Eocene temperature gradients

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To the Editor,

Sze Ling Ho and Thomas Laepple[1] argue that the TEX_{86}palaeothermometer should be calibrated to deep subsurface ocean temperature and that doing so resolves a discrepancy between data and climate model simulations for the early Eocene. Here we argue that their proposed calibration of TEX_{86} is incompatible with ecological evidence and inappropriate for the largely shallow-water Eocene data. In addition, early Eocene TEX_{86} data agree reasonably well with other proxy data, such that warm poles and a flat meridional temperature gradient are not unique to TEX_{86}.

The primary assumption behind Ho & Laepple's reinterpretation of Eocene TEX_{86} data is that the Thaumarchaeotal lipids (GDGTs) that comprise the proxy are derived from 0-1000m water depth. However, microbial, ecological, and oceanographic observations indicate the sedimentary TEX_{86} signal predominantly represents the shallow subsurface (ca. 50-300m). This is where maxima in intact polar GDGT and Thaumarchaeotal gene (16S rRNA and *amoA*) abundances occur[2,3], consistent with their ecological niche as ammonium oxidizers. Although Thaumarchaeota exist in deeper waters, their cell numbers decline sharply below about 300 m[3] and export to the sediment is less efficient[4]. Hence, sedimentary TEX_{86} values closely match those of the upper water column, indicating preservation of an upper ocean signal[4].

This evidence justifies several approaches to TEX_{86} calibration. Despite the Thaumarchaeotal niche in the shallow subsurface, TEX_{86} can be used as a sea-surface temperature (SST) proxy due to the high correlation between subsurface temperatures and SSTs[5]. This necessarily assumes surface and subsurface temperatures maintain similar variability through time. Although the assumption that surface and subsurface temperatures maintain similar variability through time can be violated, it is reasonable for inference of long-term mean SSTs. A similar assumption is made in $\delta^{18}O$ paleothermometry, which relies on foraminifera that reside throughout the upper mixed layer. Shallow subsurface (0-200 m) instead of surface calibrations for TEX_{86} are also appropriate and have been applied[5,6]. Laboratory mesocosm experiments independently confirm a TEX_{86}-temperature sensitivity similar to the surface and shallow subsurface calibrations (slope ~ 0.015 TEX_{86} units per ˚C)[7], supporting a shallow-water depth origin for sedimentary GDGTs.

Despite this observational evidence, Ho and Laepple compare the power spectra of paired alkenone $U^{K'}_{37}$ and TEX_{86} records, and use this result as the basis of their argument that TEX_{86} must integrate temperatures to at least 550 m and possibly as deep as 950 m.
The result is a calibration with a TEX_{86}-temperature sensitivity that is twice as large as that found in previous work (slope ~ 0.030), which is difficult to reconcile with the evidence discussed above. Their approach is flawed in several ways. First, their Fig. 2a demonstrates that all of the variance and explanatory power derives from shallow waters (0-300 m); extending the

calibration down to 1,000 m merely dilutes the regression with relatively invariant data. Second, they assume that $U^{K'}_{37}$ represents true SST variability, which is unjustified. An appropriate comparison between proxies requires formal modeling of uncertainties associated with both systems, including structural errors relevant to $U^{K'}_{37}$ such as non-linear temperature sensitivity, diagenetic alteration, and lateral advection[8]. Furthermore, even if $U^{K'}_{37}$ and TEX_{86} do show different variability in some places it does not follow that TEX_{86} is incorrectly calibrated; slight differences in seasonality and depth of production can and do impart variance differences between the proxies.

Using their deep-water calibration, Ho and Laepple revisit published Eocene TEX_{86} data and argue that they can resolve discrepancies between proxies and climate models. We identify two major fallacies in their approach: first, the majority of sites with early Eocene TEX_{86} data are shallow (water depths between 0 and 200m; Supplementary Table 1). Applying a calibration that predicts 0-550 to 0-950m average water temperature is inappropriate. By way of example, we apply the Ho and Laepple calibration to warm (T > 15˚C), shallow (0-200m) sites in the modern surface sediment dataset (see Supplementary Information), which have TEX_{86} indices analogous to the Eocene values. Their calibration underestimates depth-averaged temperatures by 7.5˚C in the modern ocean (Fig. 1a), and the underestimation trends with temperature, such that the warmest sites are under-predicted by a greater amount (~12˚C, Fig. 1a). Their calibration will therefore produce an artificially flat gradient between tropical and subtropical temperatures: both in the modern, and in the Eocene, oceans.

Second, TEX_{86}-inferred SSTs are not significantly different from those provided by other proxies (Fig. 1b). There is no evidence that TEX_{86}-based temperatures are too high – or produce a gradient that is too flat – relative to other proxies within uncertainties. Only foraminiferal $\delta^{18}O$ data from ODP Sites 690 and 738 indicate substantially lower temperatures (Fig. 1b); however, these data are probably biased by diagenetic alteration. In the Southwest Pacific, Mg/Ca and TEX_{86} both indicate remarkably high SSTs (~30˚C). These locations may not be representative of their latitudinal band globally; however, even if early Eocene polar temperatures were near 20˚C, as indicated by the Arctic site (Fig. 1b), these are difficult to reproduce with models (Fig. 1b)[9]. Such temperatures are not at all unlikely and are corroborated by independent evidence, such as the presence of palms, baobab and crocodiles at polar latitudes[10,11]. The equable climate problem – the lingering mismatch between proxy data and model simulations – cannot be put to rest.

TEX_{86} data have played a critical role in constraining early Cenozoic temperatures. Indeed, although we disagree with their approach and conclusions, Ho and Laepple never question the fundamental utility of the proxy. This contrasts with the News & Views accompanying the article[12], which suggests that temperature is not the dominant control on TEX_{86}. This view discounts the large body of literature that demonstrates the validity and robustness of the paleothermometer, as well as the simple fact that ocean temperature explains over 70% of the variance in modern TEX_{86} data[5]. TEX_{86} has revolutionized our view of past warm climates, and we expect that it will continue to do so.

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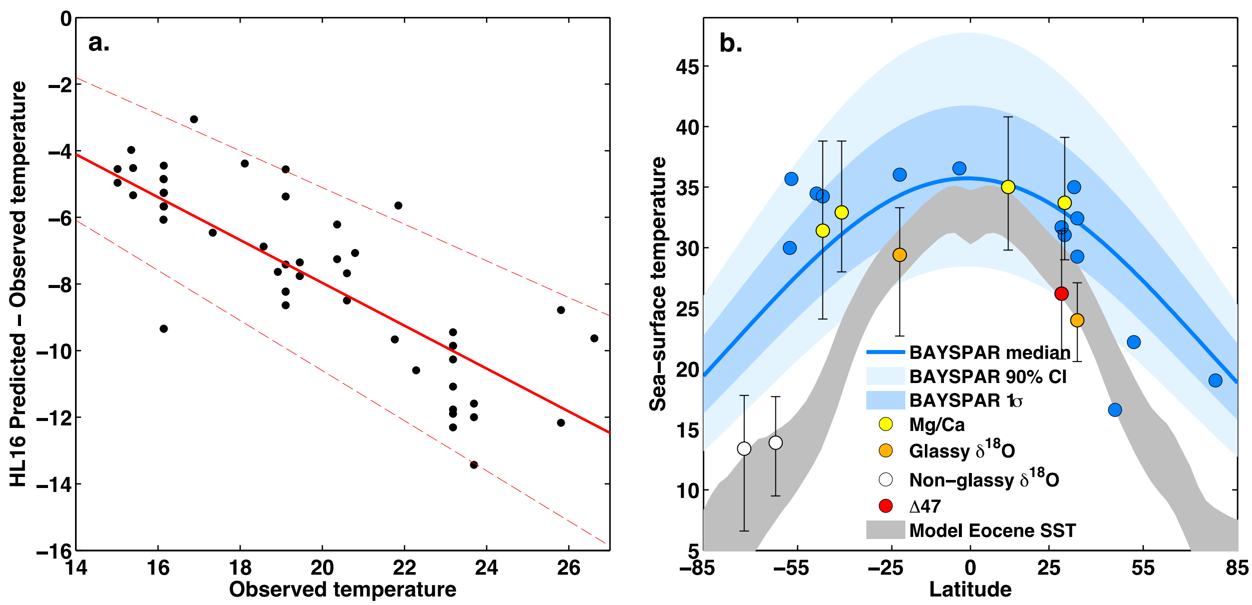

Figure 1. Bias in the calibration by Ho and Laepple[1] and Eocene temperature reconstructions. a. In warm (>15˚C), shallow (<200m) sites in the modern ocean, the Ho and Laepple calibration systematically underestimates depth-averaged temperatures (median values presented as points, linear regression as the red line, and maximum and minimum regressions based on the calibration ensemble as dashed red lines). **b.** Eocene SST predictions based on the BAYSPAR[5] calibration (blue dots, the median Gaussian fit is shown as a blue line with shading representing 1σ and the 90% CI) are comparable to other proxies (90% CI shown) and indicate higher temperatures at mid- to high-latitudes than an ensemble of simulations of early Eocene climate[9] (1σ range of SSTs shown as grey shading).