Persistent summer expansion of the Atlantic Warm Pool during glacial abrupt cold events

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Palaeoclimate records and numerical model simulations indicate that changes in tropical and subtropical sea surface temperatures and in the annual average position of the intertropical convergence zone are linked to high-latitude climate changes on millennial to glacial–interglacial timescales[1–7]. It has recently been suggested that cooling in the high latitudes associated with abrupt climate-change events is evident primarily during the northern hemisphere winter, implying increased seasonality at these times[8]. However, it is unclear whether such a seasonal bias also exists for the low latitudes. Here we analyse the Mg/Ca ratios of surface-dwelling foraminifera to reconstruct sea surface temperatures in the northeastern Gulf of Mexico for the past 300,000 years. We suggest that sea surface temperatures are controlled by the migration of the northern boundary of the Atlantic Warm Pool, and hence the position of the intertropical convergence zone during boreal summer, and are relatively insensitive to winter conditions. Our results suggest that summer Atlantic Warm Pool expansion is primarily affected by glacial–interglacial variability and low-latitude summer insolation. Because a clear signature of rapid climate-change events, such as the Younger Dryas cold event, is lacking in our record, we conclude that high-latitude events seem to influence only the winter Caribbean climate conditions, consistent with the hypothesis of extreme northern-hemisphere seasonality during abrupt cooling events[8].

The Gulf of Mexico represents an ideal location to decipher the dynamic evolution of the Atlantic Warm Pool (AWP)[9,10]. During boreal winter, warm Caribbean surface water generally does not penetrate into the northeastern Gulf and tropical waters are restricted to a narrow band in the southeastern Gulf (Fig. 1). During this time, relatively cool Gulf of Mexico Common Water characterizes the uppermost 200 m owing to increased vertical convective mixing induced by cold meteorological fronts that propagate from the North American continent over the Gulf. In summer, when warm Caribbean surface waters enter the Gulf via the Loop Current, the entire Gulf heats up and forms part of the AWP. The described seasonal contrast is particularly strong in the northeastern Gulf region and results in an intra-annual sea-surface-temperature (SST) variability ranging from a minimum of 19.6 °C in February to a maximum of 29.7 °C in August[11]. This variability is closely related to the seasonal position of the intertropical convergence zone (ITCZ). Both the ITCZ and the northern boundary of the AWP reach their northernmost positions during boreal summer (Fig. 1).

Here, we present an SST record over the past 300,000 years from the northeastern Gulf of Mexico (Fig. 1, International Marine Past Global Change Study core MD02-2575), which, when compared with other Caribbean SST records, provides insights into seasonal tropical high-latitude climate connections on orbital and millennial timescales that are associated with latitudinal shifts of the ITCZ. The chronostratigraphy[10] of core MD02-2575 is based in the upper part on nine accelerator mass spectrometry ^{14}C dates, and in the lower part on tuning the benthic oxygen-isotope $\delta^{18}O$ (*Uvigerina peregrina*) record to the global oxygen-isotope stack LR04 (ref. 12) (Fig. 2a,b). Mg/Ca ratios of planktonic foraminiferal tests (*Globigerinoides ruber*, white variety) have been determined to estimate past SSTs (see the Supplementary Information). A remarkable feature of the record is the range of estimated temperatures, from 21.0 °C during the Last Glacial Maximum up to maximum interglacial values of 31 °C (Fig. 2). These glacial–interglacial temperature changes have been found to be large compared with the core region of the western AWP (refs 13,14), which shows a deglaciation-bound temperature increase of only 2.5 °C. The glacial–interglacial SST change in the northeastern Gulf is obviously amplified through local processes, in which the changing impact of the Loop Current on the northern boundary of the AWP may have played a key role[10]. SSTs during late Marine Isotope Stage 6 are unusually warm when compared with other full glacial periods; this feature has been explained by a diminished influence of the Mississippi outflow[10]. The influence of large meltwater events, as found during the last deglaciation in the western Gulf of Mexico[15], are of subordinate importance for northeastern surface water conditions, but are reflected in the benthic isotope record. These deglacial excursions in benthic records from the northern Gulf have been described previously and have been explained by entrainment of melt water in hyperpycnal flows[16].

Cross-spectral analysis[17,18] reveals that orbital-scale SST variations in the Gulf over the past 300,000 years are dominated by 23 kyr (climatic precession) and 100 kyr periods and to a lesser degree by the 41 kyr component of obliquity (Fig. 3). SSTs are in phase with benthic $\delta^{18}O$ (0.13 ± 0.18 kyr) in the precession

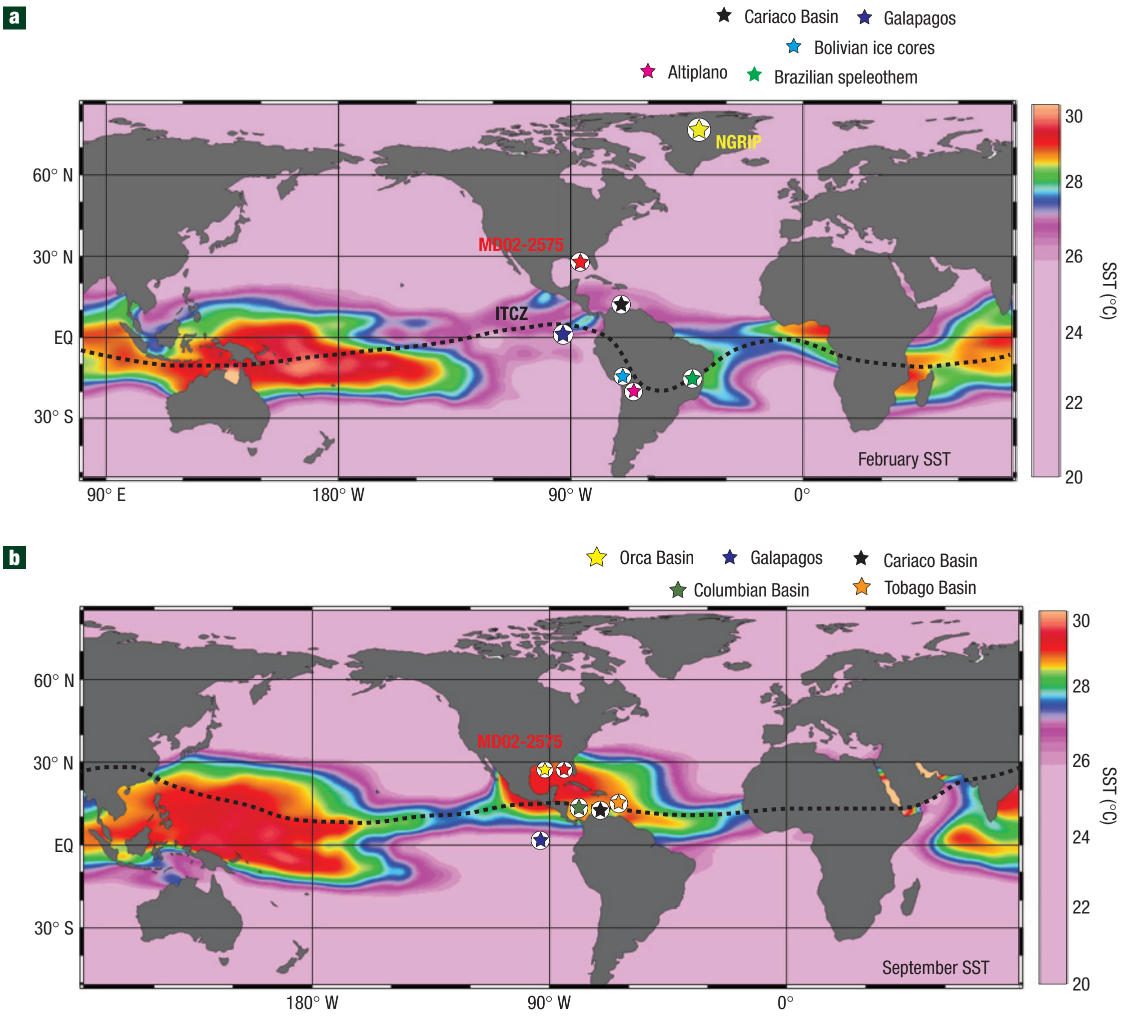

Figure 1 Global SSTs and positions of the ITCZ during February and September. a, MD02-2575 (red star) (29° 00.10′ N 87° 07.13′ W, 847 m water depth) in the northeastern Gulf of Mexico. Further stars represent δ^{18}O of the Greenland ice core (North Greenland Ice core Project (NGRIP), ref. 21), SST$_{\mathrm{Mg/Ca}}$ and elemental composition from Ocean Drilling Project (ODP) Site 1002 (refs 2,3) in the Cariaco Basin, SST$_{\mathrm{UK37}}$ of ME0005A-24 (ref. 7) near Galapagos, growth phases of Brazilian speleothem[4], wet phases on the Bolivian Altiplano[29] and δ^{18}O of Bolivian ice cores[28]. **b**, Stars indicate records of SST$_{\mathrm{UK37}}$ of M35003-4 (ref. 13) in the Tobago Basin, SST$_{\mathrm{UK37}}$ ODP Site 1002 (ref. 26) in the Cariaco Basin, SST$_{\mathrm{Mg/Ca}}$ of TR163-19 (ref. 19) near Galapagos, SST$_{\mathrm{Mg/Ca}}$ of ODP site 999 (ref. 14) in the Columbian Basin and SST$_{\mathrm{Mg/Ca}}$ of EN32-PC6 (ref. 15) in the Orca Basin.

band and lead by 4.94 ± 1.02 kyr at the 100 kyr period. For example, the last glacial termination shows a continuous SST increase from ~21.0 °C at the Last Glacial Maximum (21 kyr) to 27.5 °C during the early Holocene thermal maximum (9 kyr). The decrease of the benthic δ^{18}O, indicating the deglaciation of the northern hemisphere, starts substantially later, at approximately 17–18 kyr. This observation is in line with earlier studies showing that the increase in tropical temperatures leads changes in global ice volume at deglaciations[19,20]. We interpret the SST power spectrum and phase relationships to reflect a combined forcing related to glacial–interglacial changes in ice volume and local summer insolation variability. This is illustrated by the good fit between the SST record and the sum of the normalized summer insolation at 30° N and the normalized LR04 (ref. 12) stack (predominantly reflecting northern hemisphere glacial–interglacial ice volume variability) (Fig. 2). Accordingly, we link the very large SST increases over the deglaciations to a northward propagation of the AWP and summer ITCZ position, resulting from the combined effects of boreal summer insolation and the waning ice cover over North America. The Gulf's SST and the AWP are expected to be relatively insensitive to latitudinal paleo-shifts of the ITCZ during boreal winters, because the winter position of the ITCZ is too far south, especially during glacials, to allow for significant warming in the northeastern Gulf of Mexico. In contrast, more southern paleo-positions of the ITCZ during boreal summer (relative to its modern summer position), especially, for example, during glacials and/or northern-hemisphere summer insolation minima, should be recorded as strong cooling events in the northeastern Gulf of Mexico. These southward shifts of the ITCZ during northern-hemisphere summer insolation minima are shown by the coincidence between relatively cold Gulf SSTs and Brazilian wet periods[4] (Fig. 2).

The Holocene is characterized by a distinct temperature change (Fig. 4). From ~9 kyr onward, SST decreases from ~27.5 °C towards the modern ~24.5 °C. This Holocene SST trend is in agreement with our interpretation that Gulf SSTs reflect

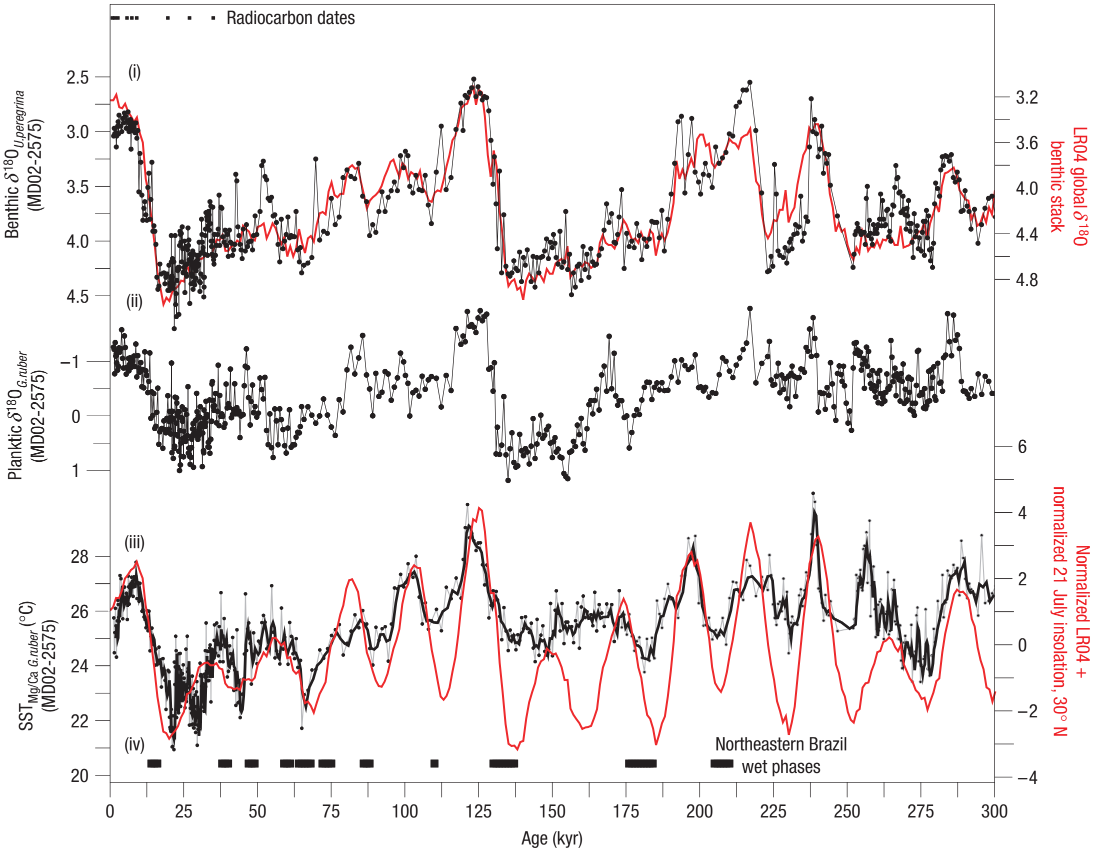

Figure 2 Paleorecords from MD02-2575. (i) Benthic $\delta^{18}O_{U.\ peregrina}$ of MD02-2575 (ref. 10) (black line with dots) and global benthic isotope stack LR04 (ref. 12) (red line). (ii) Planktonic $\delta^{18}O_{G.\ ruber}$ of MD02-2575 (black line with dots). (iii) Mg/Ca-based SST record (grey line with dots; thick black line shows three-point moving average) from MD02-2575 based on the planktonic foraminifer *G. ruber* (white variety) and the sum of the normalized LR04 stack (representing here glacial/interglacial-related North American ice volume variability) and the normalized 21 July insolation at 30° N (red line). (iv) Speleothem growth phases in northeastern Brazil[7], marking the southern maximum of the ITCZ during boreal winter.

an insolation-driven southward migration of the ITCZ during the Holocene, which has also been observed in other records[2]. Foraminiferal counts[9] suggest that the Loop Current influence on the Gulf hydrography diminished during the Holocene owing to a more southern ITCZ position.

On millennial timescales, Greenland ice-core records show that climate during the last glacial period oscillated rapidly between cold and warm states[21]. Various studies document that these abrupt climate changes in the high-latitude North Atlantic have the potential to significantly impact tropical climate[1,3], although the underlying mechanisms and climate dynamics are discussed controversially[5,22]. In contrast to this climate variability, the Gulf's SST record lacks clear expressions of the cooling events related to Heinrich Events 1, 2, 4, 5, 6 and the Younger Dryas (Fig. 4). During Heinrich events, Gulf SSTs are in general relatively warm. Warm and wet Heinrich events have also been documented in pollen records from Florida[23]. The absence of a clear SST response in the Gulf of Mexico to the strong cooling events in the North Atlantic suggests that the boreal summer position of the ITCZ and AWP was relatively unaffected by these rapid climate changes. Only Heinrich Event 3 represents an exception in the Gulf of Mexico, with relatively cold SSTs, but this could be in line with studies of sediment records from the North Atlantic showing that the origin and nature of Heinrich Event 3 are generally different compared with the other events[24].

The key to interpret the 'missing cooling events' in the Gulf of Mexico SST record is most likely seasonal differences. It has been recently suggested that the millennial-scale rapid-cooling events of the last glacial period and at Termination I are marked by extreme seasonality[8]. The large increases in seasonal amplitudes have been related to fast expanding sea ice cover, which allows for extreme winter cooling[5,8], which is balanced by relatively mild summers. Positive feedback mechanisms potentially link rapid growth of sea ice with the intensity of the thermohaline circulation. Modelling studies demonstrate that not only glacial land ice but also North Atlantic sea ice, which is coupled to thermohaline circulation intensity through positive feedbacks[25], leads to a southward migration of the ITCZ (ref. 5). This mechanism links high and low latitudes during millennial-scale climate variability, and at the same time explains why the boreal summer position of the ITCZ and the SST pattern in the Gulf are relatively insensitive to the high-latitude cooling events.

Absence of a Younger Dryas cooling in southern Caribbean SST records has been documented previously[13,14,26]. However, the small, modern intra-annual temperature variability and the generally smaller temperature change over the last deglaciation in the SST records[13,27] demonstrate that the southern Caribbean is positioned within the AWP almost throughout the year. Therefore SST records from this area reflect the AWP internal variability rather than its expansion.

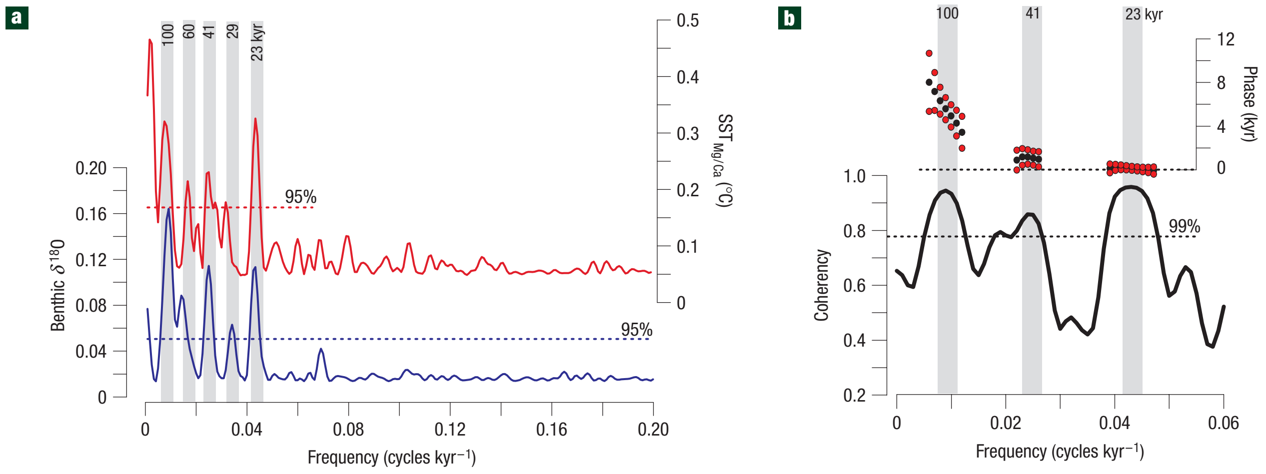

Figure 3 **Cross-spectral analysis between benthic δ^{18}O and the SST$_{\mathrm{Mg/Ca}}$ time series (MD02-2575) (ref. 15). a**, Clean spectrum[18] of δ^{18}O and SST. Horizontal lines represent significance levels. **b**, Cross-spectral analyses[17]. Lower panel: Coherency spectrum. Upper panel: Cross-spectral estimates on the basis of 0.5 kyr linear interpolated time series. Positive numbers indicate leading SST over δ^{18}O. Lower and upper confidence limits at the 99% level are given by $0.323\,492 < \Delta P(99.000\,000\%)/P < 8.879\,33$.

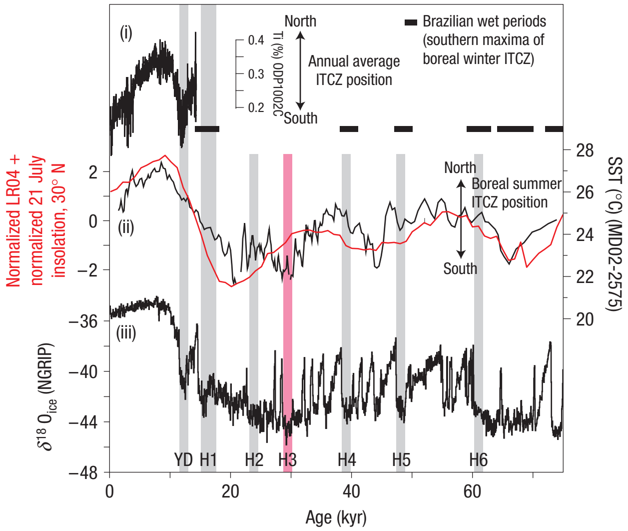

Figure 4 **NGRIP, the Cariaco Basin and the Gulf of Mexico in comparison.** (i) Ti record from ODP Site 1002, Cariaco Basin[2]. (ii) SST record from MD02-2575. (iii) δ^{18}O$_{\mathrm{ice}}$ from Greenland ice core North GRIP (ref. 21). The grey bars mark Heinrich events (the pink bar marks the unusual Heinrich event 3). Black marks indicate speleothem growth phases during maximal southern position of the ITCZ during boreal winter[4].

In contrast, proxy records from the Cariaco Basin, which are indicative of changes in laminated sediment deposition and composition, reveal a striking resemblance to the millennial-scale air temperature variations over Greenland[2,3] (Fig. 4). These changes are linked to the annual average position of the ITCZ through the combined influences of higher local river discharge during summer (northernmost position of ITCZ) and intense upwelling/higher productivity during boreal winter (southernmost position of ITCZ). However, two contrasting SST reconstructions from the Cariaco Basin may shed light on the seasonal tropical high-latitude climate connection. SST reconstructions on the basis of foraminiferal Mg/Ca show a pronounced cooling response to the Younger Dryas event[1], whereas SST reconstructions on the basis of alkenones show no Younger Dryas cooling[26]. As the planktonic foraminifers mainly calcify during the upwelling season in the Cariaco Basin, the Mg/Ca-derived SST estimates merely represent a winter-biased signal. Therefore, the extreme cooling effect on these estimates can be explained by severe upwelling during a southward winter displacement of the ITCZ. Such southward displacements of the ITCZ during boreal winters are clearly recognized in South American climate records[4,28,29] that are located close to the modern boreal winter ITCZ position, which indicate wet periods to appear synchronous with Heinrich events and the Younger Dryas. The alkenone SST signal from the Cariaco Basin on the other hand shows no response to the Younger Dryas event and thus most likely represents a summer-dominated signal. The seasonal alternation between river runoff and upwelling is recorded in the lamination of the Cariaco sediments, with dark-coloured terrigenous grain-rich layers deposited during the rainy summer/autumn and lighter-coloured biogenic-rich layers deposited during the windy winter/spring. Most pronounced laminations of Cariaco Basin sediments during the Younger Dryas provide therefore a further argument for a severe overhead migration of the ITCZ during that period.

The Pleistocene pattern of latitudinal migration of the ITCZ inferred here supports the hypothesis that seasonality is of key importance for interpreting previously poorly understood aspects of millennial-scale high-to-low-latitude climate interactions during the last glacial period and Termination I. We suggest that the imprint of high-latitude North Atlantic climate oscillations during the last glacial period is recorded in the Caribbean, Eastern Pacific and South American proxy records (Fig. 1) when reflecting the boreal winter signal[1,4,7,28,29]. Rapid climate changes and cold temperatures during North Atlantic stadials are potentially related to extremely cold winters, as the glacial winter was close to a critical sea-ice formation threshold[8]. In contrast, Pleistocene SST records, indicative of the boreal summer signal[13–15,19,26], lack the pattern of rapid North Atlantic climate oscillations and indicate that the summer ITCZ position is relatively insensitive to the abrupt cooling events, probably because of relatively mild summers during the Heinrich events and the Younger Dryas.

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