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The intensity of interglacials during the last 800 kyr

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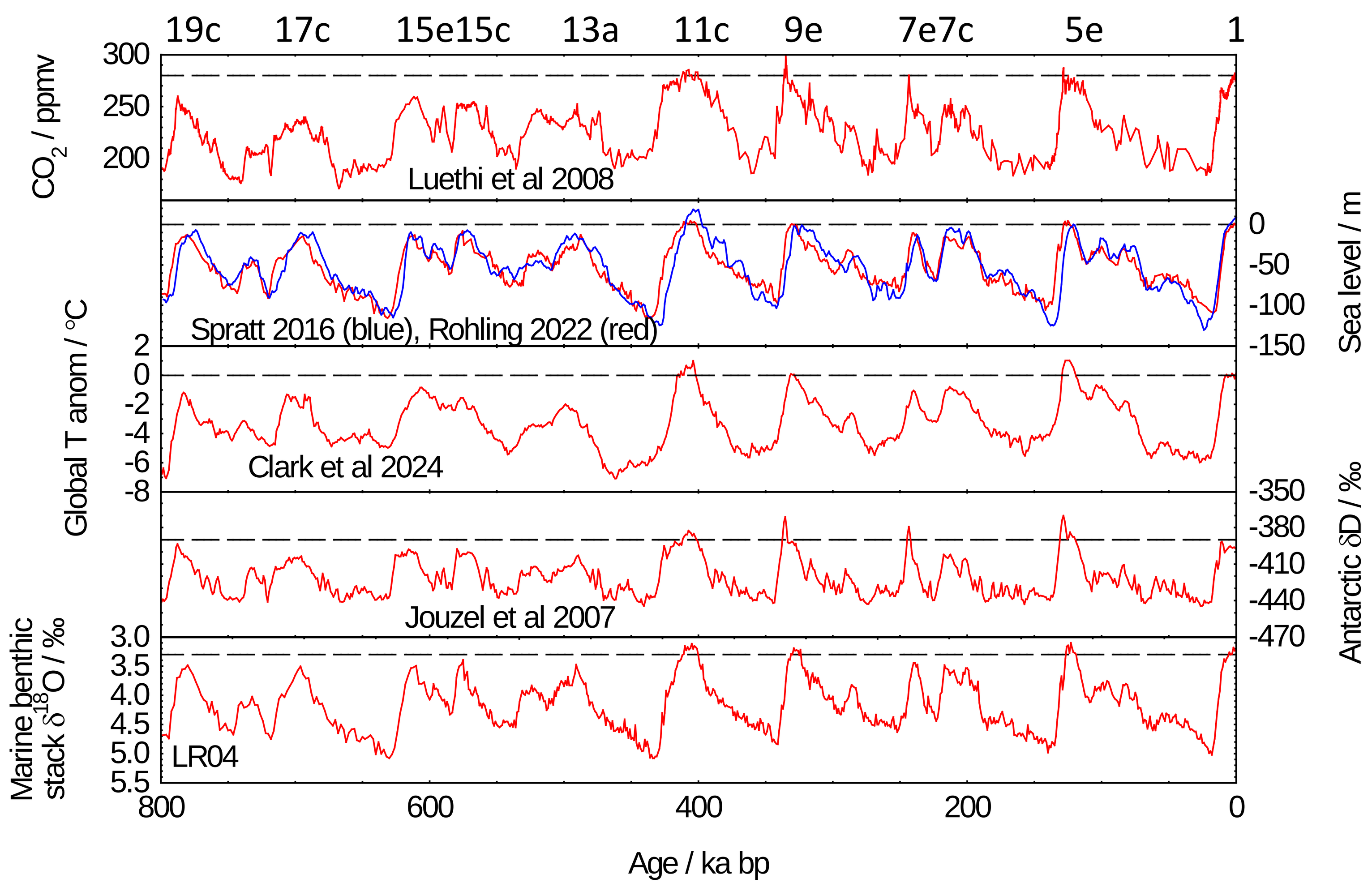
QUIGS

PAGES-PMIP WORKING GROUP ON QUATERNARY INTERGLACIALS

An ultimate target of Quaternary climate studies is to predict the strength and timing of glacial cycles using only the Milanković (astronomical) forcing as input. Here we consider just one aspect of this challenge, the intensity of interglacials. Previous work (PIGS Working Group, 2015) has identified 11 interglacials in the last 800 kyr. Are some of them globally strong or weak? Is there a step change at the mid-Brunhes (between MIS (Marine Isotope Stage) 13 and MIS 11)? And what controls the observed intensity? This poster presents ideas discussed at the last workshop of the PAGES-PMIP Working Group on Quaternary Interglacials (QUIGS, September 2023).

1. What do we mean by intensity?

Some datasets (such as mean global temperature or sea level) have a global character and might be considered more robust indicators of interglacial strength, but are more difficult to estimate compared to simpler parameters such as CO_2 concentration and Antarctic temperature. Many records show "overshoots" during most interglacials, temporary maxima that are followed by longer plateaus of interglacial character. Here we present some of the most important records.

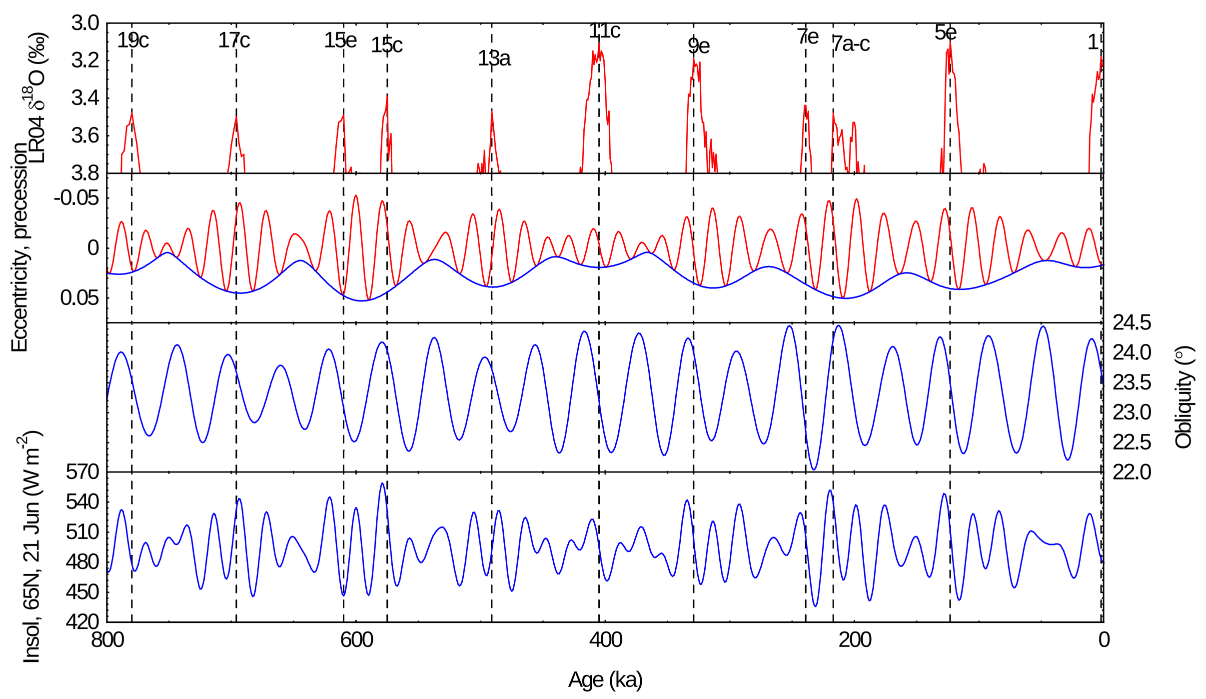


2. Some patterns do emerge *(Numbers refer to Marine Isotope Stages (MIS) as shown at top of figure):*

- In all the global scale records, 5e, 11, 9, 1 stand out as particularly warm, with 13 and 17 particularly cold
  - But note that in terrestrial records, especially from Asia, MIS 13 is a strong interglacial
- Tendency to more intense interglacials after 450 ka (Mid-Brunhes Shift, MBS), but this is not quite a general rule
  - 7e and especially 7c would sit happily in the pre-MBS population in terms of intensity
- 5e is easily the "warmest" in many individual sea surface temperature records (not shown), while 11 at least competes at global scale and in the measures of sea level

MIS	19c	17c	15e	15a	13a	11c	9e	7e	7c	5e	1
LR04	3.48	3.50	3.49	3.39	3.47	3.11	3.19	3.44	3.48	3.10	3.18
CO_2 (ppm)	259	237	259	254	247	286	291	275	257	278	280
CH_4 (ppb)	719	645	661	624	624	712	752	636	648	684	686
Dome C δD	-393	-403	-398	-397	-403	-382	-371	-379	-402	-370	-392
Global T (Clark)	-1.2	-1.3	-0.8	-1.6	-2.0	1.0	0.1	-1.1	-0.8	1.0	0.2
Sea level (Rohling)	-12.5	-14.8	-12.9	-7.8	-12.7	4.6	0.7	-10.3	-14.1	4.7	1.5
Sea level (Spratt)	-6.3	-9.9	-9.0	-6.7	-10.9	19.0	-1.8	-12.9	-3.7	0.4	9.0
1123 b Mg/Ca T	1.61	1.02	2.02	1.81	1.03	3.24	2.13	3.26	1.74	2.68	2.49

In this table, the relative "strength" of each interglacial is represented by colour, with red strongest and blue weakest



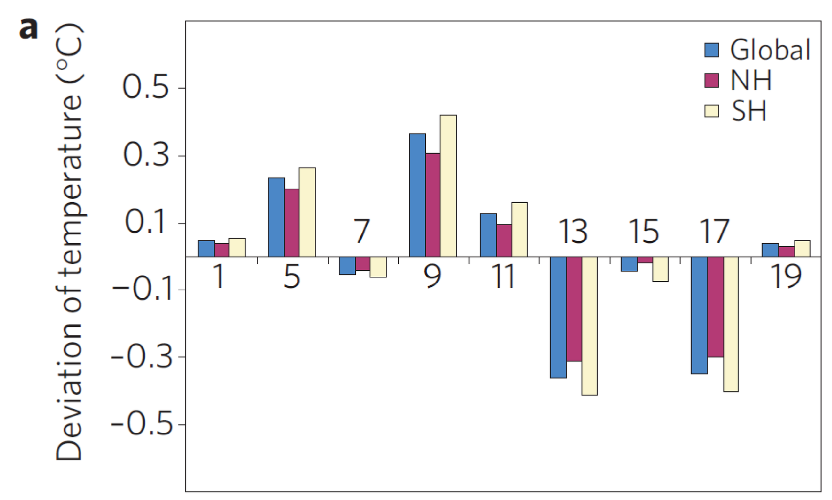
3. Why is this?

Looking at the astronomical context, it is not immediately obvious. We see the MIS 11 paradox, that weak insolation forcing leads to a strong interglacial (or the opposite, most clearly seen in MIS 15e and 7c)

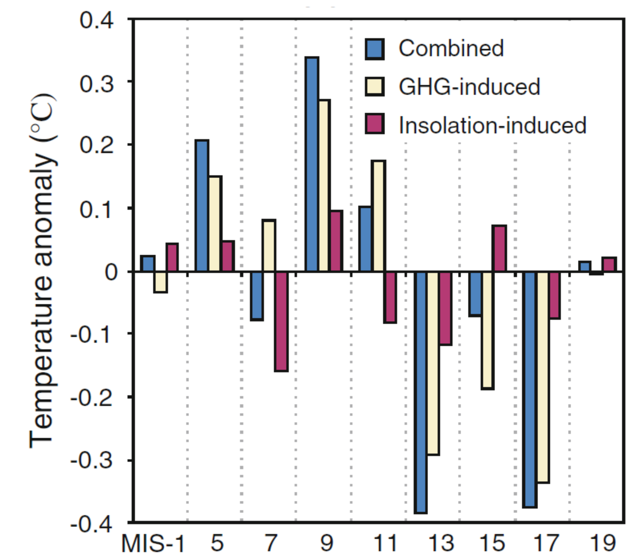
4. Two approaches have sought to explain interglacial amplitudes

Both fall short of the aim of using only Milanković forcing, but both are quite successful, and maybe point towards a more satisfying conclusion

- Yin and Berger (2010, 2012) used Milanković plus CO_2 concentration
- Mitsui et al (2022) used Milanković forcing plus the strength of the previous glacial

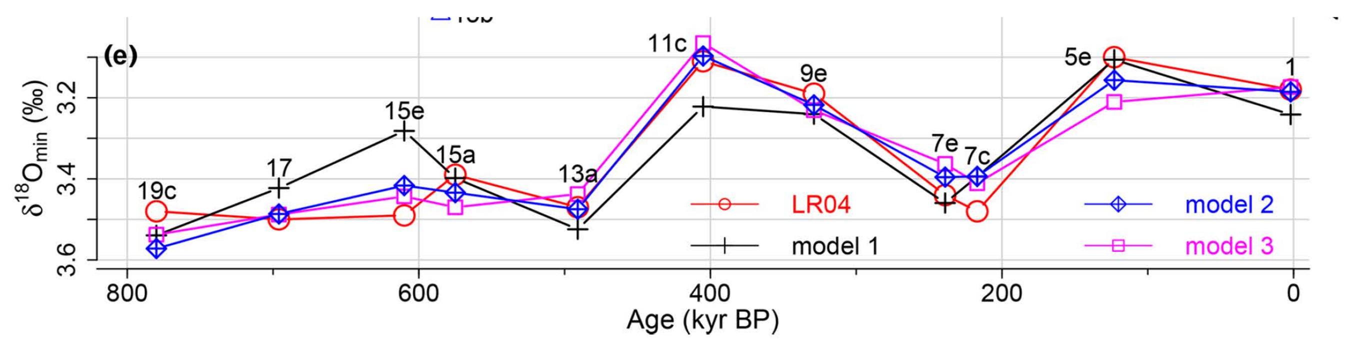


4a. Yin and Berger (2010, 2012) used insolation and CO_2 concentration in the LOVECLIM model to assess the climate for each interglacial (left). Achieving roughly the observed intensity of each interglacial, they used factor separation to isolate the influence of greenhouse gases and orbital change (right). They suggest that the main "reason" for strong interglacials post MBS is high interglacial CO_2, which obviously raises the question of what caused higher CO_2 in those later interglacials



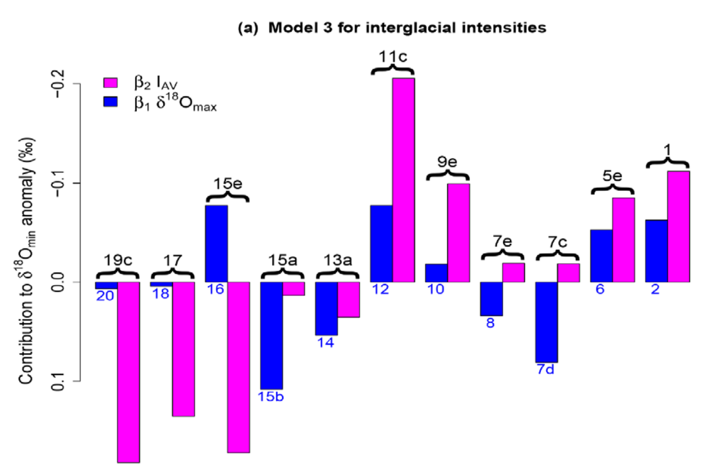
Yin (2013) suggested that pre-MBS interglacials had a stronger latitudinal insolation gradient, leading eventually to stronger formation of Antarctic bottom water (and by implication changes in CO_2). The inferred cause is a combination of orbital factors rather than a systematic change

4b. Mitsui et al (2022) used a statistical approach to describe interglacial intensity (using LR04) with the most parsimonious model they could find. They did not allow themselves to "know" CO_2 concentration, and ended up with a model that used caloric summer half-year insolation at high latitude in the northern (NH) and southern (SH) hemisphere integrated across the deglaciation, AND the strength of the preceding glacial.

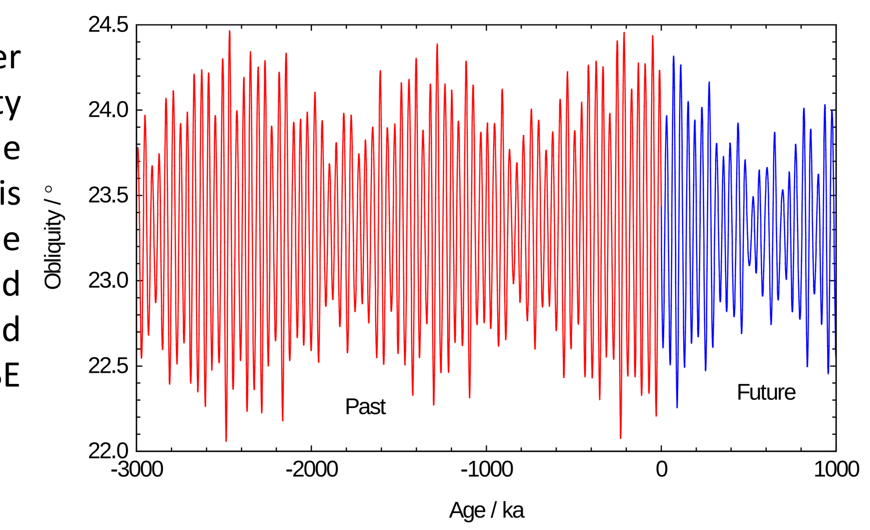


Model 2: $\delta^{18}O_{min} = \beta_0 + \beta_1 * \delta^{18}O_{max} + \beta_2 * I_N + \beta_3 * I_S$ where $\delta^{18}O_{min}$ is interglacial intensity, I_N and I_S are NH and SH caloric summer half-year insolation (integrated across the deglaciation) and $\delta^{18}O_{max}$ is intensity of the preceding glacial. In model 3, $\beta_2 = \beta_3$ and I_{AV} is $(I_N + I_S)/2$.

The excellent fit of Models 2 and 3 to the data (red) implies that interglacial strength depends on both NH AND SH insolation (the average in model 3 is proportional to obliquity) and that large ice sheets tend to lead to a stronger interglacial (large ice sheets are partly the result of long glacials)



This suggests that the tendency to stronger interglacials after the MBS is due to higher obliquity (purple bars left), a rule that is moderated by the intensity of the preceding glacial (blue). This tendency to higher values is part of the 1.2 Myr cycle of obliquity amplitude, suggesting that we could have expected weaker cycles ~1.8 Ma ago, and could have eventually expected to return to pre-MBE interglacials after another 400 kyr.



5. A unified theory?

Interglacial amplitude depends on: Insolation (in the round) and CO_2 concentration OR NH and SH insolation, plus glacial strength

Are these two solutions consistent if the higher post-MBS CO_2 is related to the orbital factors discussed by Yin (2013) boosted by longer/stronger periods of weak AMOC after strong glacials?

What else needs to be considered? (e.g phasing of precession and obliquity, carbonate dissolution, ….)

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