Climate as a contributing factor in the demise of Angkor, Cambodia

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The "hydraulic city" of Angkor, the capitol of the Khmer Empire in Cambodia, experienced decades-long drought interspersed with intense monsoons in the fourteenth and fifteenth centuries that, in combination with other factors, contributed to its eventual demise. The climatic evidence comes from a seven-and-a-half century robust hydroclimate reconstruction from tropical southern Vietnamese tree rings. The Angkor droughts were of a duration and severity that would have impacted the sprawling city's water supply and agricultural productivity, while high-magnitude monsoon years damaged its water control infrastructure. Hydroclimate variability for this region is strongly and inversely correlated with tropical Pacific sea surface temperature, indicating that a warm Pacific and El Niño events induce drought at interannual and interdecadal time scales, and that low-frequency variations of tropical Pacific climate can exert significant influence over Southeast Asian climate and society.

collapse | dendrochronology | paleoclimate | El Niño–Southern Oscillation | Palmer Drought Severity Index

The demise of the vast urban complex of Greater Angkor (1), and the sprawling kingdom of which it was the capitol, has remained unresolved despite more than a century of research. The lack of textual records dating after the thirteenth century has created a historical lacuna and divergent, unresolved claims about the causes, rate, and timing of Angkor's decline and fall. Historians and archaeologists have, with a few notable exceptions (1, 2), only rarely considered the role played by environment and climate in the history of Angkor. However, several studies have now documented the role of regional climate variation in contributing to the eventual demise of other complex agrarian societies (3), including those in Mesoamerica (4, 5), the southwestern United States (6, 7), and Mesopotamia (8). In Cambodia, the Khmer kingdom at Angkor held sway over large regions of continental Southeast Asia from the ninth through the fourteenth centuries CE and was a society dependent on the annual monsoon flooding of Cambodia's lowlands to support a vast and complex agricultural system (9). As a consequence, Angkor would have been vulnerable to variability in the strength and intensity of the monsoon at time scales of years to decades, especially as other societal and political factors had already begun to weaken the kingdom.

The annual Asian summer monsoon rains have allowed complex Southeast Asian civilizations to flourish during the past several millennia. However, two recent tree-ring-based hydroclimate reconstructions from northwestern Thailand (10) and northern Vietnam (11) reveal that decades-long periods of weak Asian summer monsoons and drought occurred over the past 500 years [Mae Hong Son (MHS) and Mu Cang Chai (MCC), Fig. 1], notably in the mid-eighteenth century coinciding with a period when all of the major regional kingdoms are known to have collapsed (12–14). Both tree-ring records also correlate negatively with tropical Pacific sea surface temperature (SST) variability (10, 11), emphasizing the influence of the El Niño–Southern Oscillation (ENSO) warm phase (El Niño) on drought and cool-phase (La Niña) induced wetness over much of Southeast Asia. This relationship is evident in instrumental and paleoclimate data.

Results

Here we present a 979-year (1030–2008 CE) ring-width record from the rare cypress *Fokienia hodginsii* growing at two sites in the highlands of Vietnam's Bidoup Nui Ba National Park (BDNP, Fig. 1). From this record we produced a robust, well-validated, and absolutely dated 759-year (1250–2008 CE) reconstruction of early monsoon (March to May) Palmer Drought Severity Index (PDSI; Fig. 2*C*), which passes all of the rigorous calibration and verification tests used in dendroclimatology and explains nearly 35% of the variance in the original instrumental PDSI series (15) (see *SI Text*). Our record reveals a multidecadal scale period of weakened monsoon in the mid to late fourteenth century and a shorter though at times more severe drought in the early fifteenth century, during what is widely cited as the time of Angkor's eventual demise (9). In fact, of the 40 (5%) most negative PDSI values in our reconstructed record, 7 fall within the early 1400s drought, and the single driest year of the entire record is 1403 with a PDSI value of −7.20. Likewise, 6 of the 40 most negative years fall within the mid-1300s drought, which was the most sustained drought of the entire record. The fourteenth century droughts are referenced in the contemporary state chronicles of the Chao Phraya basin (16), and other records suggest that it may have extended as far away as Sri Lanka (16) and India (17), and perhaps northward into central China (18) (Figs. 1 and 3).

Our PDSI record reveals a strong, inverse correlation with instrumental SST fields (19) across the tropical Pacific (Fig. 4*A*), the same relationship observed for the instrumental PDSI data (Fig. 4*B*), and one that remains stable over the available period of record. This same relationship is observed for our two previous but shorter proxy drought reconstructions (10, 11), as well as from research linking the instrumental records of drought from the central highlands of Vietnam with tropical Pacific and Indian Ocean SST (20). Based on the strength of this relationship over the past 120 years (Fig. 4 and *SI Text*), SST variability in the tropical Pacific very likely contributed to the protracted droughts evident in our record. Our reconstruction also captures the extended 1878 and 1889 ENSO warm-phase events (21), the latter

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Data deposition: Tree Ring Data have been deposited at the International Tree Ring Data Bank (ITRDB) at http://www.ncdc.noaa.gov/paleo/treering.html.

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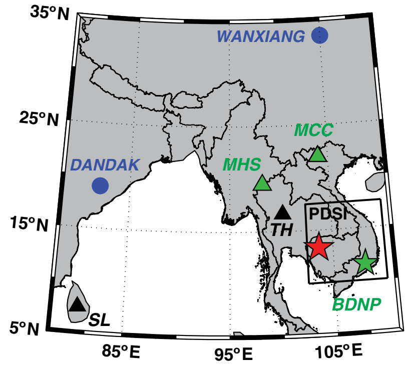

Fig. 1. Geographic context for the present study. The location of Angkor is marked by the red star in Cambodia. The map indicates the locations of the three tree-ring climate reconstructions discussed in the text with green symbols: MHS (10), MCC (11), and the BDNP *Fokienia hodginsii* site (this study, the green star in southern Vietnam) presented in this paper. Speleothem proxy records covering the fourteenth and fifteenth centuries are found at Dandak Cave in India (17) and Wanxiang Cave in China (18) as indicated by blue circles. Additional historical, documentary records of the fourteenth and fifteenth century droughts come from Phitsanulok in modern Thailand (TH) and Sri Lanka (SL) (14, 16), and whose locations are indicated by black triangles. The nine PDSI grid boxes that were used for paleoclimate reconstruction are shown by the box (15).

coinciding with one of the narrowest growth rings and the second driest year of the entire record with a PDSI value of −7.15. Both of these El Niños resulted in 4 of the top 10 most severe drought years of the past seven and a half centuries (1877–1878 and 1888–1889). Just as an El Niño (La Niña)-like warm (cool)-phase configuration over the tropical Pacific can lead to drought (wet) conditions over Indochina and India (22), the source of multidecadal scale drought in this region probably lies in multidecadal scale modes of variability in the Pacific ocean–atmosphere system. The BDNP record is inversely correlated with prior winter NINO3.4 (December to February) and the low-frequency Interdecadal Pacific Oscillation [November through February (22)]. Collectively, this demonstrates a causal link between drought and tropical SST variability that operates across multiple time scales relevant to human society.

Discussion

Climate and Societal Vulnerability at Angkor. Prolonged drought over mainland Southeast Asia, which corresponded to the time of the transition from the Medieval Climate Anomaly (MCA) into the Little Ice Age (LIA), appears to have coincided with numerous societal vulnerabilities and operational constraints to create a situation that led to the failure of Angkor as a viable city. For example, Angkor's water management system covered an area of nearly 1,000 km^2 and served to connect the main city with its extensive suburbs. By the end of the twelfth century it had become a vast and convoluted web of canals, embankments, and reservoirs. Infrastructure of this size (the West Baray, the largest of the rectilinear reservoirs, has an area of 16 km^2) and complexity is internally interdependent, resistant to change, and vulnerable to the risk of massive, unrecoverable damage. This would have limited the range of effective adaptive strategies (1, 23).

The physical remains of the water management system display terminal modifications and failures, such as blocked masonry-built water control features and large canals that became filled with sand (23, 24). The combinations of episodic water shortage and extreme flow likely led to cascading consequences for other, dependent parts of the network (2, 24, 25). Our PDSI reconstruction reveals that several abrupt reversals from drought to very intense monsoons occurred during this period of generally weak monsoon strength, such that 6 of the 20 wettest years occurred during the latest fourteenth and earliest fifteenth centuries (see *SI Text*). The result appears to have been serious flooding that damaged infrastructure at a time when agricultural productivity would have been suffering from the effects of drought.

For example, a canal that today partially carries the modern Siem Reap River and ran to the east of Angkor Thom and Angkor Wat southward to the supposed Angkorian "port" near Phnom Krom preserves a record of Angkor's collapsing water management infrastructure. The canal is now filled with approximately 1.40 m of cross-bedded, poorly sorted, coarse sand and gravel. The fact that these coarse river sands are extensively cross-bedded and lack any horizontal bedding structures, episodic reduction in mineral particle size, or other evidence of an ebbing flood, indicates the canal was filled very rapidly, possibly as a result of a single flood event. This section of the canal is preserved due to an avulsion upstream of the site, presumably related to the same flood event that entirely filled the canal. Underlying acutely this high-energy flood deposit is a thick unit composed of whole and partial *Dalbergia* sp. (Fabaceae) leaves and other macrofossils. Conventional radiocarbon dating of a subsample from this organic deposit, which provides a maximum age for the overlying flood sediment, places it in the fourteenth century AD (631 ± 69 ^{14}C years B.P.; 1270–1430 2σ calibrated years CE). The filling of this canal during the latter part of the fourteenth century must have had serious implications for Angkor, as it was one of the primary links between the capital district and Tonle Sap Lake.

Farther south near Phnom Krom, at the Thnal Puttrea site, a similar deposit also underlies the sand unit in the canal and has been dated to approximately the same period. Moreover, the abrupt supply of large volumes of sediment to canals in the south of Angkor logically necessitates intense erosion farther north in the catchment, suggesting this particular episode of destabilization was widespread through the water management network (23, 24). In the central and northern portions of Greater Angkor the channel of the former canal, now the Siem Reap River, is now cut 5 to 8 m below the former Angkorian land surface. Such erosive episodes would have destabilised Angkor's hydraulic network and reduced its capacity as an effective system for coping with an increasingly variable monsoon.

There is also evidence of water infrastructure modification in response to drought (24, 26), although without precise chronological control. Krol Romeas, the massive eastern exit channel of the East Baray, was partially blocked and then eventually completely closed by a cross-wall at its eastern end. Although no radiometric dates are available, the cross-wall masonry places it later than the thirteenth century. First the channel was reduced to about a third of its original 30 m width, and a narrow exit channel was taken off to the southeast. Then the original exit channel was completely blocked, and at a later stage the east end of the north wall was demolished and water was brought into the baray through the previous exit channel. The water that was brought in through the modified former exit was diverted from the former entry channel at the northeast corner of the baray and was brought through a new canal along the outer, eastern face of the east bank of the baray. The consequence was that intake was shifted from the northeast corner of the reservoir to halfway down its eastern bank. The inference is that the water managers in Angkor were seeking to cope with serious shortages of water to fill the baray.

Angkor and its kingdom were clearly exposed to numerous social, economic, and geopolitical pressures, particularly in the fourteenth and fifteenth centuries (9). Escalating conflict with the Siamese kingdom at Ayuddhaya has been previously cited as the proximal cause of Angkor's fall in 1431 CE (23, 27–29). Furthermore, the increasing importance of maritime trade (30) may have started to shift regional economic focus toward the

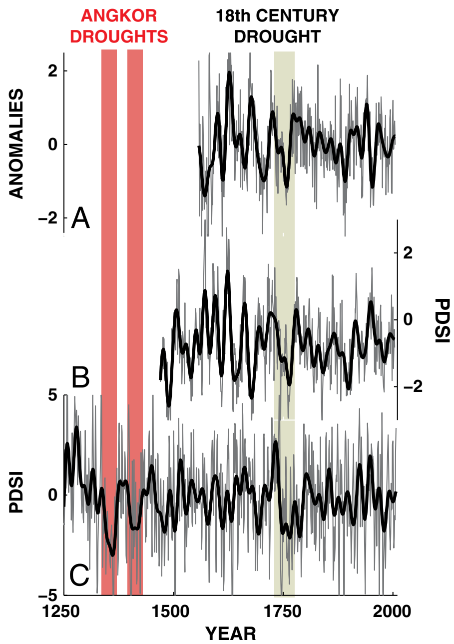

Fig. 2. Tree-ring reconstructed drought from Southeast Asia. (*A*) MHS-inferred PDSI normalized anomalies (10) from teak, (*B*) MCC reconstructed PDSI (11) from Po Mu (*Fokienia hodginsii*), and (*C*) the new BDNP reconstructed PDSI from Po Mu (*F. hodginsii*). The two Angkor Droughts in the late fourteenth and early fifteenth centuries are indicated by red vertical bars. A more recent drought in the middle of the eighteenth century is indicated in each reconstruction by the brown bar.

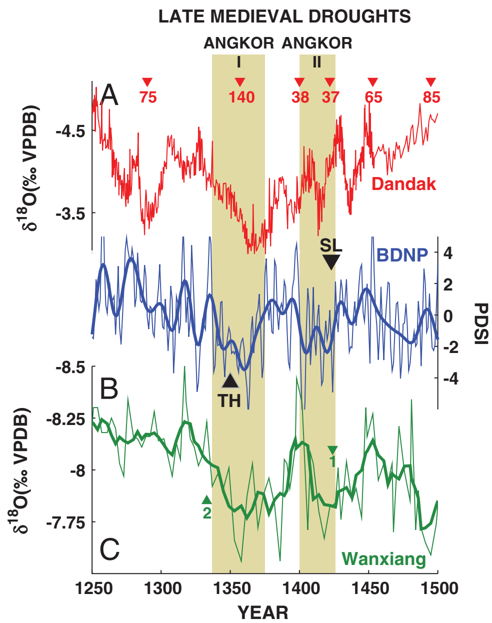

Fig. 3. Regional paleoclimate records of Medieval Drought in Southeast Asia. Dandak Cave δ^{18}O record (*A*) from the core monsoon region of India (17, 52), our Bidoup Nui Ba National Park (BDNP) PDSI reconstruction (*B*, with heavy line 15-year Butterworth filter from southern Vietnam), and the speleothem δ^{18}O record from Wanxiang Cave (*C*, heavy line, five-point boxcar filter) in China (18). Note that axes for both speleothem records are inverted such that drier conditions are down. U/Th dates for speleothems are shown by filled triangles of the same color with analytical error estimates (±years) shown by the accompanying number. The fourteenth and early fifteenth century Angkor droughts are indicated by the brown shaded bars. Historical records of the fourteenth and fifteenth century droughts come from Phitsanulok in modern Thailand (TH) and Sri Lanka (SL) (14, 16) and are indicated by black triangles.

Quatre Bras region on the Mekong River even before a new Khmer political center was established there in the fifteenth century (9). Interestingly, Vickery (28) and Chandler (31) note that Angkor turned away from inland agrarian activities and toward greater integration in regional trade in the late fourteenth century (*ca.* 1370 CE through the fifteenth century), immediately following the first Angkor Drought that we have now identified and dated. As Vickery (28) states, "The question that needs to be asked and answered is whether any known developments of the thirteenth to fifteenth centuries can account for the decline of an inland agricultural empire and the rapid rise of two of its former provincial centers located in favorable positions for maritime trade." It has also been suggested (31) that the move of the capitol to Phnom Penh may have been related to the preferences of a particular overlord and other members of a Cambodian urbanized "elite," who effectively abandoned the vastly agrarian population that remained at Angkor for a more trade-oriented capitol.

What our study demonstrates, however, is that decades of weakened summer monsoon rainfall, punctuated by abrupt and extreme wet episodes that likely brought severe flooding that damaged flood-control infrastructure, must now be considered an additional, important, and significant stressor occurring during a period of decline. Interrelated infrastructural, economic, and geopolitical stresses had made Angkor vulnerable to climate change and limited its capacity to adapt to changing circumstances. Much like the Classic Maya cities in Mesoamerica in the period of their ninth century "collapse" (32) and the implicated climate crisis (5), Angkor declined from a level of high complexity and regional hegemony after the droughts of the fourteenth and early fifteenth centuries. The temple of Angkor Wat itself, however, survived as a Buddhist monastery to the present day (33).

Regional Medieval Climate Variability. In addition to the influence of persistent warm ENSO-type anomalies, paleoclimate research (34, 35) suggests that the transition from the MCA into the LIA was marked by a southward shift of the Intertropical Convergence Zone (ITCZ) at approximately the same time as the Angkor droughts. Proxy paleolimnological evidence from the equatorial Pacific indicates that the ITCZ remained perhaps 5° south of its current mean position during the LIA, before returning northward sometime in the first half of the nineteenth century (35). In coupled climate model simulations, a southerly displaced ITCZ is associated with reduced precipitation over South and Southeast Asia (36) and El Niño-like warming of the southern tropical Pacific. Collectively, these mechanisms could explain the regional synchronization of drier conditions from southern China through Indochina and east-central India (Fig. 4) (17, 18).

Existing ENSO proxies spanning this period do not have the sample resolution nor age model precision to determine whether El Niño persisted during the Late Medieval megadroughts that coincided with the terminal decline of Angkor. Coral stable oxygen isotope records, with total radiometric dating uncertainties of 4 to 37 years, suggest several persistent ENSO events during the middle of the fourteenth century and warmer conditions again in the earliest part of the fifteenth century (37), bracketing colder La Niña conditions. Sediment proxy records from Ecuador (38) also suggest frequent El Niño events between 1345 and 1375 CE, and diatom and sediment data from the Galápagos Islands could reflect wetter conditions due to warmer eastern equatorial SSTs (39, 40) or a southward-displaced ITCZ (35). The existing, although still limited, proxy data are therefore consistent with

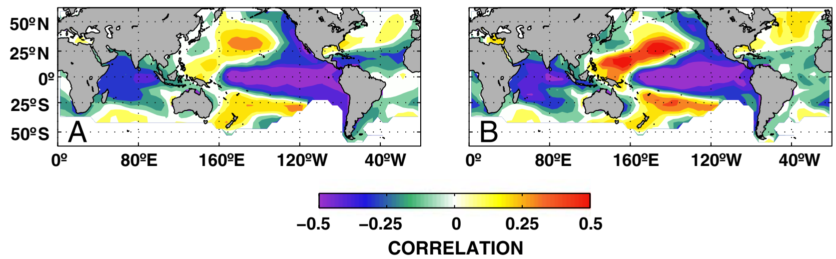

Fig. 4. Correlation maps between drought (15) and sea surface temperatures (19). Significant ($p < 0.001$) correlations are identified between (*A*) the BDNP PDSI reconstruction and tropical Pacific and Indian Ocean SSTs (1856–2006), with positive anomalies in the extratropical Pacific. The same pattern is identified for (*B*) the instrumental PDSI record [1915–2005 (15)].

a tropical Pacific influence on the Angkor droughts, although there are substantial uncertainties at interannual to decadal time scales due to proxy resolution, chronological control, and calibration.

There is no evidence from our reconstruction for a solar influence on broadscale drought or pluvials in Southeast Asia during the later MCA or the LIA. While mechanisms through which solar variability might affect tropical precipitation anomalies have been identified in model runs and from the limited instrumental climate records (41), we find no stable nor plausible temporal relationships between peaks in solar forcing and multidecadal hydroclimate variability in our proxy drought record, consistent with interpretations (17, 18) of other high-resolution monsoon proxy records from the last millennium (Fig. 3). Neither do volcanic eruptions appear to force multidecadal drought or pluvial conditions in our reconstruction, although we note with interest that the two wettest single years in our record correspond with large tropical eruptions in 1258 and 1453 (42, 43) (see *SI Text*). Although it remains possible that external radiative forcing plays an indirect role in generating anomalous multidecadal drought across Southeast Asia, it is not necessary to invoke such a mechanism, since such variability can indeed arise internally as part of coupled ocean–atmosphere dynamics (22).

Materials and Methods

We collected tree cores with standard increment borers, typically three or more cores per individual tree, and cross-dated them using graphical standard "skeleton plotting" methods (44), with rigorous quality control through visual and statistical cross-correlation methods (45). For chronology building we used methods aimed at eliminating any bias due to mean value calculation through traditional division-based methods (46) and maximizing low-frequency information (47). For detrending we used either a cubic smoothing spline with a 50% frequency response cutoff at 500 years, or alternatively the Friedman supersmoother with an α-parameter between 7 and 9 (48). After local variance stabilization using a power transformation based on the local spread and level for each core, residuals were taken from the detrending line. Overall variance due to changing sample size back in time was stabilized with a rigid 300-year smoothing spline (49). For climate reconstruction, regression of March through May mean PDSI on standardized annual radial growth increment was used for reconstruction of the time series, using current and following years' growth as predictors (50). Model selection was based on the minimum AIC criterion for a two-tailed test with significance set at the 95% level of confidence. The common, pooled autoregression present in the original PDSI averaged data were retained in the reconstructed values. Out-of-sample cross calibration–validation tests (51) (*SI Text*) were employed on both halves of the instrumental period to test the fidelity and stability of the reconstruction and to prevent any model overfitting.

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