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Influences of the seasonal Indian monsoons, 1790-1993 CE: Sub-annual sea surface temperature and precipitation reconstructed from laminated Pakistan Margin sediments

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Sub-decadal to annual climate oscillations are particularly relevant to human climate perception, including such well-known phenomena as the seasonal monsoons and El Niño-Southern Oscillation (ENSO). To assess the variability of these oscillations in the past, proxies for climate parameters that are influenced by these oscillations (e.g., temperature, precipitation) and geologic materials with a temporal resolution able to record them are both needed. However, even in settings where these two criteria are met, the sample size needed for laboratory analysis can limit temporal resolution.

We utilize a novel mass spectrometry imaging technique to measure and map distributions of climate-relevant biomarkers (e.g., GDGTs, alkenones) from intact sediment core surfaces in sub-mm increments, unlocking the ability to reconstruct sub-annual paleoclimate. These same sediment sample surfaces are analyzed with micro-XRF mapping to enable congruent examination of complementary elemental- and biomarker-derived paleoenvironmental proxies at ultra-high spatial resolution, both down-core and along-lamination.

We applied our biomarker and elemental mapping techniques to annually-laminated Pakistan Margin (northeastern Arabian Sea) sediment core SO90-58KG, spanning 1790-1993 CE. Laminated Pakistan Margin marine sediments are excellent archives of past climate and oceanographic conditions that are influenced by the summer (Southwest) and winter (Northeast) monsoons of India. We measured alkenones and GDGTs at 200 μm resolution, and elemental abundances at 50 μm resolution. Reconstructed sea surface temperatures (SSTs) were calculated from alkenone ($U^{K_{37}}$) and GDGT (CCaT) ratios, respectively, with sample resolution up to four points per year. Principal component analysis was applied to the elemental measurements. The first principal component (PC1) is associated with siliciclastic elements (Al, Si, K, Ti, Fe), and is used as a proxy for sub-annual precipitation-driven river runoff.

Reconstructed SSTs for both biomarker proxies contain congruent trends, and align with the annual range of instrumental measurements (23 to 30 °C). The annual cycles in SST, with low temperatures driven by mixing during the winter monsoon, are prominent in the time series and

highly significant in their power spectra. Using this annual cycle in SST and our paired elemental measurements, we determine the season(s) of river runoff. PC1 is typically highest when SST is low, suggesting runoff/deposition usually occurs during the winter monsoon, consistent with precipitation from westerly storms. However, some years contain PC1 peaks that occur in-phase with warm SSTs, suggesting expansion of summer monsoon rainfall west of Karachi during these years. This work demonstrates the cutting edge of high-resolution paleoclimate science, and provides new insights into the variability of the Indian monsoon from its sensitive western edge.