Remote and local drivers of Pleistocene South Asian summer monsoon precipitation: A test for future predictions

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South Asian precipitation amount and extreme variability are predicted to increase due to thermodynamic effects of increased 21st-century greenhouse gases, accompanied by an increased supply of moisture from the southern hemisphere Indian Ocean. We reconstructed South Asian summer monsoon precipitation and runoff into the Bay of Bengal to assess the extent to which these factors also operated in the Pleistocene, a time of large-scale natural changes in carbon dioxide and ice volume. South Asian precipitation and runoff are strongly coherent with, and lag, atmospheric carbon dioxide changes at Earth’s orbital eccentricity, obliquity, and precession bands and are closely tied to cross-equatorial wind strength at the precession band. We find that the projected monsoon response to ongoing, rapid high-latitude ice melt and rising carbon dioxide levels is fully consistent with dynamics of the past 0.9 million years.

INTRODUCTION

The South Asian (including Indian) monsoon region is home to a fifth of the world’s population who rely heavily on seasonal precipitation for residential, agricultural, and industrial purposes (1, 2). Hence, a great deal of effort is spent assessing the future of monsoonal precipitation (3–5). Anthropogenic aerosols have weakened the dynamical monsoon circulation and associated precipitation in past decades (6). Nevertheless, models indicate that the thermodynamic impact of increased greenhouse gases (GHGs), as well as consequent increased atmospheric moisture content, will result in increased summer monsoon precipitation overall and extreme precipitation events (3–6). Hence, the moisture source regions and transport paths have become a focus of current research (7, 8). Mei et al. (8) analyzed 18 coupled model intercomparison project 5 (CMIP5) simulations to assess the dominant controls on increased 21st-century continental precipitation. The four current sources of Indian summer monsoon precipitation (land: 5° to 30°N, 70° to 90°E) include the southern (S) Indian Ocean, local recycling, the Arabian Sea, and the Bay of Bengal (BoB). Of the four, only the remote (S Indian Ocean) source was shown to increase throughout the 21st century. Analysis of 15 CMIP6 models support the CMIP5 results; increased GHG radiative forcing leads to increased southern hemisphere (SH) sea level pressure and enhanced cross-equatorial flow of moisture and energy into the South Asian system (4) via the southeast trades, which, upon crossing the equator, recurve into the southwest monsoon winds and Somali Jet.

We seek to test the extent to which changes in GHG and the SH moisture source are also evident in Pleistocene reconstructions of the South Asian summer monsoon. To this end, we analyze several new 1.5–million year (Ma)–long records, including biomarker and Mg/Ca-based sea surface temperature (SST), planktonic oxygen isotopes (δ18O), benthic δ18O, seawater δ18O (δ18Osw), leaf wax carbon isotopes (δ13Cwax), and scanning x-ray fluorescence (XRF) Rb and Rb/Ca from Site U1446 on the Indian continental margin, northwest (NW) BoB (Figs. 1A and 2). These variables provide critical constraints; they offer a multiproxy means of assessing precipitation and runoff from the Mahanadi and the Ganges-Brahmaputra-Meghna (GBM), the largest drainage basin in South Asia, using δ18Osw, Rb, and Rb/Ca, as well as India vegetation structure, using δ13Cwax. Moreover, these data allow us to assess potential differences relative to runoff reconstructed from the Andaman Sea, which monitors the Irrawaddy and Salween catchments of Southeast Asia. Our NW BoB multiproxy records are reconstructed from the same site, on the same age model, greatly facilitating insights into monsoon response and phase (timing) over the Pleistocene. This allows us to more confidently assess critical differences in the phase of the precipitation isotopic response relative to precipitation amount. We accomplish these goals by quantifying the phase of these records relative to one another, external (insolation) and internal [global ice volume (IV) and GHG] forcing at Earth’s orbital eccentricity, obliquity, and precession bands. We interpret these new results in the context of existing precipitation isotope reconstructions from speleothem δ18O (δ18Oprecip) and leaf wax hydrogen isotopes (δ2Hprecip) as well as model simulations characterizing the monsoon response to external insolation forcing. We find that summer monsoon precipitation and runoff lag the precipitation isotopic response and are sensitive to wind-driven SH moisture export as well as global IV and GHG forcing, demonstrating that reconstructed Pleistocene dynamics are fully consistent with predicted future dynamics.

Background and motivation

The classical view of monsoons as driven by land-ocean thermal gradients may be sufficient to explain seasonal wind reversals but is insufficient to explain monsoonal precipitation (9). Deep convective precipitation requires surface air masses with sufficient buoyancy
them equatorial transport was important in the past. On the basis of speleo
into ascending flow in the northern hemisphere (NH) and descend-
When this occurs, large-scale Hadley circulation is transformed
BoB and the South Asian continent [(9, 10) and references therein].
This is in contrast to reconstructions derived from other archives
that indicate significant sensitivity to internal forcings and SH climate
dynamics (13–16). These divergent interpretations lead to substan-
tial uncertainty about the extent to which the predicted drivers of
future changes in South Asian monsoon precipitation operated in
the past as well. Specifically, (i) the extent to which orbital-scale
variability in South Asian monsoon precipitation is driven primar-
ily by external insolation forcing or by internal feedbacks within the
climate system including global IV and GHG concentrations, and
(ii) the extent to which the South Asian monsoon precipitation is,
or is not, influenced by cross-equatorial moisture and energy trans-
port from the SH. Site U1446 was drilled in the core convective region
of the Indian summer monsoon to specifically address these questions;
here, we present new records and interpret them in the context of
extent, spatially distributed South Asian records. Resolution of the
divergent interpretations stems from our finding of clear proxy group-
ings; those recording changes in the isotopic composition of pre-
cipitation, primarily reflecting changes in moisture source area and
transport path dynamics, and those primarily recording more re-
gional precipitation amount and runoff from river drainage basins.

Site U1446 climatology and oceanography
The BoB, surrounded on three sides by land, is the world’s least sa-
line ocean basin, receiving ~2950 km³ of runoff annually (17). The
entire system is strongly seasonal (Fig. 1B) with 80 to 90% of precipi-
tation resulting from summer monsoon (June to September) precipi-
tation (18). Evaporation plays a minor role with precipitation plus runoff minus
evaporation [(P + R) − E] being positive throughout the year (19). Runoff is
dominated by GBM discharge peaking at ~1 × 10⁵ m³/s between
August and September (20), approximately a month after peak
precipitation over the surrounding landmass in July (21). Hence, pre-
cipitation and runoff are strongly coupled to salinity (Fig. 1, C and D).

Ensemble model data indicate that the S Indian Ocean con-
tributes the most summer season moisture to India, representing 46%,
followed by local recycling (30.4%), the Arabian Sea (19.6%), and the
BoB (4%) (8). Reanalysis data also indicate that the S Indian
Ocean contributes the most summer season moisture to India, rep-
resenting 55%, followed by local recycling (23%), the Arabian Sea
(15%), and the BoB (7%) (8). Mei et al. (8) point out that these results
are not in conflict with those describing the considerable influence of BoB
synoptic low-pressure systems and monsoon depressions as
contributing 40 to 50% of summer monsoon precipitation (22), dif-
ferentiating the ultimate SH source of the moisture from the sys-
tems delivering it to continental India. More recent investigations
indicate an even greater role of synoptic lows and depressions, ac-
counting for 60 to 80% of total precipitation in the core monsoon
zone (23) and up to 80% of total Indian precipitation (22, 24). BoB
precipitation begins between late April and mid-May, reaching
~10°N between mid-May and mid-June, with strong precipitation
over the northern (N) BoB and India from June to September [(10)
and references therein].

Site U1446 (19°5.01’ N, 85° 44.08’ E) is located in the Mahanadi
offshore basin at 1430 m below sea level on the Indian margin
(Fig. 1) (25). The site is on a NW-southeast trending ridge, shield-
ning it from turbidite deposition. The 204-m composite section, con-
structed from three offset holes, spans the past 1.46 Ma with an
average sedimentation rate of ~14 cm per thousand year (ka). Sedi-
mants are composed of dark gray to gray hemipelagic clay with nanno-
foils and foraminifers. The lithogenic component is derived from
the Mahanadi River (26) basin with over 90% of the annual sedi-
ment delivered during the summer monsoon (June to September) (27).
Fig. 2. U1446 proxy records and spectra. Nine hundred thousand years marks shifts in the mean, variance, or spectral nature of various proxies, occurring near the midpoint of the mid-Pleistocene transition (MPT) between ~1150 and 700 ka ago. Spectra are for the 0- to 900-ka ago interval only. Red spectrum is the same in all cases, denoting ETP, an averaged record of normalized eccentricity, obliquity (tilt; T), and precession (June 21 perihelion) spanning the past 900 ka ago. Benthic and planktic $\delta^{18}$O [% Vienna Pee Dee belemnite (VPDB)], $\delta^{18}$Osw (% standard mean ocean water), and $\delta^{13}$Cwax (% VPDB). $\delta^{18}$Osw is corrected for both temperature and sea level change (see Materials and Methods).
The site is strategically located 70-km offshore of the Mahanadi River Delta beneath the N limb of the seasonally reversing East India Coastal Current (EICC). The EICC flows northward before and during the summer monsoon, reversing direction after the summer monsoon and providing for transport of fresh water out of the BoB. Interannual salinity variability within the N BoB and the ~100-km-wide EICC is directly linked to runoff, having salinities up to 10 practical salinity units fresher than those offshore, with little impact from direct precipitation (21, 28). Within the N BoB, (north of 17°N), Ganges runoff alone yields close to 3 m/year of sea level equivalent (29). Regional ocean modeling indicates that the spatial and temporal variability in seasonal sea surface salinity, sea level anomalies, the organization and strength of the equatorward flowing EICC, and aspects of coastal Kelvin wave dynamics are not well replicated without including river runoff, highlighting the critical impact of runoff on BoB oceanography (20).

**Proxy records**

The U1446 time scale is derived by six radiocarbon ages on the upper 8 m of the section and by correlation of benthic δ18O to the
LR04 global benthic stack (Fig. 2) (30), yielding high coherence (≥0.91) and near-zero phase (≤1 ka) across all orbital bands (see Materials and Methods). On this age model, we present six new records including three that independently monitor aspects of summer monsoon precipitation and runoff from the largest drainage basin in S Asia.

NW BoB δ18Osw is reconstructed by removing the local SST and global δ18Osw signals from the planktonic *Globigerinoides ruber* δ18O (see Materials and Methods). BoB δ18Osw is linearly related to salinity (19, 31, 32), reflecting both direct precipitation and runoff from surrounding catchment basins (Fig. 1). The strong influence of runoff is evident from the steep zonal and meridional salinity gradients observed presently (21, 28) and in paleoreconstructions (33). For the N BoB, where most runoff enters, the impact of direct precipitation on interannual salinity variability is minimal, and runoff dominates (21, 28). The impact of potential changes in isotopic composition of runoff is small. Runoff volume at the mouth of the Ganges (−6‰) (34) would have to change by only 17% to alter EICC δ18O by 1‰, as is observed at the precession time scale. In contrast, the δ18O of runoff [currently 19% of EICC volume (35)] would have to change by 5.3‰ (−6 to −11.3‰) to alter the EICC δ18O by 1‰. This would require that runoff at the mouth approaches the isotopic composition (−11 to −16‰) of the headwaters above 2000-m elevation that are currently composed of ~44‰ glacial meltwater (36). Hence, the U1446 δ18Osw record is interpreted as salinity, dominated by continental precipitation and runoff from the extensive South Asian river catchments (GBM and Mahanadi) with smaller contributions from direct precipitation or changes in the isotopic composition of runoff. This interpretation is supported in the following sections by comparison with trace-element XRF and δ13Cwax reconstructions that are independent of changing isotopic composition of precipitation and runoff.

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**Fig. 4.** As in Fig. 3 with the addition of proxy vectors from sites other than U1446 (Fig. 1). Proxy responses interpreted as responding to winds (blue), precipitation/runoff (green), and precipitation isotopic composition (orange) follow color coding of insolation-only simulation results (text at 0° and 180°) and that in Figs. 1, 3, and 6. Black vectors denote phase of the first derivative of the IV record, reflecting sea level (SL) change. The modifier ‘−TC’ in panel D indicates measurement at the thermocline, as opposed to measurement within the mixed-layer.
Terminations (T) 1 to 10 are denoted by vertical dashed lines. The midpoints of subsequent precipitation/runoff transitions to interglacial values are denoted by vertical dashed red lines. Red and blue dots indicate IV maxima and precipitation/runoff minima. (B) Same as in (A) but focusing on the ±15 ka surrounding IV terminations, for which the midpoints have been set to zero, with negative values indicating younger time. Thin dashed lines are individual records that have been averaged to yield thick lines. Arrow indicates the average lag between midpoints of IV terminations and midpoints of the subsequent proxy transitions. (C) Same as in (B) but showing EA YRV speleothem δ18O for T1 to T7 (50).

XRF records (see Materials and Methods) are interpreted following Phillips et al. (37) from nearby site NGHP-01-19. Changes in Ca are dominated by changes in surface ocean biogenic CaCO3 production (37); Ca, CaCO3 percentage, and CaCO3 mass accumulation rate (MAR) increase during glacial relative to interglacial intervals. Phillips et al. (37) interpret increased CaCO3 MAR to reflect reduced surface ocean stratification; decreased fresh-water input during weak glacial-age monsoons leads to reduced stratification, increased nutrient access, and increased primary production. Lithogenic MAR and sedimentation rates increase during interglacials (high sea level), indicating that continental slope sedimentation is influenced more by monsoon precipitation and runoff than by shelf exposure and erosion during glacial sea level low stands. Rb is an element common in felsic rocks and varies as a function of fine-grained lithogenic input, increasing with increased runoff. As with lithogenic MAR, Rb increases during interglacial intervals, in opposition to Ca (fig. S1, a and c). Hence, the Rb/Ca ratio (Fig. 2) represents the contribution ratio of fine grained lithogenic input to marine biogenic carbonate and is interpreted as a proxy for runoff and runoff-induced stratification. Both Rb and Rb/Ca are independent of factors that potentially affect water isotope proxies such as changing moisture source areas and changing isotopic composition of precipitation and runoff. Rb/Ca and δ18Osw are coherent at the eccentricity and precession bands, whereas Rb and δ18Osw are coherent at the eccentricity, obliquity, and precession bands (table S1), further supporting the interpretation as runoff and runoff-induced stratification proxies.

δ13Cmax reflects the relative contribution of C3 (−37.1 ± 2‰) and C4 (−19.5 ± 1.8‰) plant endmembers (38). In general, the proportion of C3 and C4 vegetation is affected by air temperature, water availability, and CO2 concentration (39); C4 plants have a lower CO2 compensation point for carbon fixation relative to C3 plants (40). In this region, at glacial-interglacial time scales (eccentricity and obliquity), this proxy is strongly sensitive to SST and atmospheric CO2 as demonstrated by high coherence (table S1) and near-zero phase (see Discussion). At the precession band, water availability (including seasonality) plays a greater role, as demonstrated by coherence and phase relationships with δ18Osw, Rb, and Rb/Ca (see Discussion). Table S2 provides a summary of these and other proxies discussed in subsequent sections.
Interpretive paradigm: Spectral structure and phase

The study of Pleistocene orbital-scale climate change is unique. The signal-to-noise ratio is large, and the external forcing (insolation) is known \((41)\). In addition, the two critical internal drivers (GHG concentration and global IV) are well constrained in the paleo record on the basis of ice cores and benthic \(\delta^{18}O\) \((30, 42, 43)\). Hence, it is possible to derive the relative sensitivity of monsoon proxy records to these potential drivers by examining the spectral structure, coherence, and phase of time series reconstructions \((44)\).

From a modeling perspective, Erb et al. \((45)\) showed that first-order aspects of monsoons are reasonably well captured by linear reconstructions using idealized single-forcing simulations that include obliquity, precession, CO\(_2\), and ice sheets. Results indicate that precipitation over the Asian landmass increases with increased summer insolation, increased GHG concentrations, and decreased global IV; hereafter, we refer to the internal forcing related to the coupled IV minima and GHG maxima as IVGHG. Modeling of the South Asian monsoon \((46)\) on Pleistocene time scales indicates that SST is equally sensitive to IVGHG and insolation; continental temperatures are found to be 37% more sensitive to IVGHG than to insolation and continental precipitation are found to be 67% more sensitive to insolation than to IVGHG. Although these simulations included large portions of the Tibetan Plateau and, hence, may not be directly applicable to the more southerly regions discussed in this work, they nevertheless indicate that the South Asian system is strongly affected by both internal (IVGHG) and external (insolation) drivers. We test these sensitivities by reconstructing precipitation and runoff into the BoB, quantitatively assessing spectral coherence and phase relationships.

At orbital time scales, interpretation of proxy records derives from analysis of spectral structure, as well as coherence and phase relationships. Spectral structure involves the relative concentrations of variance within the three primary orbital bands including eccentricity \((124-95\text{-}ka\) periods\), obliquity (also referred to as tilt; \(41\text{-}ka\) period\), and precession \((23-19\text{-}ka\) periods\) \((41)\); note that the 124- and 95-ka eccentricity bands are most often referred to as the \(\sim 100\text{-}ka\) band, as will be the case here. Coherence and phase are measures of the linear correlation and timing between time series at each frequency band. For example, climate proxies that have similar relative amounts of variance in the eccentricity, obliquity, and precession bands as is found in global IV (and are in phase with or slightly lag IV) are interpreted as being strongly influenced by changes in high-latitude IV. Global IV, in turn, is known to be strongly coupled with changes in GHG; the records are coherent at all three orbital bands, with IV minima occurring slightly after maxima in GHG (table S1). In contrast, records that are dominated by variance in the precession band and are in phase with or slightly lag precession maxima \((P_{\text{max}})\) (warm SH summers) or minima \((\text{warm NH summers})\) are interpreted as being forced dominantly by external insolation, based on the fact that precession-band variance dominates the summer insolation spectrum at all latitudes up to \(\sim 65^\circ\) \((\text{fig. S2})\).

Coherence and phase relationships among monsoon records and potential internal and external drivers are quantitatively established by conventional time series analytical techniques \((\text{see Materials and Methods})\). The results of these analyses are summarized on phase wheels \((\text{fig. 3A})\), providing a useful means of assessing the underlying physics of the climate system; the timing of a proxy response relative to known external \((\text{i.e., insolation})\) and internal \((\text{e.g., IVGHG})\) forcing provides a measure of sensitivity to those climate drivers. For example, if a climate proxy responds dominantly and directly to NH summer insolation, then its vector would plot at or near \(0^\circ\) on the precession and obliquity phase wheels \((\text{fig. 3, C and D})\). Phase is easily converted to time; for example, an obliquity-band phase lag of 70° is equivalent to a 7.9-ka lag \((70^\circ/360^\circ \times 41\text{ ka} = 7.9\text{ ka})\). Significant leads or lags relative to external forcing maxima indicate the influence of other \((\text{e.g., internal})\) factors.

RESULTS

All NW BoB records exhibit the well-known shift in dominant periodicity from 41-ka cycles to 100-ka cycles across the mid-Pleistocene transition \((\text{MPT})\) at \(\sim 900\text{ ka ago}\) \((47)\), with the 100-ka variance dominant since then \((\text{fig. 2})\). The \(G.\ ruber\) planktonic \(\delta^{18}O\) record has a structure similar to the global benthic record but with 3.2 times the variance after \(\sim 900\text{ ka ago}\) and 5.9 times the variance before \(\sim 900\text{ ka ago}\), signifying a great deal of BoB surface water variability throughout \((\text{fig. S1a})\). The planktonic \(\delta^{18}O\) mean shifts by \(+0.25\%\) at \(\sim 900\text{ ka ago}\), mostly attributed to enrichment of the heavier isotopes during glacial intervals; interglacial values remain at \(\sim 3.5\%\) over the entire record. SST has a glacial-interglacial range of \(\sim 3^\circ\text{C}\), similar to that documented for the Andaman Sea, eastern \((E)\) BoB \((13)\). SST has no substantial change in the mean \(\sim 900\text{ ka ago}\). \(\delta^{18}O_{\text{sw}}\) has a range of \(\sim 2\%\), exhibiting a shift \((+0.19\%\)\) at \(\sim 900\text{ ka ago}\), slightly less than the \(+0.23\%\) shift in planktonic \(\delta^{18}O\). Neither \(Rb\) \((\text{fig. S1c})\) nor \(Rb/Ca\) \((\text{fig. 2})\) exhibit substantial mean shifts at \(\sim 900\text{ ka ago}\) although the amplitude of \(Rb/Ca\) increases. Further discussion, including cross spectral coherence and phase analyses, are restricted to the past 900 ka ago such that variance before the MPT is not included. This is because the records available for comparison to these data are all shorter and do not include pre-MPT variance.

The spectra of all precipitation and runoff proxies are dominated by 100-ka eccentricity band variance with lesser amounts of 41- and 23-ka variance, similar to that of \(CO_2\) and global IV (benthic \(\delta^{18}O\)) but very different from NH summer insolation, which is dominated by precession throughout the low and mid-latitudes, with increasing amounts of obliquity in the high latitudes \((\text{fig. S2})\). Coherence and phase results are reported in tables S1 and S3 and summarized in Fig. 3. The three runoff and precipitation \([\delta^{18}O_{\text{sw}}, XRF (Rb and Rb/Ca averaged), and \delta^{13}C_{\text{wax}}]\) form clusters at all three orbital bands, the cluster averages \((\pm 1\sigma, n = 3)\) lag eccentricity maxima by \(21^\circ \pm 28^\circ (6 \pm 8\text{ ka})\), tilt maxima \((T_{\text{max}})\) by \(97^\circ \pm 20^\circ (11 \pm 2\text{ ka})\), and precession minima \((P_{\text{min}})\) by \(132^\circ \pm 6^\circ (8 \pm 0.4\text{ ka})\). At all orbital bands, the SST and \(G.\ ruber\) \(\delta^{18}O\) records are in phase with or very slightly lag IVGHG, whereas, after removing the SST and global IV signal from the \(G.\ ruber\) \(\delta^{18}O\) record, the resultant \(\delta^{18}O_{\text{sw}}\) record significantly lags IVGHG but is in phase with \(\delta^{13}C_{\text{wax}}\), \(Rb\), and \(Rb/Ca\) at the precession band and in phase with \(Rb\) and \(Rb/Ca\) at the obliquity band.

DISCUSSION

Several orbital-scale multiproxy reconstructions exist for South Asia, monitoring aspects of wind strength, precipitation isotopic composition, and precipitation/runoff \((\text{table S2})\). These results are added to the phase wheels \((\text{fig. 4})\) and integrated into the following discussion.

Spectral structure

All NW BoB \((U1446)\) precipitation and runoff records \([\delta^{18}O_{\text{sw}}, Rb, Rb/Ca, and \delta^{13}C_{\text{wax}}]\) are dominated by variance at the eccentricity
with a precession cycle. Since the EA YRV record is almost exclusively dominated by precession-band variance, the rapid transition to interglacial values is part of the precession-band variance, although influenced by IV as well at terminations. The dynamics have been interpreted in the context of changing and varied moisture sources, trajectories, and transport over wide continental shelf areas (51); moisture sources include the Arabian Sea, BoB, South China Sea, and North Pacific with trajectories that cross the wide exposed (glacial) and submerged (interglacial) continental shelf regions of Indonesian and the East China Sea.

In contrast, the weakest South Asian precipitation/runoff (δ18Osw) occurs, on average, 8 ka after glacial maxima, and the midpoints of the ensuing rapid transitions toward interglacial values occur, on average, 6 ka after IV terminations (Fig. 5B). Moisture sources and trajectories for the South Asian system are less variable and more independent of shelf emergence and submergence (the Indian shelf is narrow). Hence, the delayed increase in South Asian precipitation/runoff relative to terminations is regional in nature, and the two subsystems are uncoupled in this context. We show in the next section that South Asian precipitation/runoff has a phase lag of 132° (8 ka) relative to Pmin. Hence, the average 6-ka lag in intensification following IV terminations is largely accounted for by processes responsible for the precession band phase lag as opposed to dynamics related to glacial terminations.

**Precession phase**

δ18Osw is constructed by removing the calcification temperature and global IV (benthic δ18O) signals from the G. ruber δ18O record (see Materials and Methods). The impact on phase is the same across all orbital bands; the “raw” G. ruber δ18O phase (dashed lines in Fig. 4, B to D) only slightly lags IVGHG and the terrestrial precipitation isotope records (δ18Oprecip and δ2Hprecip). Removal of the local SST and global δ18O signals (recorded in the same samples) causes the phase lag to increase significantly, falling in phase with δ13Cwax, Rb, and Rb/Ca at the precession band and in phase with Rb and Rb/Ca at the obliquity band. The finding that δ18Osw reconstructions from the NW and E BoB (13) are in phase with independent monsoon proxies not affected by the isotopic composition of precipitation and runoff supports their interpretation as salinity proxies driven by runoff. If meltwater were a dominant driver, then the phase would fall near the first derivative of the benthic δ18O signal (maximum ice melt, at ~7°); instead, both δ18Osw records fall within the cluster centered on −132°. If the δ13Cwax response were dominated by GHG, then it would be approximately in phase with or slightly lag GHG maxima (−7°), whereas if it were dominated by temperature, then it would likely have the opposite phase (~110°). Again, δ13Cwax falls within the cluster centered on −132°, consistent with the δ18Osw and Rb/Ca proxies.

Precession-band phases fall into two distinct clusters, delineating continental precipitation isotope proxies (orange vectors; δ2Hprecip and δ18Oprecip) that plot in quadrant 1 from all other South Asian summer monsoon proxies (blue and green vectors) that plot in quadrant 2 (Fig. 4C). The three continental precipitation isotope records cluster near IVGHG (~71° ± 9°), indicating strong sensitivity to these internal drivers (49). This phasing is consistent with previous interpretations of these records and with simulations indicating more distal sources, longer transport paths, and lighter precipitation δ18O during Pmin compared to Pmax (52), predominantly reflecting large-scale circulation versus more local to regional rainfall

Eccentricity phase: Termination dynamics

The direct impact of eccentricity on insolation is negligible (41); hence, phase is interpreted in the context of linkages to coupled IVGHG dynamics, which are responsible for the bulk of variance across Pleistocene climate. U1446 proxies plot near the top of quadrant 1 on the eccentricity phase wheel (Fig. 4B). The proxies linked to vegetation (δ13Cwax), terrestrial precipitation isotopic composition (δ2Hprecip), fine-grained lithogenic runoff (Rb), and stratification (Rb/Ca) have zero or small phase lags with respect to IVGHG, whereas the NW and E BoB δ18Osw (precipitation/runoff) proxies have larger lags. The difference is anticipated given that the IV signal has been quantitatively removed to derive the δ18Osw records. Overall, the precipitation isotope proxies (orange vectors) and the rainfall/runoff proxies (green vectors) are not well differentiated, indicating that precipitation isotopic minima and precipitation/runoff maxima both occur at or slightly after the coupled IVGHG forcing.

The paired nature of the U1446 data allows us to assess the dynamics of South Asian δ18Osw relative to IV terminations (benthic δ18O) within the same core (Fig. 5A) and, therefore, facilitate comparison with those demarcated on the basis of EA speleothem δ18Oprecip from the Yangtze River Valley (YRV) [see figure 1 in (50)]. The weakest EA monsoons (speleothem δ18Oprecip) occur, on average, 3 ka after glacial maxima, and the midpoint of the ensuing rapid transition toward interglacial values occurs rapidly thereafter, on average, ~1 ka after the midpoint of IV terminations (Fig. 5C). Cheng et al. (50) demonstrated that each IV termination is associated
amount. Similar source area and transport dynamics have been put forth to interpret East Asia YRV speleothem δ¹³C variability (53, 54). In contrast, NW and BoB proxies that reflect lithogenic runoff and surface-water stratification (Rb and Rb/Ca), seawater isotopic composition (δ¹⁸Osw), and Indian vegetation structure (δ¹³Cwet) all cluster in quadrant 2 (−132° ± 6°), between IVGHG and Pmax (Fig. 4C), indicating different sets of drivers relative to the precipitation isotope proxies. These precipitation/runoff proxies are also in phase with two stacked wind reconstructions generated from four records in the N Arabian Sea [(15, 55 and references therein] and five records in the western (W) Arabian Sea [(14 and references therein] (Fig. 1). These wind reconstructions reflect the strong influence of the low-level southwesterly (Somali) jet that drives Ekman-induced upwelling, strong biological productivity, denitrification in the intermediate waters beneath, and eolian transport of lithogenic materials from the surrounding desert to these Arabian Sea sites. Although there is negligible precipitation in these regions, modern dynamics suggest a close association between the onset of summer monsoon rains over India and the abrupt strengthening of the Somali Jet over the Arabian Sea (56).

We therefore interpret the clustering of these multiple independent proxies (at an average of −132°) as indicating that the large-scale winds in the N Arabian Sea, W Arabian Sea, and S BoB (16) are linked to SH extraction and cross-equatorial transport of moisture into the South Asian system driving increased precipitation and runoff, akin to modern precipitation dynamics (7, 8, 22–24, 57). The inferred linkage of winds and precipitation in the proxy records is consistent with the Jalihal et al. (58) finding linking changes in BoB wind strength to latent heat flux and precipitation in the EC (European Community)–Earth simulations.

The multiproxy phase response at −132°, between the timing of IVGHG (~−73°) and December 21 perihelion (~180°), is interpreted within the context of model results (58) as the timing of maximum total column energy (Qdiv) over the BoB, if the impact of IV and GHGs were included. Total column energy over the BoB is found to be dominated by latent heat flux, which, in turn, is driven by the changes in the wind-field. In this context, the multiproxy phase response at −132° is interpreted as the combined response to maximum surface sensible heating (IVGHG) and the maximum import of moisture (latent heat) from the SH Indian Ocean at December 21 perihelion (~180°), as follows. The seasonal cycle at December 21 perihelion (Pmax) is characterized by warm SH summers and cold SH winters. The warm SH summer results in increased energy storage across the SH Indian Ocean, preconditioning the system for enhanced latent heat export at the onset of the NH summer monsoon in May. Decreased insolation during the SH winter (June to August) results in cold, dry winds over warm ocean waters, maximizing the ocean-to-atmosphere transfer of latent heat available for cross-equatorial transport and release over South Asia during the summer monsoon (14, 15). This hypothesized mechanism is supported by model sensitivity experiments (59) and modern observations (7) and is similar in nature to those found in CMIP5 and CMIP6 models that project future monsoon intensification. The −132° phase precludes NH summer insolation as the direct driver of South Asian summer monsoon precipitation. This interpretation is in contrast to that based on Bttoo and XBL South Asian monsoon speleothem δ¹⁸O, as responding directly to NH summer insolation (NHXI) without significant phase lag (11, 12, 51) and no contribution of moisture from the SH (12).

Proxy spatial coverage is now sufficient to make site-specific proxy-model comparisons. Bosmans et al. (60) synthesized results of insolation-only model simulations (precession and obliquity) run on the EC-Earth, GFDL, CESM, and HadCM3 models (obliquity experiment only). Our results are interpreted in the context of these idealized model experiments, keeping in mind two important points. First, the ability of climate models to capture subgrid-scale dynamics deteriorates at coarser resolutions due to deficiencies in simulating land-surface feedbacks, water vapor and cloud feedback processes, and factors related to topography [(61) and references therein]. While various downscaling approaches and parameterizations have been proposed to compensate for these issues, they have been met with limited success; Indian precipitation biases remain (62), even within the core monsoon zone using the latest (CMIP6) multimodel analyses (63). Simulating synoptic-scale convective responses to large-scale forcing remains a fundamental challenge in climate models (64). Second, these idealized precession and obliquity experiments do not incorporate IV or GHG as boundary conditions, both of which significantly lag NH summer-insolation forcing at the obliquity and precession bands. Hence, it follows that simulations forced only with orbital-driven insolation changes will be deficient in eliciting longer-term lags in the climate system; idealized model responses (maximum winds, precipitation, etc.) are necessarily constrained to be in phase with orbital maxima or minima. Nevertheless, these idealized experiments are very useful in contextualizing the response to the external forcing alone, helping to evaluate both the model results and the observed proxy phases.

All three models (EC-Earth, GFDL, and CESM) show increased summer monsoon precipitation over N India at Pmin, particularly in the Himalayan forefront, an orographic effect common to all models (Fig. 6). GFDL has slightly increased precipitation at Pmax in the Indian core monsoon zone, while CESM shows slightly increased precipitation at Pmax in S peninsular India. Nevertheless, the overall insolation-only model result for continental areas under the influence of the South Asian summer monsoon is increased precipitation at Pmin (0° in Fig. 4C). In contrast, all three models indicate maximum precipitation over the BoB at Pmax, corresponding to 180° on the precession phase wheel. Hence, idealized simulations indicate a 180° phase difference between the precession-band timing of maximum summer monsoon precipitation over the ocean versus the nearby continents. Jalihal et al. (58, 65) discuss the mechanisms underlying these simulation results. They find that precipitation over land is more sensitive to radiation forcing (net top of atmosphere long wave and short wave), whereas surface latent heat flux (dominated by winds) and vertical stability are more important over the BoB, again, keeping in mind that IV and GHG forcing are not included in these idealized simulations.

NW BoB proxy indicators for runoff and stratification (Rb and Rb/Ca) and vegetation structure (δ¹³Cwet) have similar phasing as the δ¹⁸Osw salinity proxies. Hence, we conclude that maximum continental precipitation does not occur near Pmin (0°) but, rather, at ~−132°, closer to the idealized model result for the timing of maximum precipitation over the BoB at Pmax. This may point toward model deficiencies in accounting for the contribution of BoB synoptic low-pressure systems and monsoon depressions in driving continental precipitation, possibly due to insufficient model resolution, and deficiencies in tropospheric temperatures or SST biases [(62, 66) and references therein]. Acosta and Huber (66), for example, find that only high-resolution models (1/² or smaller spatial resolution)
capture the Indo-Gangetic low-level jet responsible for bringing moisture into India from the BoB. We suggest that high-resolution models run in transient mode, and incorporating known IVGHG boundary conditions would simulate less divergent timing of precipitation over land and ocean, converging on a phase near -132° at the precession band. We note that GFDL is most consistent with our proxy phase results, simulating a weak increase in precipitation over the India core monsoon zone and Indochina Peninsula at Pmax.

The proxy result of strengthened Arabian Sea and BoB summer monsoon winds at -132° (closer to Pmax than Pmin) is difficult to assess relative to idealized model results. All three models indicate strengthened 850 hPa winds at Pmin in the N Arabian Sea and Arabian Peninsula but in different locations and with transitions from stronger at Pmin to stronger at Pmax taking place in the vicinity of the proxy core sites (fig. S3 a, c, e). Hence, proxy-model wind comparisons are not definitively convergent or divergent in the N Arabian Sea region. However, all models do show strengthened winds at Pmax over the S Arabian Sea and BoB, consistent with the S BoB wind reconstruction (Fig. 4C) (16).

**Obliquity Phase**

The NW BoB proxies that reflect lithogenic runoff and surface-water stratification (Rb and Rb/Ca), seawater isotopic composition (δ¹⁸Osw), and Indian vegetation structure (δ¹³Cwax) at -97° ± 20° (Fig. 4D). For example, the NW BoB δ¹³Cwax record (in phase with the δ¹⁸Osw and Rb/Ca at the precession band) plots early, in quadrant 1; the high coherence with, and close proximity to, IVGHG indicates sensitivity to IVGHG at the eccentricity and obliquity (tilt) bands. The E BoB δ¹⁸Osw record from the Andaman Sea has a phase only slightly lagging obliquity minima (Tmin), significantly different from the NW BoB cluster. This may be accounted for by the impact of obliquity-band sea level changes in the Andaman, as hypothesized by Gebregiorgis et al. (13); it is in phase with the maximum rate of sea level fall and physical isolation of the Andaman Sea, which would reduce the export of runoff to the larger BoB and reduce Andaman salinity. In any case, the runoff/stratification proxy cluster (-97° ± 20°) significantly lags the S Arabian Sea (SA) precipitation isotope records, which plot at -52° ± 3°. The -97° phase indicates that strengthened Arabian Sea precipitation/stratification is not a direct response to NH summer insolation at the obliquity band; rather, it is directly driven by the strengthened summer intertropical insolation gradient (67). Our interpretation, in the context of simulations and other proxy records, follows.

Simulated precipitation responses to changes in obliquity are weaker and more variable than at the precession band. Obliquity maxima (Tmax) are characterized by increased precipitation over N India in all four models, again, an orographic effect held in common (Fig. 6). GFDL shows a weak tendency for increased precipitation in the Indian core monsoon zone and Indochina Peninsula at Tmin, while CESM and EC-Earth show increased precipitation in central and S peninsular India at Tmin, a pattern somewhat different from HadCM3 and GFDL.

The -97° proxy phase induced by NW BoB δ¹⁸Osw, Rb/Ca, and δ¹⁸O is more consistent with the timing of model precipitation over the BoB where all except HadCM3 show increased BoB precipitation at Tmin (Fig. 6). Increased BoB precipitation at Tmin is internally consistent, with all models showing BoB-wide Tmin responses characterized by increased evaporation (figure C.8 in (60)), increased SST (figure C.14 in (60)), and decreased sea level pressure (figures 6a, C.4a, C.5a, and C.6a in (60)).

Similar to our precession-band interpretation, we interpret the -97° Indian margin phase as direct BoB precipitation and continental runoff having similar obliquity-band timing. In the context of model results, we interpret the -97° phase as consistent with stronger simulated BoB precipitation at Tmin but taking place earlier in the tilt cycle due to the influence of IVGHG forcing. We hypothesize that maximum summer monsoon precipitation at -97° is sensitive to both (i) internal IVGHG radiative forcing at -65° (warm surface ocean and increased atmospheric water content) and (ii) external (obliquity) forcing toward increased BoB precipitation at Tmin, possibly associated with tropical summer insolation maxima at Tmin. Again, these results suggest that the increased BoB precipitation is propagated onto the continents via synoptic lows and depressions, as in the modern. As with precession, the GFDL model response is most consistent with the proxy phase response in terms of increased precipitation over land closer to Tmin than Tmax.

Unlike the precession-band results, BoB precipitation proxies are not in phase with wind-strength proxies in the N and W Arabian Sea (both of which are found in quadrant 1). Nevertheless, the Arabian Sea wind strength proxies are consistent with model results; all four models show increased N Arabian Sea wind strength at Tmax (fig. S3). We interpret this as indicating a decoupling of N Arabian Sea winds and moisture transport into India at the obliquity band, as has been observed during anomalous monsoon years on interannual time scales (68). NW BoB δ¹⁸Osw and Rb/Ca have the same phase as the S BoB wind proxy suggesting a link to BoB wind forcing (Fig. 4D). While weak, the model simulations also show increased S BoB winds at Tmin, consistent with the proxy phase.

**Summary**

Our results indicate that Pleistocene precipitation/runoff amount is decoupled from changes in the isotopic composition of that precipitation at orbital time scales, a result that is consistent with isotope-enabled model simulations. Seawater δ¹⁸O is uncoupled from terrestrial water isotope proxies (speleothem δ¹⁸Oprecip and leaf wax δ³Hprecip) at the obliquity and precession bands. At these bands, the consistent response of δ¹⁸Osw and non-isotopic indicators of terrestrial runoff and vegetation leads to the conclusion that these proxies primarily reflect changes in terrestrial precipitation and runoff, as opposed to changes in the isotopic composition of precipitation, driven primarily by source area and transport path variability now thought to dominate the timing of Asian terrestrial water-isotope proxies. Precipitation maxima occur well after NH summer insolation maxima at both orbital bands (-132° relative to Pmin and -97° relative to Tmax), precluding external insolation as the primary driver of changes in South Asian summer monsoon precipitation and runoff. Proxy-inferred precipitation maxima occur between the timing of coupled IVGHG forcing and the timing of model-inferred precipitation maxima over the BoB (at Tmin and Pmax); BoB precipitation maxima are, in turn, driven by increased total column energy, latent heat flux, and large-scale wind fields. Consistent timing with an array of proxies for wind strength in the Arabian Sea and BoB supports the strong link between precipitation and large-scale winds in cross-equatorial moisture transport. The dominance of 100-ka spectral power in precipitation/runoff proxies further supports sensitivity of South Asian summer monsoon precipitation to decreased IV and increased CO₂. These summer monsoon dynamics, evident in our Pleistocene multiproxy reconstructions, are fully consistent with CMIP5 and CMIP6 simulations linking future
increased monsoonal precipitation and moisture source area changes to increased GHG concentrations.

**MATERIALS AND METHODS**

**Stable planktonic isotopes**

U1446 was sampled at 30-cm resolution from 0 to 204 composite meters below sea floor (mbsf). Samples were freeze-dried, wet-sieved at 63 μm, and dried in an oven at 50°C. The >63-μm fraction was sieved into four size fractions: 63 to 150, 150 to 250, 250 to 355, and >355 μm. Approximately 8 ± 3 G. ruber individuals (white, sensu stricto) were picked from the 250- to 355-μm fraction for stable isotope analysis and, where sufficient numbers were present, 35 ± 10 individuals for Mg/Ca analysis. Samples were analyzed on an MAT252 isotope ratio mass spectrometer (IRMS) coupled to a Kiel III carbonate device. Samples were reacted by individual acid addition (99% H3PO4 at 70°C). A total of 811 standards [Brown Yule Marble (BYM) and Carrara] were analyzed. Repeated analyses of BYM (n = 43, 1σ) yield −2.25 ± 0.03 for δ13C and −6.46 ± 0.08 for δ18O. Repeated analyses of Carrara Marble (n = 64, 1σ) yield 2.05 ± 0.02 for δ13C and −1.88 ± 0.04 for δ18O. Replicate analysis of foraminifera samples (n = 83, 1σ) yields a median half range of 0.07 for δ18O and 0.11 for δ13C. All results were calibrated to National Institute of Standards and Technology (Gaithersburg, MD) carbonate isotope standard NBS19 and are reported as ‰ Vienna Pee Dee belemnite (VPDB).

**Stable benthic isotopes**

Individual *Uvigerina* spp. and *Cibicidoides wuellerstorfi* (depending on availability) were picked from the 250 to 355 μm and >355 μm (when necessary) fractions. Samples were analyzed on an MAT252 IRMS coupled to a Kiel III carbonate device, reacted by individual acid addition (99% H3PO4 at 70°C). A total of 1323 samples and 180 standards (BYM and Carrara) were analyzed. Repeated analyses of BYM (n = 72, 1σ) yield −2.24 ± 0.03 for δ13C and −6.40 ± 0.08 for δ18O. Repeated analyses of Carrara Marble (n = 108, 1σ) yield 2.06 ± 0.02 for δ13C and −1.85 ± 0.05 for δ18O. Replicate analysis of foraminifera samples (n = 42, 1σ) yields a median half range of 0.03 for δ18O and 0.05 for δ13C. Isotopic offsets between C. *wuellerstorfi* and *Uvigerina* spp. were accounted for by subtracting 0.61 and adding 0.77 to *Uvigerina* spp. values for δ18O and δ13C, respectively, based on median offsets of paired samples (n = 452). All results were calibrated to National Institute of Standards and Technology (Gaithersburg, MD) carbonate isotope standard NBS19 and are reported as ‰ VPDB.

**Chronology**

Age control is established by 53 tie points, including four accelerator mass spectrometry (AMS) radiocarbon dates between 1.7 and 6.1 m, the base of the Toba ash at 15.6 mbsf (74.5 ka ago), and 48 tie points correlating structure in the benthi δ18O record to the LR04 (30) global benthic stack using AnalySeries (Fig. 2) (69). For eccentricity, obliquity, and precession, coherence is 0.98, 0.99, and 0.91, respectively, with phase offsets of less than 1 ka (less than our average 2-ka sample resolution). For AMS, specimens of upper-ocean planktonic foraminiferal species primarily consisting of *G. ruber* (white variety), *Trilobatus sacculifer*, and *Globigerinoides conglobatus* species were picked for radiocarbon analysis, which was performed at the Woods Hole Oceanographic Institution National Ocean Sciences Accelerator Mass Spectrometry (WHOI NOSAMS) facility. Each radiocarbon date was individually calibrated into calendar years using the R code BACON (70) using the standard marine reservoir correction and the Marine13 curve (71).

**TEX86**

Lipids were extracted (in triplicate) from approximately 3 g of freeze-dried sediment using the Dionex Accelerated Solvent Extractor ASE-200 with dichloromethane-methanol (6/4). The extract was separated into neutral and acid fractions, followed by amino- propyl silica gel chromatography (72). The neutral fraction was separated into four fractions by column SiO2 chromatography: F1, 3 ml of hexane; F2, 3 ml of hexane-toluene (3:1); F3, 4 ml of toluene; F4, 3 ml of toluene-CH3OH (3:1). The F4 was analyzed using an Agilent 1260 high-performance liquid chromatography system coupled to 6130 quadrupole mass spectrometer following the method of Schouten et al. (73). The analysis was duplicated for all samples.

The tetraether index of 86 carbon atoms (TEX86) was calculated from the concentrations of glycerol dialkyl glycerol tetraethers (GDGT)-1, GDGT-2, GDGT-3, and a regiosomer of crenarchaeol using the following expressions (74, 75)

\[
\text{TEX86} = \frac{([\text{GDGT-2}]+[\text{GDGT-3}]+[\text{Crenarchaeol regiosomer}])}{([\text{GDGT-1}]+[\text{GDGT-2}]+[\text{GDGT-3}]+[\text{Crenarchaeol regiosomer}])}
\]

\[
\text{TEX86}^H = \log (\text{TEX86})
\]

Temperatures were calculated according to the following equations based on a global core top calibration (75)

\[
T = 68.4 \times \text{TEX86}^H + 38.6 \quad \text{(when } T > 15°C)\]

where \(T\) = temperature (in degrees Celsius); analytical accuracy was 0.45°C. Because the contribution of Archaea other than pelagic Thaumarchaeota modifies the TEX86 temperature signal (76), we excluded the data showing an anomalous methane index (>0.23 and <0.17).

**Leaf wax δ13C**

The acid fraction of extracted lipids was methylated with methanol-acetyl chloride (95:5) and purified with SiO2 column chromatography. The δ13C of the methylated n-fatty acid was analyzed using an Agilent 6890 series gas chromatograph combined with a Finnigan MAT Delta Plus mass spectrometer. The δ13C values of fatty acids (FA) were obtained from the measured values of fatty acid–methyl esters by correcting for methyl carbon (−34.1‰). The reproducibility of the measurement based on repeated analyses was better than ±0.1‰. The δ13CFA was calculated by averaging the δ13C of C26, C28, C30, and C32 n-fatty acids. Values are reported in ‰ relative to VPDB.

Compound-specific radiocarbon analysis of surface sediments from the Santa Monica Basin indicates that the Δ14C values of long-chain n-fatty acids are the same as those of phytoplankton biomarkers (77). By contrast, the Δ14C values of long-chain n-alkanes are more depleted than those of phytoplankton biomarkers. This indicates that n-fatty acids are better for monitoring paleovegetation changes than n-alkanes due to their smaller continental retention time.

In the BoB, French et al. (78) estimated the continental reservoir age based on the depth profile of the radiocarbon concentration in Bengal Fan sediments. A two-endmember model indicated that 79 to 83% of the long-chain n-fatty acids were stored in continental
reservoirs for an average of 1000 to 1200 calendar years (slow-cycling component), and the remainder was stored for an average of 15 years (fast-cycling component). However, the millennial-scale retention time of the slow-cycling component does not markedly delay the timing of multimillennial scale $\delta^{13}C_{\text{p}}$ events because it represents a broad distribution of $n$-fatty acids with different ages that tend to smear each other out (78).

**Mg/Ca**

A total of 539 Mg/Ca analyses from Site U1446 have been performed at three different laboratories. Here, we use the subset of the samples that have paired TEX$_{86}$ SST, allowing a direct comparison of $\delta^{18}O_{\text{sw}}$ generated from the two SST proxies. Of the 243 samples presented here, 25 samples from 0 to 7.5 m (−0 to 20 ka ago) were analyzed at Rutgers University (Rosenthal), 53 samples from 16.07 to 33.57 m [70 to 140 ka ago] were analyzed at the Open University, UK (Kerr and Anand), and 165 samples from three time intervals (18 to 70, 143 to 204, 215 to 390, and 415 to 673 ka ago) were analyzed at the United States Geological Survey (USGS) St. Petersburg (Richey). The 165 USGS States Geological Survey (USGS) samples were from splits of the Brown University samples and required no interpolation to match the depths (age) of the TEX$_{86}^{H}$ data. The 25 samples from Rutgers are from a high-resolution study to be published separately and required nominal interpolation to TEX$_{86}^{H}$ depths; offset from nearest sample is 0.08 ± 0.22 ka (1σ, n = 25). The 53 Open University samples also required minimal interpolation; offset from nearest sample is 0.58 ± 1.1 ka (1σ, n = 53).

Typical samples contained 6 to 50 G. ruber sensu stricto individuals (250- to 355-μm fraction). Samples analyzed at Rutgers and the Open University went through rigorous clay removal and a full-trace element cleaning (reductive + oxidative) method (79, 80). Samples analyzed at the USGS laboratory were subjected only to oxidative cleaning without the added reductive cleaning step. Samples were dissolved in diluted HNO$_3$ to achieve constant [Ca] concentration to minimize matrix effects. Samples were analyzed using an Agilent Technologies Triple-Quad inductively coupled plasma-mass spectrometer (ICP-MS) 8800 and Element XR Sector Field ICP-MS at the Open University and Rutgers, respectively. Element to Ca ratios were calculated using a calibration derived from matrix-matched synthetic standards with varying trace element concentrations (81). At USGS, samples were analyzed on a PerkinElmer 7300 DV inductively coupled optical emission spectrometer. Mg/Ca was corrected for instrumental drift using the internal gravimetric standard method devised by Schrag (82). Reproducibility of Mg/Ca measurements, as determined by repeated analysis of synthetic CaCO$_3$ standards, was better than 1.8% (1σ) in all three laboratories. Contaminant ratios (Al/Ca and Fe/Ca) were monitored, and samples with Al/Ca (>300 μmol/mol) and Fe/Ca (>10 μmol/mol) were discarded if their Mg/Ca ratios were significantly different from the samples next to them.

Following previous studies (79, 83, 84), Mg/Ca data obtained with the full cleaning method were corrected by +6%, to be consistent with samples undergone only oxidative cleaning including the calibration studies. No regional Mg/Ca calibration exists for the BoB. We estimated SST from the Mg/Ca data using the calibration of Tierney et al. (85) and the Paleo-Seawater Uncertainty Solver (PSU Solver) code of Thirumalai et al. (86) that accounts for both changes in temperature and salinity. This calibration uses all available culture data in a multivariate calibration that accounts for both salinity and temperature.
record in reconstructing δ¹⁸Osw. We further tested the temperature sensitivity by comparing δ¹⁸Osw that was reconstructed using the TEX8⁶¹¹ SST and the Shakun et al. (95) global SST stack (fig. S1f). The Shakun stack was sampled at U1446 resolution and adjusted constructed using TEX 86.

**Supplementary material for this article is available at http://advances.sciencemag.org/cgi/.

**T**ime series analysis

Cross-spectral analyses were performed with the Blackman–Tukey approach using AnalySeries software (69). All spectra used a Bartlett window and a 100% lag). The coherence of spectral peaks relative to orbital parameters and intercomparison proxies, are given in tables S1 and S3.

**Supplementary materials**

Additional material for this article is available at http://advances.sciencemag.org/cgi/.

**References and notes**


Acknowledgments: This research used samples provided by the International Ocean Discovery Program Expedition 353. Funding: S.C.C. and S.M.M. were supported by U.S. NSF OCE1634774. M.Y. was funded by JSPS grants JPMXS05R2900001 and 19H05595 and JAMSTEC Exp. 353 postcruise study. K.N.-K. and P.A. were supported by UK-IODP, Open University, and NERC (NE/L002493/1). K.T. was supported by the Technology and Research Initiative Fund, Arizona Board of Regents. Author contributions: S.C.C. conceptualized and designed the study. S.C.C. generated foraminifera $\delta^{18}$O data and age-depth model. M.Y. generated $\delta^{13}$CFA and TEX86$^H$ SST data. K.T. produced AMS dates and modern climatological analyses. L.G. generated XRF data. J.N.R., K.N.-K., Y.R., P.A., and K.T. generated Mg/Ca SST data. S.C.C. wrote the manuscript with reviews, edits, and significant intellectual contributions from all authors. The manuscript was improved by two anonymous reviewers and review by J. Rodysill of the U.S. Geological Survey. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. government. Competing interests: The authors declare that they have no competing interests. Data and materials availability: All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Data necessary to understand and evaluate the conclusions of this paper are archived at www.ncdc.noaa.gov/paleo-search/study/33213. Additional data related to this paper may be requested from the authors.

Submitted 4 January 2021
Accepted 21 April 2021
Published 4 June 2021
10.1126/sciadv.abg3848

Remote and local drivers of Pleistocene South Asian summer monsoon precipitation: A test for future predictions

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Sci Adv 7 (23), eabg3848.
DOI: 10.1126/sciadv.abg3848