patterns, their spectral characteristics and the morphologies of their glacial-interglacial cycles.

Our compilation reveals a glacial amplification from MIS 22 onwards, evident in most marine and terrestrial archives, whereas interglacial patterns vary more between the records. Interglacial intensity of marine records over the past 1.5 Myr is characterized by strong interglacials after the MBS and during the early part of the interval (MIS 49–43), and systematically weaker interglacials during the period MIS 13a–29. In contrast, terrestrial archives exhibit fundamentally different climatic responses: interglacial intensities over the Quaternary show no consistent large-scale pattern and, in some cases, contradict the marine signal. A notable example is the strength of MIS 13a in loess records from the CLP, which is indicative of an intensified East Asian winter monsoon, while the same interval is relatively weak in SST and benthic $\delta^{18}\text{O}$ records. Nevertheless, the particular strength of MIS 31 is evident in numerous archives, indicative of a globally consistent climate event.

Furthermore, when considering all our compiled marine and terrestrial archives, no linear relationship is evident between interglacial and preceding glacial strength, except for isotopic records following the MBS. However, the other archive types consistently indicate pronounced post-MBS interglacials during MIS 5e, 9e and 11c that all follow strong glacials. The strong positive correlation identified in benthic $\delta^{18}\text{O}$ records after the MBS may reflect the existence of a critical ice volume threshold,



beyond which large enough ice sheets can influence the subsequent interglacial stage. Moreover, the majority of records exhibit distinct glacial and interglacial states, clearly separated in their value ranges. Long-term trends, such as the observed long-term cooling in SSTs over the MPT, can lead to the overlap of these distributions.

Although this compilation incorporates a substantially larger number of suitable terrestrial records than previous efforts, spatial coverage of the continental domain remains limited, as the dataset currently lacks terrestrial data from North America, Africa, and Oceania. Nevertheless, the methods and framework developed here are readily applicable and can be expanded as new records become available. Future research should therefore prioritize retrieving more diverse continental archives to improve the geographical and climatic coverage of the terrestrial realm, intensifying efforts to construct coherent and cross-archive chronologies, and model-data comparisons across the MPT.

We present a new data compilation of available long marine and terrestrial records covering the last 1.5 Myr. A particular focus lies on the comparatively scarce terrestrial archives. For each record, we evaluate the relative intensity of glacials, interglacials, and terminations across this interval. We examine which stages were especially pronounced or weak, whether there were coherent patterns among the records, identify potential regional or proxy-specific differences, and whether glacial and interglacial strength depend on each other.

Code and data availability. The Python code to generate the figures and perform the analyses is hosted on GitHub at <https://github.com/felyx04/MetaDatabase-Pollak-et-al-2026> (Pollak, 2026), and the archived version for this publication is published on Zenodo at <https://doi.org/10.5281/zenodo.23214422> (Pollak et al., 2026b).

The data of interglacial, glacial, and termination strengths are available on Zenodo at <https://doi.org/10.5281/zenodo.23214641> (Pollak et al., 2026a). References to the source data of all records included in this compilation can be found in Table S1 of the SI.

The interactive web-based dashboard to explore the records of this compilation is hosted on *Hugging Face* and is accessible at: <https://huggingface.co/spaces/felyx04/meta-database-dashboard>.

Author contributions. F.Po. and E.C. designed the study; F.Po. compiled the records and performed the analysis with input from all co-authors; P.C.T. provided the pollen data from Tenaghi Philippon; F.Po. wrote the original draft with subsequent review and editing of E.C., Z.C., P.C.T., F.Pa., and L.J.

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