

Reviewer 2_Comments in black, Responses in Violet

Stoll et al. present an interesting multi-proxy comparison of upper ocean temperatures over the last 15 million years, combining new coccolith clumped isotope-based temperature estimates with published alkenone-based estimates from the same sites. The fact that both proxies are produced by the same organism, but otherwise based on very different principles, makes this comparison especially interesting because it rules out several possible reasons for discrepancies. Yet, the paper presents a huge difference in temperature estimates from the two proxies. Several lines of reasoning including comparison with other evidence suggest that the colder clumped isotope based estimates are more realistic (though possibly slightly cold biased), whereas the Uk'37 based estimates probably suffer from a substantial warm bias. This result has important implications for the interpretation of previous alkenone-based temperature estimates from high latitudes and thus for previous estimates of latitudinal temperature gradients.

The data and message presented here are very clear and I have only minor suggestions for further improvements.

Section 4.1.5 about a suggested warm bias of the Uk'37 data from Site 1088 could be made clearer. If I understand correctly, the bias is suggested to only be present at Site 1088, not 1090, because at the latter site a different index is used (Uk37). This interpretation could be made clearer in this section and it would help non-alkenone-experts like me if the difference between different alkenone indices was introduced earlier in the paper (e.g. before the data are presented in Figure 3).

I was also left wondering whether it would be possible to recalculate the respective other index out of raw alkenone data from either site.

Another question I have is whether the potential calibration bias due to calibration versus SST rather than production depth temperature (mentioned in section 4.1.1) is specific for either of the two indices or applies to both? It would also be good to know whether using different alkenone calibrations (e.g., culture-based) change the picture in any significant way? In the same vein, it could be added that on the clumped isotope side, any other calibration choice would make the D47 temperatures even colder.

We thank the reviewer for prompting us to clarify the different alkenone indices and their application here. We add the following at the end of section 2.2:

Alkenone temperatures for Site 1088 are calculated with the Uk'37 index based on the C37:2 and C37:3 alkenone abundances; no C37:4 abundances are reported for these samples. This record employed the calibration based on regression of sea surface temperatures to globally distributed core top Uk'37 (Müller et al., 1998). Alkenone temperatures for Site 1090 employ the Uk37 index which is based on the C37:2, C37:3, and C37:4 abundances. This latter index is proposed to be better suited for colder temperature settings (Ho et al., 2012) as long as contributions from non-marine haptophytes can be ruled out (Kaiser et al., 2019). The temperature calculation at Site 1090 employs a calibration based on cultures of a strain of *Gephyrocapsa (Emiliania) huxleyi*

(Prah1 et al., 1988) which is not significantly different from the calibration obtained from regressions between SST and Uk'37 in core top sediments (Sikes et al., 1991; Ho et al., 2012).

And the following lines at the end of section 4.1.5

The Uk37 core-top calibration applied at Site 1088 is similar to that for cultured *G. huxleyi* strain 55 of (Prah1 et al., 1988) but cultures of other strains in other environmental conditions reveals an array of SST-Uk37 intercepts and application of other culture relationships would yield even warmer temperature estimates (Conte et al., 1998; D'andrea et al., 2016).

Finally in the end of section 4.1.5, adding the phrase in bold below:

This comparison suggests that the calculated the Uk37' SSTs at Site 1088 may feature a significant warm bias in the calibration, leading to overestimated temperatures for the last 1 and 5 Ma, **whereas such a warm bias is not identified in the Site 1090 Uk37 SST record.**

Section 4.2: The comparison with the proxy difference at Sites 1171 and 594 seems to be better placed earlier as additional argument for warm bias in the Uk'37 estimates, rather than in this section about latitudinal gradients. That would allow this section to focus on the implication for reconstructed latitudinal gradients, introduced in the introduction as a major motivation for this work. The figure (Fig 6b) could instead be incorporated into Figure 3.

We appreciate the suggestion to move figure 6b to Figure 3. At the same time, its inclusion in section 4.2 provides an outlook that the discrepancy in estimating temperature gradients may not be limited only to Site 1088 in late Miocene time window but also apply to older and even warmer periods. Additionally, reviewer 1 suggests the inclusion of a larger set of proxies for SST which we propose to add to Figure 6. We thus propose to clarify that this part of section 4.2 addresses the question – is the alkenone warm bias seen in Site 1088 potentially characterizing other high latitude locations and time intervals?

Minor suggestions and typos

Line 22: «must» – maybe change to «should», if it could in principle be possible that calcification occurs at somewhat different water depth than alkenone synthesis.

We are aware of no evidence that calcification and alkenone synthesis occur at different water depths (as indicated in our response to and clarification of comment line 192 below). Given that coccolithophores do not undertake vertical migrations (like some planktonic foraminifera), we prefer to retain the original wording.

Line 45: Check TEX86 spelling - revised

Line 46: Check reference formatting revised

Line 51: Add a comma after “thermometry” revised

Line 92-93: Check reference formatting revised

Line 95: analyzed - revised

Line 101-102: Check sentence structure – this section has been rewritten in response to Reviewer 2's request to clarify the meaning, so should have clear sentence structure now

Line 111: Check reference formatting revised

Line 114: Is it correct that each sample replicate was corrected with the closest 12 standard measurements (ETH 1-3), i.e., less than a run worth of standards?

This is clarified with the following:

Each analytical run consists of 10 aliquots of ETH-3, 5 aliquots each of ETH-1 and ETH-2 organized in three blocks: one at the beginning, one in the middle and one at the end of the autosampler carousel, two aliquots of IAEA-C2 and not more than 3 aliquots each of unknown samples for a total of 22 aliquots. For each sample from Site 1088 a minimum of 14 replicates and for 1090 a minimum of 10 replicates distributed in 4 to 5 analytical runs was measured. For standardization, a moving window of 12 standards measured before and 12 standards measured after each sample (spanning two to three analytical runs) was used.

Line 116: What is meant by “batches”? – this is now replaced with the term “analytical runs”

Line 124: Give references for the alkenone records - revised

Line 141-142: How are the samples containing detrital carbonate treated for interpretation? Are they disregarded (as the crosses in Fig 2 suggest)?

In section 3.1 we now clarify:

Since the origin and burial history of the detrital carbonates cannot be readily constrained for this setting, and they cannot be effectively isolated from the coccoliths for analysis of their clumped temperature, it is not possible to predict if they appreciably impact the measured temperatures in the samples containing them. As a conservative approach, we do not make further interpretations from these samples.

Line 148: At ODP Site 1090,...revised

Line 191-192: Can it be ruled out that coccolith and alkenone production occur at different water depths? Is this statement linked to the second sentence of this section, possibly implying continuous production of both phases during the lifetime of the organisms? If so, that could be made clearer.

We have clarified the statement to confirm that both organic and inorganic phases are produced continuously during the lifetime of the organisms.

Line 193-195: Specify that the calcification temperature is known for the D47 calibration as it is based on cultures.

We agree to clarify by stating: *The calibration of Δ_{47} to temperature is made using calcification temperature based on experimentally grown cultures, and therefore reflects the temperature at which coccolithophorids grow and calcify in the photic zone, in this case during the bloom season.*

Line 196: Add space after “depth” - revised

Line 197: Add space after “temperatures” - revised

Line 199-202: relating the alkenone index to SST or even summer SST even though the signal is produced deeper in the water column or in a different season must assume that vertical or temporal differences are similar at all sites used in the calibration and where the calibration is applied, which seems problematic and could be made even more clear here. Even though the gradient is weak at Site 1088, it could be stronger in most core top locations from the calibration, which would still bias the signal too warm.

We emphasize this important point by adding: *This calibration approach assumes that vertical or temporal differences are similar at all sites used in the calibration and where the calibration is applied.*

Line 204-207: Is this only true/known for part of the record?.

We clarify,

Therefore, at this setting in modern oceanographic conditions, the distinct temperature calibration targets may explain up to 3°C difference

Line 216: Check reference formatting - revised

Line 216-217: Could there be other particles of similar size as the coccoliths that are produced at colder temperatures/at the seafloor?

We propose to add to the beginning of section 2.2 (which describes the composition of the size fraction) the clarification that:

This analysis verifies that there is no significant non-coccolith biogenic or abiogenic carbonate in this size fraction.

Line 217: Add “in our record” or “here” to make it clear that the results from this study are referred to. revised

Line 231: Add space after “biomineralization” revised

Line 266: Diagenetic processes? Instead of “cool ... signals” I suggest reformulating to “introduce a cold bias to...” (same for the next part of the sentence) revised

Line 268: Check formatting of Uk_{37} revised

Line 271: Add space after “index” revised

Line 288-289: Check sentence structure revised

Line 311: Check sentence structure revised

Line 314: Check sentence structure revised

Line 316: Check sentence structure. Here and subsequent sentences: Check use of U_{37}^k versus U_{37}^k . revised

Line 320: The reference to a potential salinity effect comes a bit out of the blue and makes the sentence convoluted. Rather split up the sentences and introduce this potential effect better. – Revised to:

While the significance of non-thermal effects on the C37:4 alkenone has been discussed, recent work documents that increased abundance of C37:4 in marine alkenone producers is not due to salinity sensitivity (Liao et al., 2023; Zhang et al., 2023) but because the cell's biochemical response to temperature involves adjustment of the entire suite of alkenones, not only the ratio of the di- to tri-unsaturated C37 methyl alkenones (Conte et al., 1998).

Line 326: Check sentence structure with double brackets - revised

Line 335-336: the scale of suggested warm bias would be better established in the previous section where the basis for this statement is discussed, and then repeated here. – now added in section 4.1.5 as well as in 4.1.6

Line 347: Check sentence structure – the alkenone index saturation is correctly described.

Line 350: If the U_{37}^k index is saturated at Site 926, the calculated gradient should be a minimum estimate - revised

Figure 2:

The figure caption could give some more detail on the different kinds of data shown in the figure to allow the reader a quicker overview. E.g., that the species listed here are dominating the respective size fractions (with reference to the supplement), that crossed out samples contain abundant detrital carbonate,... clarified

Caption for Fig 2: Panel b) is for Site 1090, not 1088. revised

Format axes titles consistently for all Figures (e.g. "Age (Ma)", "D47 temp. (°C)") revised

Figure 4: Figure caption: Check sentence for panel a). revised