



# The Marine Isotopic Stage 7: a relic of the «41-ka world»? Perspectives from a global-scale sea-surface temperature synthesis

Etienne Legrain<sup>2,3,1\*</sup>, Nathan Stevenard<sup>1\*</sup>, Emilie Capron<sup>1</sup>, Frédéric Parrenin<sup>1</sup>, Natalia Vazquez Riveiros<sup>4</sup>

<sup>1</sup>Université Grenoble Alpes, CNRS, IRD, Grenoble INP, IGE, Grenoble, France

<sup>2</sup>Department of Water and Climate, Vrije Universiteit Brussel, Brussels, Belgium

<sup>3</sup>Laboratoire de Glaciologie, Université libre de Bruxelles, Brussels, Belgium

<sup>4</sup>Geo-Ocean, UMR 6538, CNRS/Université de Bretagne Occidentale/Ifremer, Plouzané, France,

\* These two authors contributed equally to this work.

Correspondence to: Etienne Legrain ([etienne.legrain@vub.be](mailto:etienne.legrain@vub.be))

**Abstract.** The Marine Isotope Stage 7 (MIS 7, ~245-190 ka) displays an unusual morphology compared to the other interglacials of the late Pleistocene. It comprises two major warm periods (MIS 7e and MIS 7c) each preceded by multi-millennial-scale warming intervals (Termination III (TIII) and TIIIa, respectively) and separated by a brief return to glacial conditions (MIS 7d). When considered as two distinct warm phases, MIS 7 has been compared to the 41-ka obliquity-driven climate cycles of the pre-mid-Pleistocene transition (MPT) world. However, a coherent spatio-temporal picture of MIS 7 surface temperature remains lacking to enable a comprehensive comparison with other interglacials. Here we compiled 132 high-resolution (better than 4 ka) sea surface temperature (SST) records derived from 85 marine sites over the time interval 260-190 ka. In order to provide a spatio-temporal comparison of these records, we (i) align them on a common temporal framework relying on the AICC2023 reference ice core chronology and (ii) recompute SSTs using a homogenized proxy-calibration, both steps applying Bayesian and Monte Carlo approaches to quantify the attached uncertainty. Finally, we produce global and regional stacks of SST anomalies relative to the pre-industrial covering TIII and the following MIS 7.

Our results evidence that global mean surface temperature remains below pre-industrial (PI) values over both MIS 7e ( $-1.4 \pm 0.3$  °C) and MIS 7c ( $-1.0 \pm 0.3$  °C) periods. The warmest phase across MIS 7 occurs during the MIS 7c substage, a period when atmospheric CO<sub>2</sub> concentrations are 30 ppm lower than during MIS 7e, highlighting a decoupling between radiative forcing and the global surface temperature response. In addition, TIII exhibits a greater warming amplitude than TIIIa, both globally and regionally. The spatial and temporal dynamics of the two terminations differ markedly. TIII follows a “classic” sequential deglaciation pattern, with an early warming initiated in the Southern Hemisphere, which then gradually propagates toward the Northern Hemisphere. In contrast, TIIIa displays near-synchronous warming across all latitudes, lacking the interhemispheric pattern typical of classical terminations. This suggests that TIIIa is not a standard glacial termination, but rather a distinct climatic transition. Supporting this, correlation analyses between orbital parameters and regional SST stacks evidence the role of obliquity in shaping MIS 7 temperature records, likely due to the most extreme obliquity values of the Pleistocene occurring over this period. We therefore propose that TIIIa is the result of a self-sustained climatic oscillation that temporarily re-synchronised to the 41-ka cycles because of an exceptional orbital context. As a



result, MIS 7 represents a hybrid interglacial, embedded within the post-MPT 100-ka framework, yet shaped by obliquity-driven forcing such as during the early Pleistocene.

## 40 1. Introduction

Interglacial periods of the Pleistocene are characterized by a wide diversity of external orbital forcing, ice-sheet configurations, atmospheric greenhouse gas concentrations, and global-to-regional climate patterns (Lang and Wolff, 2011; Past Interglacials Working Group of PAGES, 2016; Tzedakis et al., 2009). This diversity offers a unique opportunity to investigate the mechanisms driving the establishment of warm climates under different  
 45 boundary conditions. Global-scale syntheses of multi-archive-based surface temperature records rely on harmonized paleorecords from different regions across the Earth, which is essential to investigate the spatio-temporal evolution of climate changes. Such approach has been applied to the current interglacial (the Holocene), the last interglacial (Marine Isotope Stage 5e, MIS 5e), MIS 9, and MIS 11, as well as to their respective preceding Termination I (TI), TII, TIV and TV, relying on the abundance of highly resolved paleoclimate records spanning  
 50 these intervals (Capron et al., 2014; Hoffman et al., 2017; Milker et al., 2013; Osman et al., 2021; Stevenard et al., 2025). Furthermore, they offer key comparative insights into present-day climate dynamics and establish benchmarks for climate model simulations to enable robust data–model comparisons (e.g. Capron et al., 2017; Gao et al., 2025; Hoffman et al., 2017). MIS 5, MIS 11 and MIS 9 stand out as warm interglacials of the last 800 ka and are representative of the late Pleistocene interglacials occurring after the Mid-Pleistocene Transition (MPT, ~1.2 – 0.7 Ma; Berends et al., 2021; Past Interglacials Working Group of PAGES, 2016). In contrast, MIS 7 (~245–190 ka) remains relatively understudied, in part due to its weaker climatic optimum compared to other late  
 55 Pleistocene interglacials, making it less relevant than MIS 5 or MIS 11 to inform on the state of the Earth system components in a warmer-than pre-industrial (PI) context.

The structure of MIS 7 is well documented in the Antarctic ice core archive, through both local temperature proxies (Landais et al., 2021; Watanabe et al., 2023) and global atmospheric greenhouse gas reconstructions (Legrain et al., 2024; Loulergue et al., 2008; Petit et al., 1999) (Fig. 1i, j). It is also recorded in a variety of marine and continental proxy records (e.g. Desprat et al., 2006; Martrat et al., 2007; Roucoux et al., 2008; Wendt et al., 2021). MIS 7 follows TIII and is composed of several sub-stages, starting with the warm stage MIS 7e, which is marked by an abrupt onset and coincides with an overshoot in atmospheric CO<sub>2</sub> concentrations (Legrain et al., 2024). This  
 65 phase is followed by a return to glacial conditions during MIS 7d, characterized by low CO<sub>2</sub> concentrations characteristic of a full glacial period (<200 ppm, Legrain et al., 2024). Subsequently, a major warming event occurs, referred to as TIIIa, around ~218 ka, leading into the warm stage MIS 7c. The amplitude of TIIIa in Antarctic surface temperature and atmospheric CO<sub>2</sub> records is smaller than that of the preceding TIII (Jouzel et al., 2007; Legrain et al., 2024). However, regional climate reconstructions based on pollen and biogenic silica suggest that the climatic response during TIIIa was comparable to, or even exceeded, that of TIII (Prokopenko et al., 2006; Roucoux et al., 2008). Due to its poorly constrained global amplitude and its close succession to MIS 7e, MIS 7c may or may not be classified as an interglacial period, depending on the criteria used to define interglacials (Past Interglacials Working Group of PAGES, 2016). This period concludes with a short and relatively poorly marked stage MIS 7b. Finally, the climate system enters a third warm interval, MIS 7a, before  
 75 gradually transitioning into the full glacial conditions of MIS 6 around 190 ka. Depending on the resolution and



geographical location of the records, MIS 7a and MIS 7c may not be distinguished. Consequently, we considered MIS 7c, MIS 7b and MIS 7a as a single interval referred to as MIS 7c in the discussion section.

Global ice-volume variations during MIS 7 remain poorly constrained (Dutton et al., 2009; Lea et al., 2002; Siddall et al., 2003; Spratt and Lisiecki, 2016). Conceptual models driven solely by orbital forcing struggle to replicate the various data-derived ice volume reconstructions, capturing only part of the complexity of the climatic sequence (Imbrie et al., 2011; Legrain et al., 2023; Parrenin and Paillard, 2012). The relative influence of orbital vs. greenhouse gases forcings has also been investigated using more sophisticated physical models (Choudhury et al., 2020; Colleoni et al., 2014; Ganopolski and Brovkin, 2017).

The complex structure of MIS 7, characterized by a double warm peak, differs from the other recent interglacials (Fig. 1). Because of its relatively cold temperature optimum and its two-peaks morphology, MIS 7 has been compared to the pre-MPT cycles, characterized by a 41-ka periodicity and a relatively low amplitude (Tzedakis et al., 2012; Watanabe et al., 2023). The occurrence of the two-peaks during MIS 7, among of the single-peak interglacials MIS 1, MIS 5, MIS 9 and MIS 11 remains unexplained, although it is suspected to be linked to the exceptional amplitude of orbital variations during this period (Tzedakis et al., 2012, 2017) (Fig. 1a, b, c). Given this pattern of climatic variability, MIS 7 provides an excellent framework for examining how the climate responds at both regional and global scales, as well as how these responses relate to orbital forcing and the carbon cycle. The variety of global and regional climate signals recorded during MIS 7, along with the need to identify their respective drivers, calls for an approach that accounts for the spatial and temporal heterogeneity of the warming, as performed in syntheses for the other interglacials (e.g. Capron et al., 2014; Hoffman et al., 2017; Stevenard et al., 2025). To date, only few syntheses have compiled sea surface temperature (SST) records spanning this period (e.g. Clark et al., 2024; Lang and Wolff, 2011; Shakun et al., 2015; Snyder, 2016). However, these syntheses rely on a limited number of paleoclimatic records and primarily target longer timescales ( $\geq 800,000$  years). Hence, they are largely composed of low-resolution (albeit temporally extensive) records that are aligned to the LR04 benthic  $\delta^{18}\text{O}$  stack, which was dated through orbital tuning. By focusing on MIS 7 and Termination III, a larger number of higher-resolution records can be aligned within a more robust chronological framework, thereby enabling a more detailed characterization of the spatio-temporal variability in surface temperature during this interval.

In this study, we provide the first SST compilation focused on the MIS 7 and TIII interval in which surface temperature records are aligned on a unified chronological framework. Relying on this synthesis, we (i) assess how the magnitude of warming varied spatially between TIII and TIIIa and between MIS 7e and 7c, (ii) describe the temporal evolution of sea-surface temperatures across major ocean basins, and (iii) place MIS 7 within the broader context of Pleistocene climate cycles.

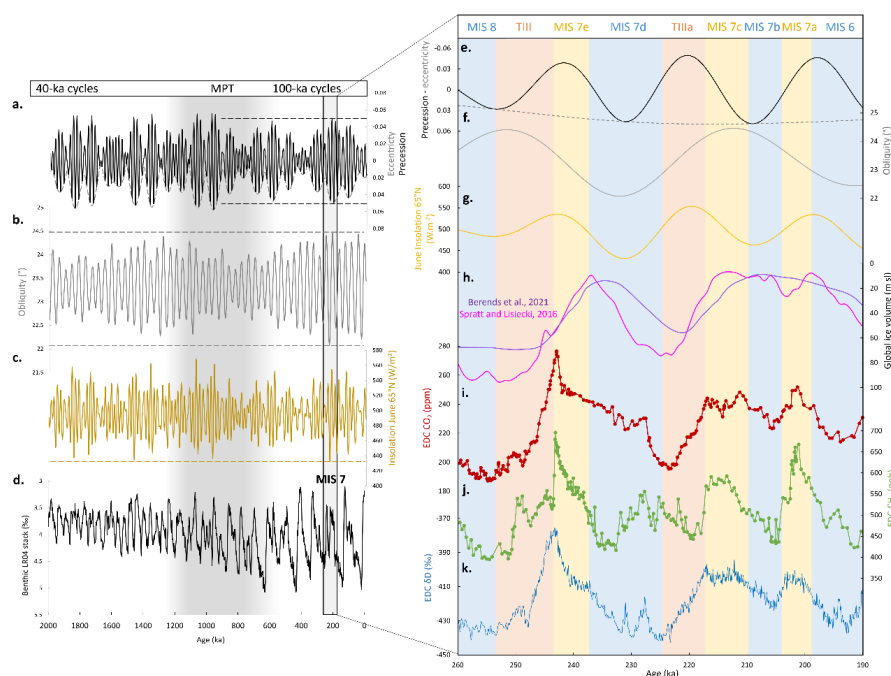


Fig. 1 : **Left panel: MIS 7 shown within the context of the past 2 million years.** From top to bottom: (a) precession (black), eccentricity (grey) (Laskar et al., 2004) (b) obliquity (Laskar et al., 2004) (c) June insolation at 65°N (Laskar et al., 2004), and (d) the benthic LR04  $\delta^{18}O$  stack (Lisiecki and Raymo, 2005). The grey box highlights TIII and MIS7. The shaded area marks the interval of the Mid-Pleistocene Transition. Dashed horizontal lines indicate the maximum and minimum orbital values (precession evaluated over 800–0 ka; obliquity and June 65°N insolation over 2000–0 ka). All of these extrema occur during the MIS 7 interval. Colour coding: black shows the precession extrema over the last 800 ka, grey corresponds to obliquity extrema over the past 2 Ma, and yellow represents the minimum June 65°N insolation over the past 2 Ma. **Right panel: Orbital and climatic datasets spanning 260–190 ka.** From top to bottom: (e) eccentricity (dotted) and precession (solid) (Laskar et al., 2004), (f) obliquity (Laskar et al., 2004), (g) June insolation at 65°N (Laskar et al., 2004), (h) global ice-volume estimates expressed as sea-level equivalents from Berends et al. (2021b) (purple) and Spratt and Lisiecki, (2016) (pink), (i). Atmospheric CO<sub>2</sub> record from the Epica Dome C ice core (EDC) (Legrain et al., 2024), (j) Atmospheric CH<sub>4</sub> record from EDC (Legrain et al., 2024; Loulergue et al., 2008), and (k) EDC  $\delta D$  record (Jouzel et al., 2007). The colored shaded areas help to identify the different climatic periods discussed in this study, but do not correspond to a strict definition. We acknowledge that these boundaries are arbitrary, but they are only used here to clarify reference to the climatic intervals throughout the manuscript.

## 2. Material and methods

The methods used for the SST synthesis construction and the stacking over TIII and MIS 7 are identical to those employed in Stevenard et al. (2025), which focused on TIV and MIS 9. Below is a summary of the main steps, while a detailed description of the methodology and calibration modelling choices can be found in Stevenard et al. (2025).

### 2.1. Selection of paleoclimatic data sites



We compiled 132 SST records from 85 marine cores spanning the 260-190 ka interval (Fig. 2). We apply a threshold resolution filter of 4 ka, leading to an average resolution of 1.7 ka for the whole dataset. 106 and 26 of the records represent annual and seasonal temperatures, respectively. Four different SST proxies are included in the synthesis: the alkenone unsaturation index ( $U^{K'}_{37}$ ), the Modern Analog Technique (MAT) relying on faunal microfossil assemblages, the ratio of magnesium to calcium (Mg/Ca) and the oxygen isotope ( $\delta^{18}O_p$ ) of planktic foraminifera (Fig. 2). Table S1 compiles all details of the selected records.

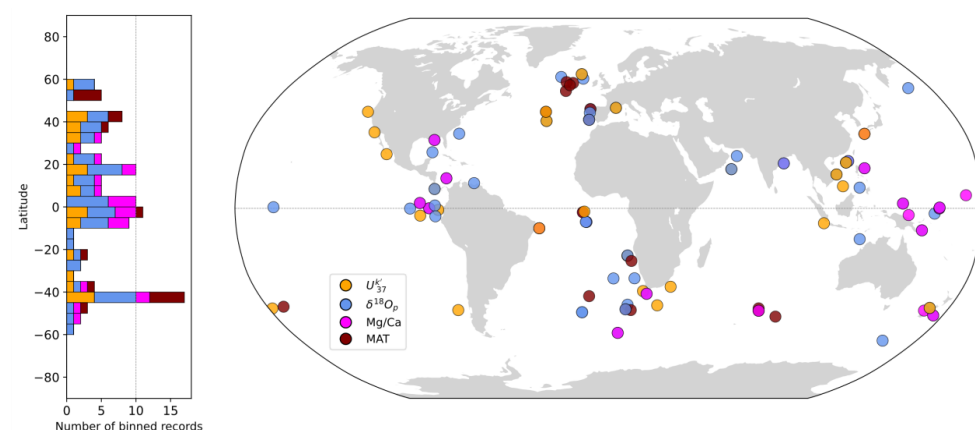


Fig. 2: **Location and latitudinal distribution of SST records.** Left: Distribution of the records per 5° latitude bins. Right: SST reconstructions based on  $U^{K'}_{37}$  (orange),  $\delta^{18}O_p$  (blue), Mg/Ca (pink) and Modern Analog Technique (MAT) (brown).

## 2.2 SST calibrations

Following the approach developed in Stevenard et al. (2025), we recalibrate the original SST records applying a Bayesian approach.

To calibrate the 27  $U^{K'}_{37}$  records, we applied a Bayesian calibration with a prior standard deviation of 5°C using the BAYSPLINE Matlab package that produced a  $N \times 1000$  matrix of SST possibilities for each age  $N$  (Tierney and Tingley, 2018). The 22 Mg/Ca records are calibrated with a Bayesian calibration using the BAYMAG Matlab package (Tierney et al., 2019), applying a prior standard deviation of 6°C (Osman et al., 2021). The seawater salinity and pH estimates are defined with a modified function from (Gray and Evans, 2019) and using the benthic stack LR04 (Lisiecki and Raymo, 2005) as reference for sea-level changes. This calibration produces a  $N \times 2000$  Mg/Ca matrix of SST possibilities for each age  $N$  then randomly subsampled to produce a  $N \times 1000$  matrix. To calibrate the 55  $\delta^{18}O_p$  records, we used the BAYFOX Matlab package, applying a Bayesian calibration with a prior standard deviation of 10°C that produced a  $N \times 1000$   $\delta^{18}O_p$  matrix of SST possibilities for each age  $N$  (Malevich et al., 2019). The prior sea water  $\delta^{18}O$  values were estimated from the Bretkreuz et al. (2018) database and the ice-volume correction use the benthic LR04 stack (Lisiecki and Raymo, 2005) as reference. To our knowledge, no Bayesian approach has been developed for MAT calibrations. We propagate the uncertainties of the 28 MAT records applying a Monte-Carlo analysis creating 1000 scenarios for each data point that follows a normal distribution based on the uncertainty  $\sigma$  provided in the original publications. If this error ( $\sigma$ ) was not published in



155 the original publications, we estimated it as the standard deviation of the SST record over the period 260-190 ka period. To be consistent with other approaches, the ensemble of MAT records is a  $N \times 1000$  matrix.

### 2.3 Anomaly from the pre-industrial period

160 Following approaches developed in previous interglacial syntheses, the SST records are transferred into anomaly compared to the pre-industrial (PI) (e.g. Capron et al., 2014; Hoffman et al., 2017; Osman et al., 2021; Stevenard et al., 2025). As most of the records have no core-top data indicative of recent SST, PI-SST are derived from the HadISST database (Rayner et al., 2003) over the 1870-1899 interval (Capron et al., 2017; Stevenard et al., 2025). These PI-SST were forward modelled to estimate a proxy-value relative to the PI-SST, and then recalibrate using the Bayesian calibrations described above to propagate the proxy-based SST uncertainties for the PI period (Osman et al., 2021; Stevenard et al., 2025).

### 2.4 Chronologies

165 In this study, we harmonize the chronologies of marine sediment records using a three-step approach based on alignment to ice core-based records and Bayesian modelling (Stevenard et al., 2025). All alignments are performed with the *AnalySeries* software (Paillard et al., 1996). Due to the absence of radiocarbon constraints for the 260-190 ka period, we apply a strategy similar to previous syntheses by aligning high-latitude basin reference records to surface air temperature reconstructions from Antarctic ( $\delta D$  of EPICA Dome C) and Greenland ice cores (Hoffman et al., 2017; Stevenard et al., 2025; Vázquez Riveiros et al., 2010). For Greenland, where direct surface air temperature reconstructions are unavailable beyond 130 ka, we use the synthetic temperature curve GLT\_syn (Barker et al., 2011). We do not use directly the  $CH_4$  records as the terrestrial biosphere response to hydroclimatic changes in lower latitudes may affect the  $CH_4$  concentrations and decoupled them from Northern Hemisphere sea surface temperature changes at high latitudes (Kleinen et al., 2023). Despite some millennial-scale discrepancies with  $CH_4$  and Greenland isotope records, GLT\_syn provides a practical reference for northern high-latitude temperature and has been widely used to align marine records with ice-core chronologies (e.g., Barker et al., 2015; Hodell et al., 2023). Then, every record in an oceanic basin is aligned to the reference record through benthic foraminifera  $\delta^{18}O$  record. In case of absence or low-resolution of a benthic  $\delta^{18}O$  record, the SST is directly aligned on the ice core record for high-latitude sites ( $>40^\circ N$  or S), or to the closest already-aligned record for low-latitude sites ( $<40^\circ N$  or S). Then, the age and depth uncertainties associated with the alignment are merged into a single age uncertainty through a Bayesian approach ( $10^5$  iterations) using the “*Undatable*” software (Lougheed and Obrochta, 2019) with a *xfactor* of 0.1 and no bootstrap. The absolute age uncertainty is estimated by calculating the quadratic sum of all uncertainties (i.e. alignment, basin reference, and ice-core). To build the final chronology of each marine sediment core, we run a final Bayesian age-depth model with the absolute uncertainty,  $10^5$  iterations, a *xfactor* of 0.1 and 15% of bootstrap through each iteration (Stevenard et al., 2025). Finally, each original SST record corresponds to an ensemble of 1000 probable ages ( $N \times 1000$  matrix) directly or indirectly aligned to the AICC2023 ice-core chronology (Bouchet et al., 2023).

### 2.5 Global and regional stack reconstructions

190 To estimate global SST anomalies during MIS 7, we used the “*sststack*” Python package (Stevenard et al., 2025) built to facilitate the stacking of ensemble-based SST. It includes the Monte Carlo approach detailed in Stevenard et al. (2025). The ensemble of both age and SST is redrawn to ensure that  $N^{th}$  age-SST pairs are different for each



iteration. To reduce spatial bias, we average the site SST, the randomly gridded SSTs (2-5°) and then the randomly  
 latitudinal SSTs (2.5-10°) for each 500-year time bin. Global and regional SST stacks at hemispheric (North,  
 195 Tropics, South) and ocean-basin scales (North Atlantic, North Pacific, Equatorial Pacific, South Atlantic, Indian  
 Ocean and South Pacific) were calculated at each iteration. All stacks were defined as the weighted mean of all  
 latitudinal band averages. The global mean surface air temperature ( $\Delta$ GMST) is defined as the global SST anomaly  
 ( $\Delta$ GSST) using a random factor (1.5-2.3) derived from climate model comparisons (Osman et al., 2021; Snyder,  
 2016; Stevenard et al., 2025). This Monte Carlo process is repeated 10,000 times to ensure the propagation of all  
 200 uncertainties.

## 2.6 Correlation analysis with internal and external variables

To constrain the drivers of surface temperature evolution during MIS 7, we conducted correlation analyses  
 between global and regional temperature stacks, and various external forcing parameters, including external orbital  
 parameters (eccentricity, obliquity, precession, and June insolation at 65°N) and global variables (sea level and  
 205 atmospheric CO<sub>2</sub> concentrations). We calculated the r-Pearson value between each pair, using inverse values for  
 precession record. We used r-Pearson and not R<sup>2</sup> as negative correlations between surface temperature and the  
 specific reference record used (orbital parameters, atmospheric CO<sub>2</sub> concentrations and global sea level) are not  
 physically meaningful for exploring potential causal mechanisms. During the comparison, we allow the reference  
 records to shift within a  $\pm 10$  ka window for CO<sub>2</sub> and global sea level, and within a 0-10 ka window for orbital  
 210 parameters. The choice of the 10 ka is considered as the order of magnitude of the maximum delayed Earth climate  
 responses considering the reference record (e.g. the response time of ice sheets to insolation changes). This value  
 also helps prevent any potential chronological shift between the surface temperature stack and the reference record.  
 In the case of orbital curves, the reference record is only shifted toward younger ages, since it is not physically  
 possible for surface temperatures to causally influence orbital parameters, unlike atmospheric CO<sub>2</sub> concentrations  
 215 or global sea level, which are affected by climate dynamics. For each stack/reference pair, we discuss the highest  
 r-pearson value and the corresponding time shift (Fig. 8).

## 3. Results

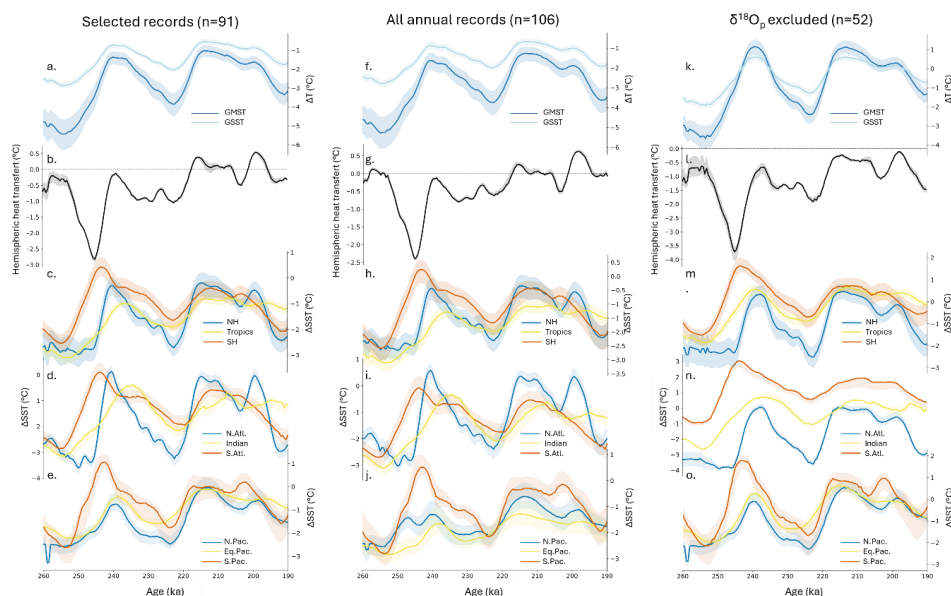
### 3.1 Sensitivity tests of global and regional stacks

220 Based on the specific description of individual records (section S1 in supplementary Materials, Figs. S1, S2 ,S3),  
 we identified discrepancies among SST reconstructions from the same sites (i.e., using different proxies) and,  
 in some cases, within the general trends of a given region. Most inconsistencies are associated with  $\delta^{18}\text{O}_p$ - and, to a  
 lesser extent, Mg/Ca-derived SSTs. This observation has also been made in the MIS 9 synthesis from Stevenard  
 et al. (2025) and likely reflects a lack of environmental constraints used for calibrations. To assess the influence  
 225 of these records on the stacking procedure, we performed three sensitivity tests: (1) including all annual SST  
 records ( $n = 106$ ); (2) excluding all  $\delta^{18}\text{O}_p$ -based SST reconstructions ( $n = 56$ ), which may yield lower temperature  
 estimates or distinct variability patterns; and (3) retaining only records showing consistent amplitude and/or  
 variability within the same region, resulting in the exclusion of 15 records ( $n = 91$ ), mostly derived from  $\delta^{18}\text{O}_p$  and  
 Mg/Ca proxies (Fig. 3). The selection in this third test was based on visual assessment, and the list of excluded  
 230 record is given in the supplementary material (section S1.8).



Overall, the resulting stacks exhibit highly consistent variability across the different tests, independent of the method applied. At both global and hemispheric scales, the amplitude and timing of the main climatic features (e.g., glacial inception, glacial termination and interglacial optimum) remain virtually unchanged. As in the MIS 9 synthesis (Stevenard et al., 2025), the absence of  $\delta^{18}\text{O}_p$  shifted South Atlantic and Indian Ocean stacks towards warmer value (+1 to 3°C). The tests including all records (1) and the one only excluding 15 selected records (3) are very similar, with temperature slightly colder for the “all records” stacks (-0.3°C in average for GMST and GSST stacks). The main regional difference occurs in the Equatorial and Northern Pacific with a more pronounced (+1°C) and better-defined MIS 7e in the “selected” record stacks. This result confirms the potential bias of proxies influenced by other parameters than sea surface temperature (e.g. water salinity) in region where water properties can change drastically due to regional climate (e.g. monsoon events).

The exclusion of  $\delta^{18}\text{O}_p$ -based SST (2) almost divided by two the number of available records and reduces the spatial coverage of the synthesis before the stacking process. The “selected” stack (3) appears as a reasonable compromise, preserving most of records while removing suspicious ones. In addition, the results are very coherent with the stacks from the “all records” test (1). We thus decided to choose this stacking approach for the results description and the interpretation made in this study.

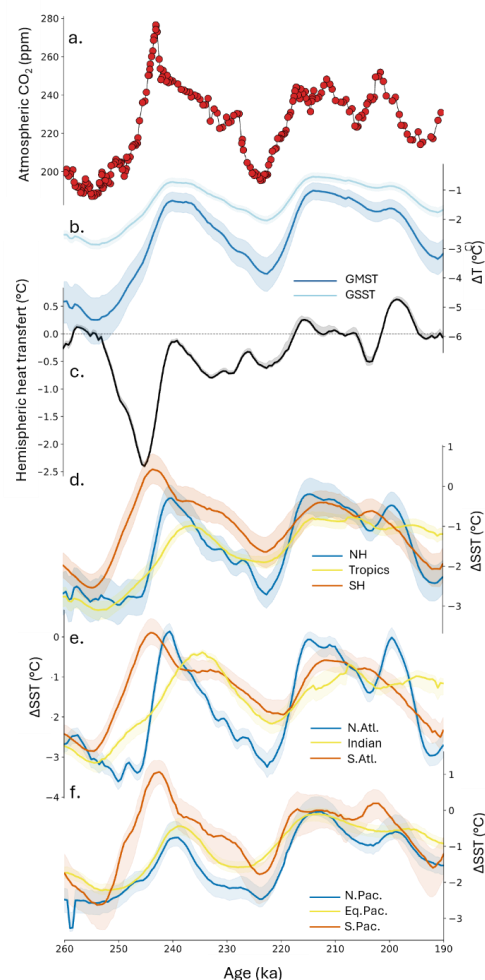


**Fig. 3:** Sensitivity tests on the stacking procedure. (a–e) Stacks built from selected SST records (15 records excluded, chosen version for this study); (f–j) stacks including all annual records. (k–o) stacks excluding  $\delta^{18}\text{O}_p$ -based SST records. (a, f, k) Global  $\Delta\text{GSST}$  (light blue) and  $\Delta\text{GMST}$  (dark blue) stacks; (b, g, l) Hemispheric heat transfer (black line), computed as the Northern Hemisphere minus Southern Hemisphere temperature stacks. (c, h, m) hemispheric  $\Delta\text{SST}$  stacks for the Northern Hemisphere (blue), Tropics (yellow), and Southern Hemisphere (red); (d, i, n) Atlantic and Indian Ocean  $\Delta\text{SST}$  stacks for the North (blue), South (red) Atlantic and Indian Ocean (yellow); (e, j, o) Pacific  $\Delta\text{SST}$  stacks for the North (blue), Equatorial (yellow), and South (red) Pacific.



### 255 3.2 Basin scale

The regional  $\Delta$ SST stacks (Fig. 4e) of the different oceanic basins display a very pronounced regional variability of the MIS 7: it can vary from a structure associated to three temperature peaks clearly identified as the warm substages MIS 7e, 7c and 7a (e.g. North Atlantic) to a weakly amplified signal (e.g. Equatorial Pacific).



260 **Fig. 4: Global and regional records over MIS 7 and Termination III.** From top to bottom: a. Atmospheric  $\text{CO}_2$  concentrations (red dots) measured in the EDC ice core (Legrain et al., 2024). b.  $\Delta$ GMST (dark blue) and  $\Delta$ GSST (light blue). c. Hemispheric heat transfer (black line), computed as the Northern Hemisphere minus Southern Hemisphere temperature stacks. d. Northern Hemisphere (blue), tropics (yellow) and southern Hemisphere (red) temperature stacks. e. Basin temperature stacks: North Atlantic (blue), Indian Ocean (yellow), South Atlantic (red). f. Basin temperature stacks: North Pacific (blue), Equatorial Pacific (yellow), South Pacific (red). All stacks records have been realized with the annual records of the synthesis, at the exception of 15 excluded records (see methods). Colored envelopes are  $1\sigma$  interval of the corresponding stacks.

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During TIII and the following MIS 7e, all basins show a marked warming trend from preceding glacial conditions, though the amplitude and timing of the peak vary. The North Atlantic exhibits the strongest and most abrupt SST rise, reaching PI values, with a TIII amplitude of  $+3.8 \pm 0.2^{\circ}\text{C}$  ( $1\sigma$ , here and after) (Fig. 5) and displays a sharp peak centered around 240 ka. In the South Atlantic and South Pacific, MIS 7e is also well-expressed, but the TIII occurs earlier than in the rest of the basins, around 254 ka, and is slightly lower in amplitude ( $+3.0 \pm 0.3^{\circ}\text{C}$  and  $+3.7 \pm 0.6^{\circ}\text{C}$ ) compared to North Atlantic. The Indian Ocean also registers a major warming ( $+2.8 \pm 0.1^{\circ}\text{C}$ ) but with a significant delay, with MIS 7e peak registered around 236 ka. In contrast, the Equatorial and North Pacific basins reveal a less intense warming ( $+1.8 \pm 0.2^{\circ}\text{C}$  and  $+1.8 \pm 0.5^{\circ}\text{C}$ , respectively), with MIS 7e expressed as a colder broad plateau.

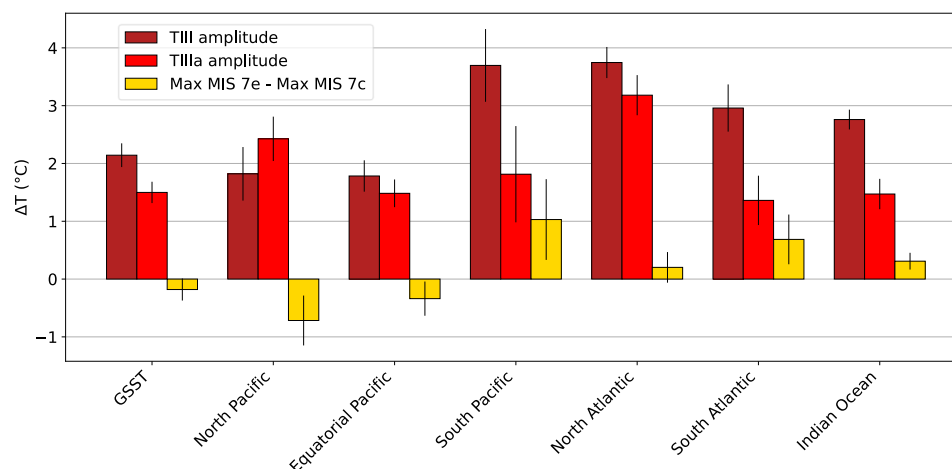
The MIS 7d cold period is expressed as a distinct cooling in the North Atlantic and South Pacific, with SSTs dropping by  $3^{\circ}\text{C}$ , marking the two most abrupt stadial onsets in the regional stacks. This cooling is also evident in the South Atlantic, North Pacific and Indian Ocean but occurs more gradually and with reduced amplitude ( $\sim 2^{\circ}\text{C}$ ). In the Equatorial Pacific, MIS 7d appears as a subtle inflection of  $1^{\circ}\text{C}$ .

The MIS7d is then interrupted by the TIIIa. In general, TIIIa is characterized by a more gradual and less pronounced warming than TIII, except in the North Pacific, where the temperature rise during TIIIa exceeds that of TIII by  $0.2 \pm 0.3^{\circ}\text{C}$ . During TIIIa, the North Atlantic and the North Pacific exhibits the stronger SST rise, starting at 222ka ( $+3.1 \pm 0.3^{\circ}\text{C}$  and  $+2.3 \pm 0.3^{\circ}\text{C}$  respectively) and culminating at around 214 ka. In the four other basins, the warming is of lower amplitude (ranging from  $+1.3 \pm 0.4^{\circ}\text{C}$  in South Atlantic to  $+1.8 \pm 0.8^{\circ}\text{C}$  in South Pacific).

The following climate optimum corresponds to the MIS 7c. In the North Atlantic, MIS 7c is comparable in magnitude to MIS 7e ( $\Delta 7\text{e-c} = +0.2 \pm 0.3^{\circ}\text{C}$ ), though more prolonged (Fig. 5). In the North Pacific ( $-0.7 \pm 0.5^{\circ}\text{C}$ ) and in the Equatorial Pacific ( $-0.3 \pm 0.3^{\circ}\text{C}$ ), MIS 7c is the most prominent substage during MIS 7. In the South Atlantic, South Pacific, and Indian Ocean, MIS 7c peak is colder than MIS 7e ( $-0.7 \pm 0.4^{\circ}\text{C}$ ,  $-1.0 \pm 0.6^{\circ}\text{C}$  and  $-0.3 \pm 0.1^{\circ}\text{C}$  respectively).

During MIS 7b, the oceanic basins registered varying degrees of cooling. The North Atlantic and North Pacific shows a clear and rapid SST decline with an identifiable minimum ( $-1.4^{\circ}\text{C}$  and  $-1^{\circ}\text{C}$ , respectively), while South Pacific exhibit a smoother, more gradual decrease. The Indian Ocean shows only a weak inflection, and MIS 7b is almost absent in the South Atlantic (Fig. 4e). The Equatorial Pacific maintained an almost flat profile until 190 ka.

MIS 7a is the least consistently expressed of the three warm periods. The North Atlantic, North Pacific and South Pacific exhibit a small but coherent SST rebound following MIS 7b ( $+1.4^{\circ}\text{C}$ ,  $+0.3^{\circ}\text{C}$  and  $+0.4^{\circ}\text{C}$  respectively) though its amplitude is much lower than during TIII and TIIIa. In the Indian Ocean, South Atlantic, and Equatorial Pacific, the signal is barely distinguishable (Fig. 4e).



**Fig. 5: Termination amplitude and warm phases intensity.** Amplitude of the temperature change over TIII (dark red) and TIIIa (red) for the GSST stack and regional basin stacks. b. Difference of interstadials intensity (yellow). Errors bars correspond to 1 $\sigma$  uncertainty.

### 3.3 Hemispheric scale

Here we present the results from the extra-tropical Northern Hemisphere stack (North to 23°N, referred to as Northern Hemisphere stack after), the extra-tropical Southern Hemisphere stack (South to 23°S, referred to as Southern Hemisphere stack after) and the Tropics stack (between 23°N and 23°S).

The amplitude of TIII is larger in the Southern Hemisphere (3.0°C) than in the Northern Hemisphere (+2.4°C) and the Tropics (+2.1°C), and the only MIS 7 SST values exceeding PI are in the Southern Hemisphere during MIS 7e (+0.5 ± 0.4°C).

The hemispheric and tropical SST stacks reveal a clear phasing pattern during Termination III and MIS 7e (Fig. 4d). Deglacial warming begins in the Southern Hemisphere around 254 ka and subsequently propagates to the tropical region (warming starting at ~251 ka), with the Northern Hemisphere warming last (~246 ka). The MIS 7e optimum is reached first in the Southern Hemisphere (~244 ka), then in the Northern Hemisphere (~240 ka) and finally in the Tropics (~236 ka). In contrast, no such temporal offset is observed during Termination IIIa, as all regions appear to both initiate warming and reach the optimum synchronously (at ~222.5 ka and ~214 ka respectively). This phasing difference between TIII and TIIIa is illustrated with the Interhemispheric heat transfer reconstruction, computed as the Northern Hemisphere stack – Southern Hemisphere stack (Fig. 4c). It appears clearly that only the period of TIII registered the large interhemispheric temperature difference (up to 3°C) characteristic from Terminations, consequent to the delayed warming of Northern Hemisphere associated with a weak AMOC during TIII.

The MIS 7d cold period is very pronounced in both hemispheres, with SSTs dropping by 2°C (SH) and 2.5°C (NH), compared to the tropics, while average SSTs decrease by 0.9°C. MIS 7c evidences similar temperature between Northern and Southern Hemisphere, with MIS 7c slightly warmer than MIS 7e in the Northern



Hemisphere ( $-0.1 \pm 0.4^{\circ}\text{C}$ ) and Tropics region ( $-0.3 \pm 0.1^{\circ}\text{C}$ ), whereas MIS 7c is colder in the Southern Hemisphere ( $+0.8 \pm 0.5^{\circ}\text{C}$ ).

Regarding the final stages of MIS 7, only the Northern Hemisphere exhibits a well-defined tripartite interglacial structure (MIS 7e, 7c, 7a), while MIS 7a remains indistinct in both the tropical and Southern Hemisphere stacks.

### 3.4 Global scale

The  $\Delta\text{GSST}$  and  $\Delta\text{GMST}$  stacks are characterized by a clear two-peak morphology, with prominent interglacials during MIS 7e and MIS 7c. A third warm period, MIS 7a, is also present but expressed with less intensity (Fig. 4b).

335 TIII has an amplitude of  $2.2 \pm 0.2^{\circ}\text{C}$  in the  $\Delta\text{GSST}$  stack and of  $4.1 \pm 0.5^{\circ}\text{C}$  in the  $\Delta\text{GMST}$  stack, starting at  $253.5 \pm 0.5$  ka. Optimum temperatures during MIS 7e are reached at  $240.0 \pm 0.5$  ka and remain below PI values ( $-0.7 \pm 0.2^{\circ}\text{C}$  and  $-1.4 \pm 0.3^{\circ}\text{C}$ ). MIS 7d is characterized by a temperature drop of  $1.3^{\circ}\text{C}$  and  $2.5^{\circ}\text{C}$  in the  $\Delta\text{GSST}$  and  $\Delta\text{GMST}$  stacks. MIS 7c stands out as the warmest interval over the MIS 7 sequence but remains significantly below pre-industrial levels, with peak anomalies compared to PI of  $-0.5 \pm 0.1^{\circ}\text{C}$  ( $\Delta\text{GSST}$ ) and  $-1.0 \pm 0.3^{\circ}\text{C}$  ( $\Delta\text{GMST}$ ) during the climate optimum at  $214.0 \pm 0.5$  ka. Reversely, the amplitude of TIIa, preceding MIS 7c, is reduced compared to TIII, with  $\Delta T$  differences between the TIIa and TIII of  $-0.7 \pm 0.4^{\circ}\text{C}$  ( $\Delta\text{GSST}$ ) and  $-1.3 \pm 1.1^{\circ}\text{C}$  ( $\Delta\text{GMST}$ ), respectively (Fig. 5). It illustrates a much warmer MIS 7d compared to MIS 8 (by  $1.5 \pm 1.0^{\circ}\text{C}$  and  $+0.8 \pm 0.3^{\circ}\text{C}$  in  $\Delta\text{GMST}$  and  $\Delta\text{GSST}$ , respectively). MIS 7a is characterized by a temporary warm rebound of less than  $0.2^{\circ}\text{C}$  in  $\Delta\text{GMST}$  and  $\Delta\text{GSST}$  stacks. At  $199.5 \pm 0.5$  ka, GMST and GSST stacks initiate a cooling leading to MIS 6.

The comparison of MIS 7e and MIS 7c with atmospheric  $\text{CO}_2$  concentrations (Fig. 4a) reveals contrasting signals between atmospheric radiative forcing and surface temperature response. In the GMST and GSST stacks, MIS 7c emerges as the warmest period of MIS 7 ( $+0.4 \pm 0.4^{\circ}\text{C}$  and  $+0.2 \pm 0.2^{\circ}\text{C}$ , respectively). In contrast, the atmospheric  $\text{CO}_2$  record shows a higher concentration during MIS 7e (275 ppm) than during MIS 7c (245 ppm), highlighting a partial decoupling between radiative forcing and global surface temperature variations.

## 4. Discussion

### 4.1 Limitations and contextualization of the synthesis

#### 4.1.1. Limitations of the study

355 This synthesis was constructed using the same approach and methodology as the MIS 9 surface temperature synthesis by Stevenard et al. (2025). As a result, all approach and methodology-related limitations are similar, and are summarized in the points below:

- Significant discrepancies observed between records from the same site but reconstructed using different proxies represent a major limitation in the interpretation of our SST synthesis during MIS 7. These differences, sometimes substantial, affect both the temporal structure of the variations and the absolute temperature values. These observations can arise (i) from the proxy itself which can integrate other parameters than surface temperature variations (ii) not be representative of the same water depth or (iii) from the Bayesian methodology applied to reconstructed temperature from these proxies. While this limitation is important, it is partially mitigated by the use



of intra-basin regional stacks, which help minimizing interpretations based on a single core while providing an analysis of regional trends.

- 365 - The use of PI SST reference from the HadISST database (Rayner et al., 2003) can be questioned. Although well-constrained for the PI period, recent comparisons by Gao et al. (2025) show that model-data differences in the Southern high latitudes can reach  $\pm 5^{\circ}\text{C}$ . This uncertainty may bias the absolute anomaly values reported here. However, all other interpretations than comparison with PI is not affected by this bias.
- This study uses Bayesian methods and Monte Carlo processes to account for uncertainties and produce continuous SST reconstructions. However, uneven spatial coverage, particularly in the Pacific, Indian Ocean, Nordic Seas, and Western Atlantic, may distort latitudinal trends. While this limitation is inherent to all stacking procedures (e.g., Clark et al., 2024; Shakun et al., 2015; Tierney et al., 2020), the stacking process developed in this study aimed to minimize this limitation (Stevenard et al., 2025).
- 370
- Differences in the timing of temperature changes across regions, especially during deglaciations and the interglacial peaks, lead to a smoothed global response. Thus, interpreting temperature changes across TIII and MIS 7 requires considering regional, hemispheric, and global GMST stacks together.
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#### 4.1.2. Comparison with the synthesis from Clark et al. (2024)

This synthesis of surface temperatures is the first to focus specifically on TIII and MIS 7. While previous global syntheses have examined temperature variations for MIS 7 across much longer timescales, the added value of this study is twofold: (i) it focuses on high-resolution ( $< 4,000$  years) data specifically for the MIS 7 period, whereas others rely on averaged resolutions over million-year timescales; and (ii) it aligns this period (260–190 ka) with a chronology not primarily based on orbital targeting (the AICC2023 ice core chronology). This is unlike previous syntheses, which are aligned on the benthic  $\delta^{18}\text{O}$  LR04 stack dated by fitting an ice volume model to the 21<sup>st</sup> June insolation curve at  $65^{\circ}\text{N}$ , making it highly dependent on orbital forcing and with large absolute uncertainty ( $\pm 4$  ka).

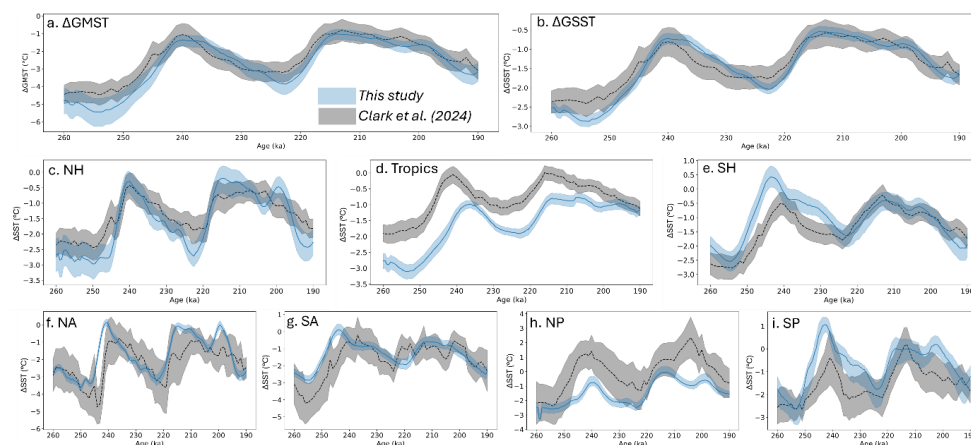
To date, the most comprehensive and up-to-date global synthesis is the one recently published by Clark et al. (2024). Their “high-resolution” synthesis compiled 47 sea surface temperature records of resolution better than 20 ka encompassing the 260–190 ka interval. However, the average resolution of these records is 3.9 ka, close to our resolution threshold (4 ka) and more than double the mean resolution of this study (1.7 ka).

390 The  $\Delta\text{GSST}$  and  $\Delta\text{GMST}$  derived from the two syntheses exhibit comparable amplitudes, with discrepancies remaining below  $1^{\circ}\text{C}$  throughout the entire TIII and MIS 7 interval (Fig. 6). The offset between the two  $\Delta\text{GMST}$  is  $0.26 \pm 0.5^{\circ}\text{C}$  in average, with the Clark et al. (2024) synthesis slightly warmer. Nevertheless, pronounced hemispheric differences are revealed with the comparison. During MIS 7e, Southern Hemisphere temperatures are lower in the Clark et al. (2024) synthesis by  $1.1^{\circ}\text{C}$  and during MIS 7c, Northern Hemisphere is cooler in the Clark et al. (2024) synthesis by  $0.7^{\circ}\text{C}$ . In terms of timing, the Southern Hemisphere maximum temperature also occurs 3,000 years later in the Clark et al. (2024) synthesis compared to this study. Finally, in the tropics, MIS 7e optimum is recorded 3,500 years earlier in Clark et al. (2024), and the two syntheses display an average temperature offset of  $1^{\circ}\text{C}$  over the whole MIS 7 (Fig. 6). At the basin scale, North Atlantic temperatures are colder, whereas North Pacific temperatures are warmer in the synthesis of Clark et al. (2024). The structure of Southern Pacific



400 temperature also diverges between the two reconstructions, with substage MIS 7a absent from Clark et al. (2024)  
 synthesis (Fig. 6).

These findings indicate that the apparent agreement at the global scale primarily reflects compensating regional  
 biases rather than genuine similarity in spatial-scale patterns. This highlights the critical need for high-resolution,  
 temporally constrained syntheses to characterize and discuss the spatio-temporal evolution of surface temperature  
 405 over a specific interglacial.



**Fig. 6: Comparison of the syntheses with Clark et al. (2024).** All panels: Surface temperature from this study (blue) vs  
 results from Clark et al. (2024) synthesis (black). Black and blue envelopes are  $\sigma$  interval of the corresponding stacks. GMST:  
 410 Global Mean Surface Temperature. GSST: Global Sea Surface Temperature. NH: Northern Hemisphere. SH: Southern  
 Hemisphere. NA: North Atlantic. SA: South Atlantic. NP: North Pacific. SP: South Pacific. Comparison is not performed for  
 Indian Ocean and Equatorial Pacific stacks as corresponding stacks have not been produced in Clark et al. (2024).

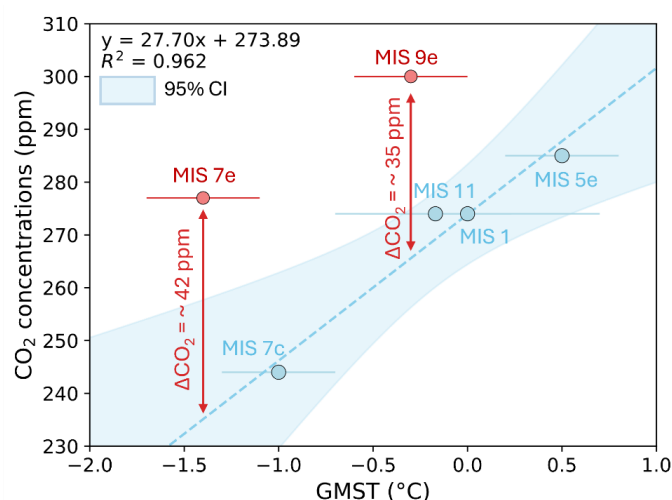
#### 4.2 Decoupling of ΔGMST vs. atmospheric CO<sub>2</sub> concentrations over MIS 7e

Past atmospheric reconstructions evidence that atmospheric CO<sub>2</sub> and CH<sub>4</sub> concentrations were significantly higher  
 415 during MIS 7e than during MIS 7c, with estimated differences of  $\Delta\text{CO}_2 = +30$  ppm and  $\Delta\text{CH}_4 = +100$  ppb (Legrain  
 et al., 2024; Loulergue et al., 2008) (Fig. 1i,j). In parallel, Antarctic surface temperatures, reconstructed from water  
 isotopes in ice cores, identify MIS 7e as the warmest phase of the MIS 7 sequence in the high southern latitudes  
 (Fig. 1k). This regional temperature pattern aligns with our Southern Hemisphere SST stacks from the South  
 Atlantic and South Pacific, which both register temperature maxima during MIS 7e. However, these greenhouse  
 420 gas variations and Antarctic surface temperature reconstructions contrast with the global surface temperature  
 signal. In our ΔGMST reconstruction, MIS 7c emerges as the warmest phase of the MIS 7 sequence, with global  
 mean surface temperatures  $0.4 \pm 0.4^\circ\text{C}$  warmer than during MIS 7e. This result is consistent with the SST synthesis  
 of Clark et al. (2024), which also identifies MIS 7c as slightly warmer than MIS 7e while relying on fewer and  
 less resolved records (Fig. 6). Furthermore, sea-level reconstructions suggest higher stands during MIS 7c than  
 425 during MIS 7e (Berends et al., 2021b; Spratt and Lisiecki, 2016) (Fig. 1h), reinforcing the interpretation that MIS  
 7c was not only warmer globally but also associated with a reduced global ice volume. From a radiative forcing



perspective, the greenhouse gas difference between MIS 7e (~275 ppm CO<sub>2</sub>, ~700 ppb CH<sub>4</sub>) and MIS 7c (~245 ppm CO<sub>2</sub>, ~600 ppb CH<sub>4</sub>) corresponds to an estimated radiative forcing of ~1 W/m<sup>2</sup>, which would produce a global temperature change of ~0.8°C (Hansen et al., 2011; Past Interglacials Working Group of PAGES, 2016). Given that MIS 7e was cooler than MIS 7c by 0.4°C despite higher GHG concentrations, this implies an anomalous offset of ~1.2°C between the two periods, indicating a significant decoupling between radiative forcing and global temperature response over at least one of them.

High-resolution records of CO<sub>2</sub> concentrations and GMST estimates are now available over MIS 1 (Bauska et al., 2021; Hoffman et al., 2017), MIS 5 (Hoffman et al., 2017; Landais et al., 2013), MIS 7 (Legrain et al., 2024; this study), MIS 9 and MIS 11 (Clark et al., 2024; Nehrbass-Ahles et al., 2020; Stevenard et al., 2025). A comparison of maximum CO<sub>2</sub> concentrations and climate optimum over these interglacials reveals that both MIS 7e and MIS 9 evidence anomalously high CO<sub>2</sub> concentrations of 42 ± 22 ppm and 35 ± 9 ppm (2σ), respectively, compared to the expected CO<sub>2</sub> concentrations value based on their GMST (Fig. 7). These two interglacials are characterized by the most pronounced overshoots of atmospheric CO<sub>2</sub> concentration of the past 500 ka, which consist in an abrupt increase followed by a similarly abrupt decrease of atmospheric CO<sub>2</sub> concentrations at the end of a Termination (Bereiter et al., 2015; Legrain et al., 2024; Nehrbass-Ahles et al., 2020). Over MIS 7e, atmospheric CO<sub>2</sub> concentrations increase and drop by 30 ppm in 2,000 years, while during MIS 9 concentrations fluctuate by 35 ppm in 4,000 years. In comparison, the CO<sub>2</sub> concentrations at the slope break after the overshoot for MIS 7e (~240 ppm) and MIS 9e (~270 ppm) are in line with the climate optimum-CO<sub>2</sub> concentrations relationship (Fig. 7). Based on GMST estimates from both periods (Fig. 4b, Stevenard et al., 2025), it appears that the global climate of the Earth does not equilibrate with these overshoots of atmospheric CO<sub>2</sub> concentrations.



**Fig. 7:** Relationship between global mean surface temperature (GMST) anomalies (MIS 1: Osman et al., 2021; MIS 5e: Hoffman et al., 2017; MIS 7c and MIS 7e: this study; MIS 9e: Stevenard et al., 2025; MIS 11: Clark et al., 2024) and atmospheric CO<sub>2</sub> concentrations during interglacial optimum (Bereiter et al., 2015; Legrain et al., 2024; Nehrbass-Ahles et al., 2020). The dashed line shows the best-fit linear regression (excluding MIS 9e and MIS 7e) with its 95 % confidence interval (blue shading). Blue circles represent interglacials used in the regression, while red circles denote outliers (MIS 9e and MIS 7e) associated with atmospheric CO<sub>2</sub> concentrations anomalies ( $\Delta\text{CO}_2 \approx 35\text{--}42$  ppm) relative to the regression line.



During MIS 7c, the GMST are within the range of expected values considering the atmospheric CO<sub>2</sub> concentrations over this period and the CO<sub>2</sub> – GMST relationship of the past interglacials (Fig. 7). Reversely, MIS 7e was anomalously cold by ~1.2°C, indicating a significant decoupling between radiative forcing and global temperature response over this period.

Given this observed decoupling, alternative mechanisms to radiative forcing must be considered to explain the anomalously cold conditions recorded during MIS 7e. One plausible explanation involves albedo feedback associated with the increase of sea ice and seasonal snow cover in the Northern Hemisphere. The growth of sea ice, particularly in the Arctic and sub-Arctic regions, increases surface albedo and refrains absorption of solar radiation, thereby lowering SSTs through negative feedback mechanisms (Cronin et al., 2017; Notz and Marotzke, 2012; Screen and Simmonds, 2010). This process can operate independently of atmospheric CO<sub>2</sub> variations, and proxy evidence supports the notion that sea ice extent can evolve asynchronously with global radiative forcing trends (Masson-Delmotte et al., 2011; Polyak et al., 2010). Crucially, sea ice extent, as well as snow cover at high latitude is strongly modulated by Earth's obliquity (Levy et al., 2019; Turney et al., 2015), which controls the seasonal distribution of solar insolation at these latitudes. During intervals of low obliquity, polar regions receive lower summer insolation, promoting more efficient seasonal growth of sea ice and snowpack (Huybers and Wunsch, 2005). This insolation-driven growth in cryosphere covers ocean and land surfaces with sea-ice and snow surfaces, further limiting solar absorption and amplifying regional cooling (Flanner et al., 2011). MIS 7e is an interglacial that takes place within a range of low obliquity value (from 23.5° to 22.1°, Fig. 1). This 22.1° value is the lowest value of obliquity of the past 2 million years (Fig. 1). In addition to occurring over a decreasing phase of obliquity, MIS 7e takes place under the most extremely low obliquity conditions of the 100-ka world. This obliquity effect is transcribed into the June insolation at 65°N, that reaches its lowest value of the past 800 ka (433 W/m<sup>2</sup>) at 232 ka (Fig. 1a).

The sea-ice and snow cover feedbacks in the Northern Hemisphere are corroborated by our hemispheric SST stack analyses, which evidence a less pronounced temperature peak during MIS 7e in the Northern Hemisphere compared to the Southern Hemisphere (Fig. 4d). However, the cooling effect in the Northern Hemisphere can also partially be attributed to the end of the Heinrich stadial occurring over TIII. These observations support the hypothesis that the anomalously cool conditions of MIS 7e were decoupled from radiative forcing by obliquity-modulated cryosphere feedbacks.

### 4.3 Drivers of the MIS 7 surface temperature variations

Understanding the global morphology of the whole MIS 7 sequence requires investigating the forcing mechanisms behind these climatic variations. The pacing of glacial-interglacial periods is directly related to the amplitude and timing of orbital forcing, which acts as an external modulator of interglacial strength and duration (Tzedakis et al., 2017; Yin and Berger, 2012). Statistical analyses performed by Barker et al. (2025) further highlight the deterministic nature of glacial cycles with respect to orbital phasing, particularly the importance of low obliquity values for driving the end of an interglacial. Previous simulations aimed at disentangling the roles of orbital and atmospheric CO<sub>2</sub> forcing during interglacials have focused exclusively on MIS 7e (Yin and Berger, 2012), MIS 7d (Choudhury et al., 2020) or on interglacials outside the MIS 7 sequence (e.g. Herold et al., 2012; Yin and Berger, 2015). To our knowledge, no simulations from Earth system Models of Intermediate Complexity investigating the distinct role of orbital vs. CO<sub>2</sub> forcing spanning the whole MIS 7 sequence and TIII are published.



However, a transient simulation spanning TIIIa and MIS 7a performed with a coupled climate–ice sheet model shows a dominant role of orbital forcing over greenhouse gases in the return to cold glacial conditions during MIS 7d and in the occurrence of TIIIa (Choudhury et al., 2020).

A qualitative assessment of orbital forcing across MIS 7 shows that obliquity underwent the most extreme variations of the entire Pleistocene, reaching both its absolute minimum (232 ka) and maximum (212 ka) values (Fig. 1). The extremely low values of obliquity (down to 22.1°) occurring over and after MIS 7e likely trigger the return to glacial conditions during MIS 7d, due to its impact on insolation at high latitudes. Consequently, the lowest 65°N summer insolation value of the past 2 Ma is also reached during this MIS 7e – MIS 7d transition (Fig. 1). While MIS 7e occurred during a declining phase of obliquity, a pattern common to most of the recent interglacials, MIS 7c is the only interglacial of the past 800 ka that coincides with an obliquity maximum, the highest of the past 2 million years (Laskar et al., 2004; Past Interglacials Working Group of PAGES, 2016). These exceptional orbital conditions during MIS 7c suggest a direct influence of insolation on the triggering of MIS 7c, occurring several tens of thousands of years earlier than the expected « 100-ka » pacing of climate cycles during this period.

To further explore the drivers of the MIS 7 surface temperature variations, we performed correlation analyses between global and regional surface temperature stacks and external forcings, including orbital parameters, insolation curve, greenhouse gas and sea level records (Fig. 8, see methods). As expected, best correlations are obtained for internal parameters (atmospheric CO<sub>2</sub> and global sea level, average r-pearson of 0.84 and 0.89, respectively). All global sea level/stack optimum correlations are reached for a shift toward older ages of the sea level record, evidencing the delayed time response of ice sheets compared to change in global surface temperature (e.g. Yang et al., 2022). The delayed time for the optimum correlation is 4,100 years relatively to the GMST stack (Fig. 8e). Regarding the CO<sub>2</sub>/stack pairs, the delayed time is regionally dependent, with atmospheric CO<sub>2</sub> concentrations shifted toward younger ages for GMST, Northern Hemisphere and Tropics, while almost synchronous with Southern Hemisphere (Fig. 8f). This result is also in agreement with previous studies evidencing a synchronous rise of Southern Hemisphere temperature and atmospheric CO<sub>2</sub> concentrations, and the delayed response of Tropics and Northern Hemisphere over glacial terminations (e.g. Chowdhry Beeman et al., 2019; Parrenin et al., 2013; Shakun et al., 2012).

Regarding external orbital forcing, these analyses reveal a strong correlation with eccentricity (average r-pearson of 0.62), consistent with MIS 7 position within the 100-ka world. However, correlation with 65°N June insolation and precession are relatively weak (average of r-pearson of 0.34 and 0.27, respectively). In contrast, obliquity exhibits a higher correlation (average of r-pearson of 0.45), suggesting a major role of obliquity in shaping the MIS 7 temperature structure. Interestingly, both eccentricity and precession exhibit their strongest correlations with regional surface temperature in the Equatorial Pacific. The influence of these orbital parameters on equatorial surface temperatures has already been well documented throughout the Pleistocene (Berger et al., 2006; De Garidel-Thoron et al., 2005; Wu et al., 2025). In contrast, obliquity shows the highest correlation values in the Southern Hemisphere, particularly over the South Pacific and South Atlantic, with maximum r-pearson values of 0.57 and 0.56, respectively. Another interesting aspect is the high averaged value of the optimum obliquity shift for positive correlation (9.3 ka) compared to other orbital parameters (precession: 4.2 ka and eccentricity: 2.9 ka). The large time lag between obliquity and the surface temperature stacks prevents interpreting these high

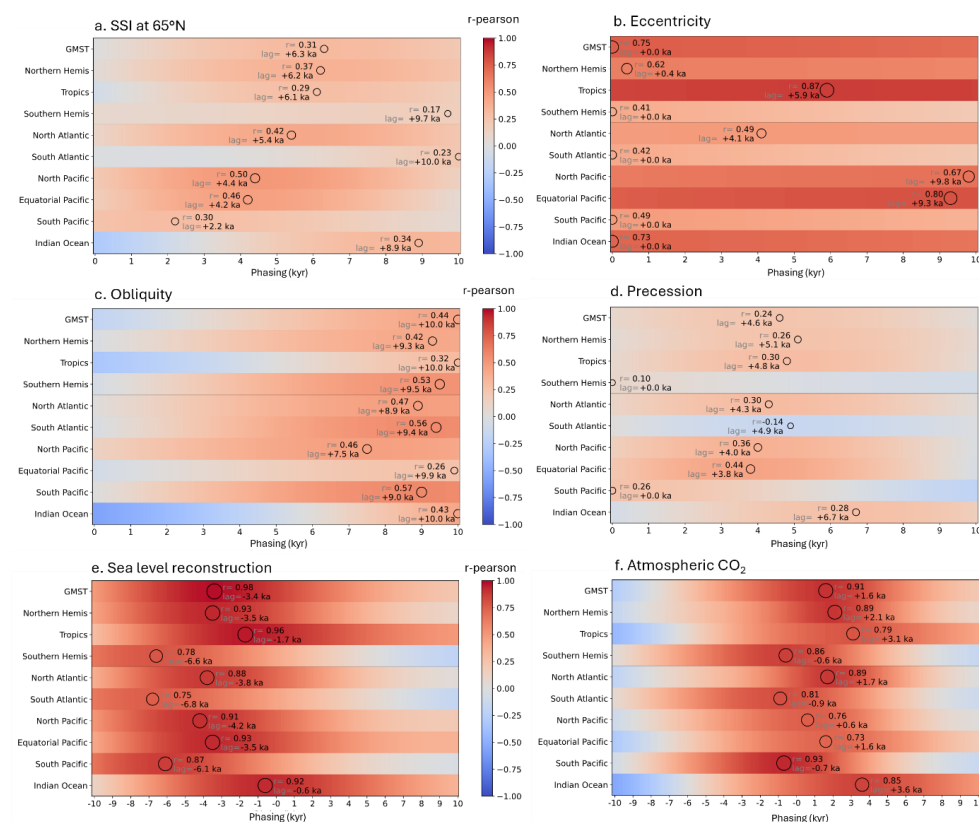


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correlations as a linear response of climate to obliquity forcing, even considering time response of the climate system. Instead, the obliquity maximum around 252 ka coincides with the onset of Termination III in the Southern Hemisphere. The strongest correlations associated with a consistent multi-millennial lag (except in the tropical region) therefore suggest that the obliquity peak played a role in triggering TIII.

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A conceptual modelling approach identified both precession and obliquity as crucial to constrain the timing of glacial terminations over the past 800 ka (Parrenin and Paillard, 2012). However, statistical analyses suggest that precession can trigger glacial terminations by itself in the 100-ka world (Barker et al., 2025). Interestingly, during earlier periods of the 41-ka world (1,600–1,200 ka), three-dimensional ice-sheet modelling substantiates the indissociable role of both obliquity and precession as necessary conditions for initiating and pacing deglaciations (Watanabe et al., 2023).



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**Fig. 8: Comparison of surface temperature stacks to global climatic values and external forcing.** For each subplot: Black circle locates the highest r-pearson value of the surface temperature stack vs. the reference record, with the reference record shifted within a  $\pm 10$  ka window for  $\text{CO}_2$  and sea level, and within a 0-10 ka window for external forcing curves. A positive value indicates that the reference record is shifted towards younger ages. Color bars refer to the r-pearson value computed for each phasing value. a. Reference record: June 21th Insolation at  $65^\circ\text{N}$ . b. Reference record: Eccentricity. c. Reference record:



550 Obliquity. d. Reference record: Precession. e. Reference record: Global Sea Level (Berends et al., 2021b). f. Reference record:  
 atmospheric CO<sub>2</sub> concentrations (Legrain et al., 2024).

#### 4.4 Comparison of MIS 7 with the other interglacials of the Quaternary

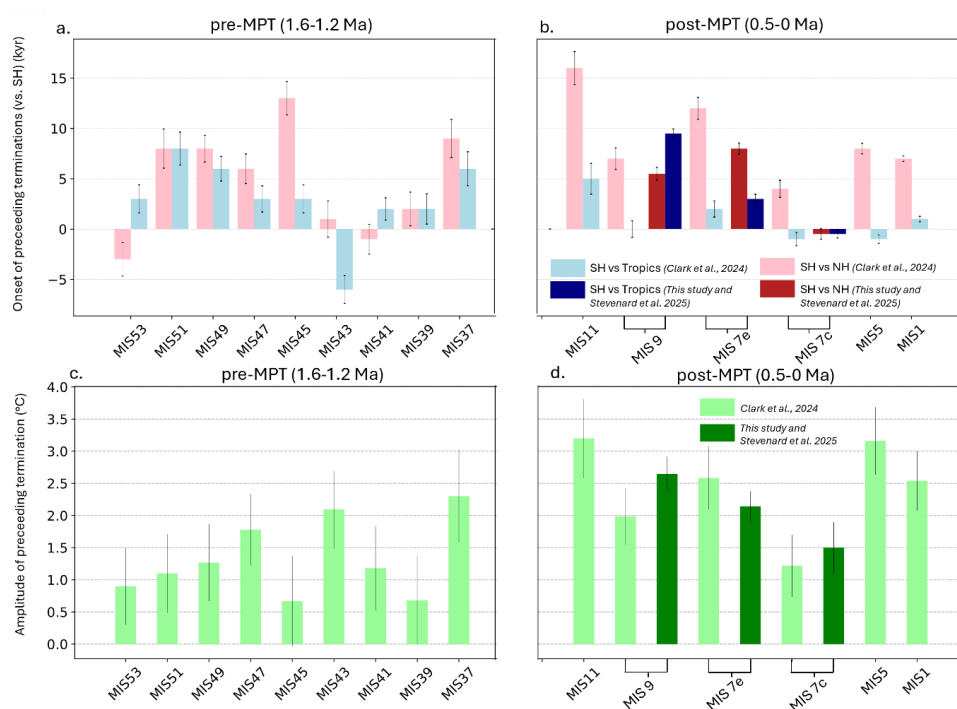
The interval from 1.6 to 1.2 million years ago is recognized as the most clearly defined 41-ka climate cycle period of the Pleistocene. During this time, obliquity paced glacial-interglacial cycles, and their phasing with respect to precession, appear crucial in shaping the intensity and duration of interglacials (Watanabe et al., 2023). These dynamics are particularly relevant when interpreting the nature of TIIIa, which precedes MIS 7c. In our ΔGSST stack, TIIIa shows an amplitude of  $1.5 \pm 0.2^\circ\text{C}$ , significantly lower than TIII ( $2.2 \pm 0.2^\circ\text{C}$ ), which led into MIS 7e (Fig. 9). This amplitude is comparable to that of terminations from the 1.6–1.2 Ma interval (average of  $1.3 \pm 0.5^\circ\text{C}$ ; Clark et al., 2024); Fig. 9c), further supporting the idea that TIIIa behaves more like an early Pleistocene obliquity-paced termination. Further evidence suggests that MIS 7c may not have involved full-depth ocean warming, despite its strong global surface warming. At a South Pacific site, high-resolution record of Mg/Ca-based bottom water temperatures suggests that MIS 11c, 7e, 5e, 1, and 9e were significantly warmer in the deep ocean than MIS 7c (Elderfield et al., 2012). This implies that MIS 7c warming would mostly be restricted to the ocean surface, consistent with a different dynamic origin, possibly amplified by reduced sea ice, lower albedo, and high obliquity-driven feedbacks. However, a global synthesis evidence warmer deep ocean temperature during MIS 7C, similar to what observed during Holocene (Clark et al., 2024). Regarding termination mechanisms, previous studies have evidenced a key role of Agulhas Leakage over these periods (e.g. (Caley et al., 2011; Nuber et al., 2023; Stevenard et al., 2025)). During glacial terminations, a southward shift of the Southern Hemisphere westerlies enhances the Agulhas Leakage, increasing the inflow of warm, salty Indian Ocean waters into the South Atlantic. This would strengthen the Atlantic Meridional Overturning Circulation (AMOC), promotes interhemispheric heat exchange, and triggers early Southern Hemisphere warming that may accelerate global deglaciation (Caley et al., 2011; Nuber et al., 2023). The role of Agulhas leakage appears minor during TIIIa, as the only SST record from the Agulhas corridor shows no significant warming during this interval, contrary to during TIII (core MD96-2077, Fig. S3). As MIS 7d is shorter in duration than other glacial periods, it is likely that the Indian Ocean is not isolated long enough (Nuber et al., 2023) to produce the necessary warming to accelerate the glacial termination. This mechanism could explain why the early South Atlantic warming during TIIIa is imperceptible compared to TIII.

Watanabe et al. (2023) conducted sensitivity experiments with artificially reduced obliquity amplitude (to 60% of modern values). Under this reduced obliquity scenario, their model produced 100-ka cycles over the early Pleistocene interval (1.6-1.2 Ma). In contrast, using the real full-amplitude obliquity produced the 41-ka pacing. These experiments demonstrate that the amplitude of obliquity alone can regulate the frequency of glacial cycles. Applying this framework to MIS 7, the exceptionally high obliquity peak synchronous with MIS 7c (Laskar et al., 2004; Past Interglacials Working Group of PAGES, 2016) may have temporarily shifted the climate system away from 100-ka eccentricity pacing and back into a 41-ka rhythm. This interpretation resonates with the self-sustained oscillation climate hypothesis (Mitsui et al., 2023). Simulations performed with an Earth system model of intermediate complexity evidences the existence of self-sustained climate oscillation at glacial-interglacial timescales, and develop the idea that the synchronization of such oscillation to orbital parameters may have driven major climate transition such as the MPT (Mitsui et al., 2023). Our results suggest that MIS 7c represents a



temporary re-synchronization of the self-sustained climate oscillation with the obliquity forcing as it was the case during the 41-ka world period, temporarily overriding the prevailing 100-ka periodicity of the late Pleistocene.

Before MIS 7, two other interglacials of the Late Pleistocene, MIS 15 and in a lesser extent MIS 13, also exhibited a double warm peak structure (Past Interglacials Working Group of PAGES, 2016). These sequences are considered as the onset of 100 ka cycle occurring after the Mid-Pleistocene Transition, as it was preceded by the first extreme glaciation (MIS 16) of the Late Pleistocene. However, a comprehensive synthesis of surface temperature data for MIS 15 and MIS 13 remains unavailable. Unlike MIS 7, MIS 15 and MIS 13 did not occur under exceptional orbital forcing (Fig. 7) and took place in between the Mid-Pleistocene Transition and the Mid-Brunhes Shift (Past Interglacials Working Group of PAGES, 2016). Over this period, climate cycles were still shifting from a 41 ka to a 100 ka periodicity, resulting in interglacials including both periods signatures, restricting a direct comparison with MIS 7.



**Fig. 9: MIS 7 in the context of the post- and pre-MPT interglacials.** Data are from Clark et al. (2024), excepted for MIS 7 (bold colors, this study) and MIS 9 (bold colors, Stevenard et al., 2025). a. Timing of the onset of the preceding glacial termination between Southern and Northern Hemispheres stacks (pink) and between Southern Hemisphere and Tropics stacks (light blue), for the pre-MPT period (1.6-1.2 Ma). A positive value indicates an early onset of glacial termination in the Southern Hemisphere compared to the other stack. No value corresponds to a synchronous glacial termination onset. b. Same as a. but for post-MPT interglacials. c. Temperature amplitude of the termination (green) based on GSST reconstruction d. Same as c. but for post-MPT interglacials. Errors bars correspond to  $1\sigma$  uncertainty.



Although MIS 7 appears to have been paced by mechanisms reminiscent of the 41-ka glacial cycles, the warming pattern of TIIIa questions this comparison. TIII, which precedes MIS 7e, exhibits the classic characteristics of a glacial termination: deglaciation begins in the Southern Hemisphere at ~254 ka, progresses to the Tropics by ~251 ka, and finally reaches the Northern Hemisphere at 246 ka (Fig. 4d). This hemispheric progression is characteristic of the bipolar seesaw mechanism, whereby Southern Hemisphere warming leads Northern Hemisphere deglaciation through oceanic heat redistribution (Stocker and Johnsen, 2003), and of the role of the Agulhas leakage (Caley et al., 2011; Nuber et al., 2023; Stevenard et al., 2025). Such phasing pattern has already been observed for late Pleistocene Termination (e.g. T1: Shakun et al. (2012); TIV: Stevenard et al., 2025). In the Clark et al. (2024) synthesis, all terminations of the past 500 ka registered an early warming in the Southern Hemisphere compared to the Northern Hemisphere (Fig. 9b). In contrast, our results regarding the TIIIa, which leads into MIS 7c, is marked by a near-synchronous SST rise across all latitudes, with no detectable phasing between hemispheres at the beginning of the warming (Fig. 9b). This globally uniform warming signal differs from late Pleistocene terminations and suggests other underlying dynamic, as the role of the Agulhas Leakage (Stevenard et al., 2025; Fig. 9b). However, the analysis of recently published SST hemispheric stacks over the whole Pleistocene (Clark et al., 2024) revealed that the warming sequence, with an early warming of the Southern Hemisphere, seems also a dominant feature of the 41 ka world. Some exceptions may occur during MIS 53 and MIS 41 (Fig. 9a), but chronologies uncertainties over this period are large and analyses relies on a few number of records (Clark et al., 2024).

The deviation of TIIIa from classical Pleistocene glacial terminations suggest that MIS 7 was not a return to pre-MPT dynamics, but rather a manifestation of 100-ka climate cyclicity operating under extreme obliquity conditions. As such, MIS 7 represents a hybrid interglacial, embedded within the post-MPT 100-ka framework, yet shaped by obliquity-driven forcing typical of the early Pleistocene.

## 5. Conclusions

This study presents the first comprehensive global-scale synthesis of SST focusing on TIII and MIS 7 including 132 high-resolution SST records aligned on a common chronological framework (i.e. the AICC2023 ice core chronology). Based on local, regional and global analyses of surface temperature variations, our results show that:

- Regional temperature stacks evidence a pronounced regional variability during MIS 7: across ocean basins, the structure can range from a well-defined pattern with three distinct temperature peaks corresponding to warm substages MIS 7e, 7c, and 7a (e.g., North Atlantic), to a more subdued signal characterized by low-amplitude of variations (e.g., Equatorial Pacific).
- Hemispheric temperature stacks revealed a heterogeneity in magnitude of the different warm and cold stages of MIS 7. While the Southern Hemisphere indicates an optimum during MIS 7e, the Northern Hemisphere and the Tropical areas reach their temperature maxima during MIS 7c.
- At the global scale, MIS 7c is the warmest period of the MIS 7 sequence. Global mean surface temperatures during both MIS 7e and MIS 7c remain below PI values ( $\Delta\text{GMST} = -1.4 \pm 0.3^\circ\text{C}$  and  $-1.0 \pm 0.3^\circ\text{C}$ , respectively).



- 645        - The global mean surface temperature reconstruction evidences a decoupling with atmospheric CO<sub>2</sub> concentrations: the warmest period, MIS 7c ( $\Delta T = +0.4$  °C compared to MIS 7e), is characterized by atmospheric CO<sub>2</sub> concentrations much lower than during MIS 7e ( $\Delta \text{CO}_2 = -30$  ppm).
- Qualitative investigation and correlation analyses performed between orbital forcing and temperature stacks suggest a major role of obliquity in shaping the temperature structure of MIS 7, with the minimum and maximum obliquity values of the Pleistocene reached during MIS 7.
- 650        - Our results reveal that, while TIII displays the classical structure of a glacial termination characterized by a hemispheric phasing consistent with the bipolar seesaw hypothesis, TIIIa is marked by a near-synchronous SST rise across all latitudes, suggesting a distinct underlying mechanism.

655        Based on these key results and comparative analyses, our study highlights the unique character of MIS 7, situated within the 100-ka world yet exhibiting features uncharacteristic of late Pleistocene interglacials. We propose that MIS 7 represents a brief and temporary re-synchronization of internal climate oscillations with the 41-ka obliquity cycle, driven by the unusually extreme obliquity values reached during this interval. Rather than being a strict analogue of the early Pleistocene 41-ka world, MIS 7 should be viewed as a hybrid interglacial, resulting from the occurrence of specific orbital context within the post-MPT world.

660        Beyond the characterization of MIS 7, this synthesis represents a unique accessible dataset that compiles SST records with up-to-date methods that have been aligned on a common chronology. This effort provides a benchmark to evaluate Earth System Model simulations that have been performed over this period. Data-model comparison would help disentangling the role of greenhouse gases variations, oceanic dynamics and orbital forcing in shaping the unique morphology of surface temperature changes over MIS 7.

#### Authors contribution

665        EL, EC and NS designed the research. NS collected the datasets building on a preliminary effort undertaken by EL. NS computed age models, SST calibrations and developed the method to infer the global and regional temperature stacks. NVR provides the yet unpublished  $\delta^{18}\text{O}_p$  dataset for the MD07-3077 core. EL performed the comparison and correlation analysis. EL led the writing of the manuscript with subsequent inputs from EC, NS, FP and NVR.

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#### Data availability



680 All references of data used in this synthesis are listed in Table S1. The revised age models, SST and tie-points will be published in Zenodo repository (insert doi once published). The code used for the stacking procedure is available at <https://doi.org/10.5281/zenodo.17209465> (Stevenard, 2025).

### Competing Interest

The authors declare that they have no conflict of interest.

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