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Impact of the Atlantic Warm Pool on precipitation and temperature in Florida during North Atlantic cold spells

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Abstract Recurrent phases of increased pine at Lake Tulane, Florida have previously been related to strong stadials terminated by so-called Heinrich events. The climatic significance of these pine phases has been interpreted in different ways. Using a pollen–climate inference model, we quantified the climate changes and consistently found that mean summer precipitation (P_{JJA}) increased (0.5–0.9 mm/day) and mean November temperature increased (2.0–3.0°C) during pine phases coeval with Heinrich events and the Younger Dryas. Marine sea surface temperature records indicate that potential sources for these moisture and heat anomalies are in the Gulf of Mexico and the western tropical Atlantic. We explain this low latitude warming by an increased Loop Current facilitated by persistence of the Atlantic Warm Pool during summer. This hypothesis is supported by a climate model sensitivity analysis. A positive heat anomaly in the Gulf of Mexico and equatorial Atlantic best approximates the pollen-inferred climate reconstructions from Lake Tulane during the (stadials around) Heinrich events and the Younger Dryas.

Keywords Heinrich events · Abrupt climate change · Atlantic Warm Pool · Loop Current · Low latitudes · Florida

1 Introduction

Paleoecological reconstructions spanning the past 60 ka (all ages cal BP) from Lake Tulane (subtropical central Florida, USA, Fig. 1) revealed a series of sharp vegetation switches from open scrub-oak and prairie communities to pine dominated forests (Grimm et al. 1993, 2006). A recently improved age model (Grimm et al. 2006) shows that the pine phases (TP1–TP6) coincide with strong North Atlantic stadials that are terminated by massive iceberg discharges known as Heinrich events (H-events H1–H6) (Heinrich 1988; Bond et al. 1992, 1993). Pine phases at Lake Tulane were initially interpreted as indicative of wetter and cooler periods (Grimm et al. 1993), whereas the most recent interpretation considers them to represent wetter and warmer conditions in Florida (Grimm et al. 2006). The latter interpretation would involve a strong antiphase relationship between climate in Florida and the

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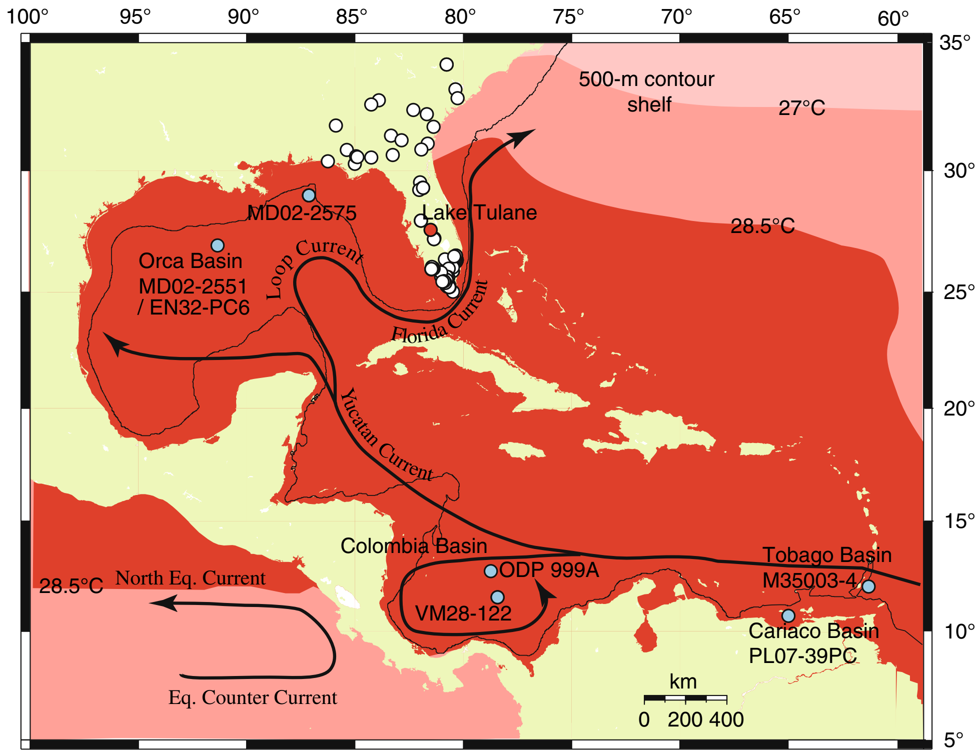

Fig. 1 Location of Lake Tulane (*red circle*), surface sediment samples used in the calibration (*empty circles*), and marine sites (*blue circles*) discussed in the text. *Arrows* indicate approximate large-scale warm sea-surface circulation (Cherubin et al. 2005). *Red contours* indicate September SSTs. SSTs > 28.5°C indicate the Atlantic Warm Pool

North Atlantic region, and strengthens the concept of low latitude warming in response to North Atlantic surface freshening and subsequent reduction of the Atlantic Meridional overturning circulation (AMOC) (e.g. Stocker 1998; Rühlemann et al. 1999; Flower et al. 2004).

More evidence for the linkage between North Atlantic Cooling events and the AMOC comes from climate model simulations (e.g. Rahmstorf 1996; Ganopolski and Rahmstorf 2001; Flückiger et al. 2008). Proxy records of water mass reorganisation (e.g. Charles et al. 1996; Vidal et al. 1997; Rühlemann et al. 1999; McManus et al. 2004) also indicate abrupt reductions in northward heat transport during these time intervals. However, with regard to changes in low latitude Atlantic Sea surface temperatures (SSTs), model and proxy studies show less agreement. Although some combined climate model and proxy studies suggest a warming of low latitude Atlantic SSTs (e.g. Rühlemann et al. 2004; Menviel et al. 2008, Flückiger et al. 2008), the results of several other SST reconstructions are not uniform in sign and magnitude (Lea et al. 2003; Flower et al. 2004; Hill et al. 2006; Ziegler et al. 2008) (Fig. 3).

The size and northward expansion of the Atlantic Warm Pool (AWP) could hold the key to explaining the observed antiphase relationship between North Atlantic cooling and warming over Florida. The AWP is a region of surface waters warmer then 28.5°C and comprises the Gulf of Mexico (GoM), Caribbean Sea and the western tropical North Atlantic (Wang and Enfield 2001; Wang et al. 2006) during summer in the present day climate (Fig. 1). In the present-day climate, the AWP reaches its northern most position in September. The size and northward extent of the AWP in summer determines the summer position of the Inter-tropical Convergence Zone (ITCZ) and thereby affects precipitation and trade winds over the (sub)tropical North Atlantic region. Summer trade winds over the (sub)tropical North Atlantic partly drive the flow of warm surface waters from the Caribbean Sea through the GoM by the Loop Current (Johns et al. 2002).

To investigate the relation between low latitude SSTs and Florida climate, we provide an objective quantitative climate reconstruction from Lake Tulane based on newly developed pollen-climate inference models. We compare these results with available SST records from the (sub)tropical Atlantic section of the AMOC that are potential source areas for enhanced precipitation in Florida (Chen and Gerber 1992). The now fully layer-counted NGRIP Greenland ice core (Rasmussen et al. 2008; Svensson et al., 2008) provides an improved chronological framework, which allows better assessment of the correlation with South Florida. We use contrasting low-latitude Atlantic SST reconstructions as a basis for a series of climate model sensitivity experiments. Based on our model results, we discuss the mechanistic relation between low-latitude SST anomalies, specifically the role of Loop Current intensity, and land-surface temperature and precipitation changes in Florida during the periods with presumed AMOC reorganizations.

2 Environmental setting and data

Lake Tulane is one of numerous deep sinkhole lakes on the Lake Wales Ridge highland in south-central Florida (Fig. 1), which locally rises to 55 m elevation. Unconsolidated sands cause the area to be excessively well drained with highly permeable soils. As a consequence, natural vegetation on the Lake Wales Ridge consists mainly of a mosaic of sand pine scrub and sandhill high pine communities. The first consists of scrub oak species (*Quercus myrtifolia, Q. inopina, Q. geminata, Q. chapmanii*), rosemary (*Ceratiola ericoides*), rusty lyonia (*Lyonia ferruginea*), and palmettos (*Serenoa repens* and *Sabal etonia*), with scattered sand pine (*Pinus clausa*) while the second is dominated by South Florida slash pine (*Pinus elliottii* var. *densa*), with wire grass (*Aristida stricta*) and scrub (*Quercus laevis*, *Carya floridana*) undergrowth (Abrahamson et al. 1984; Grimm et al. 2006). The vegetation mosaic depends largely on precipitation during the wet summer-growing season. The sandy soils and seasonal precipitation make the site sensitive to regional climate variations.

Our principal dataset consists of pollen counts on 191 samples taken from an 18-m long core collected at Lake Tulane (Grimm et al. 2006). To assess within and between site variability, we use pollen records from an earlier core collected at Lake Tulane (Grimm et al. 1993) and a record from Lake Annie 100 km south of Lake Tulane (Watts 1975; Supplemental material 138 S1, Fig. S3). A study by Willard et al. (2007) from Tampa Bay that shows significant dry/wet variations was assessed but was not used in the quantitative climate reconstruction because the catchment area and depositional setting of that site vary strongly through time, whereby changes in local vegetation disproportionately drive the results. All pollen percentages were calculated based on the taxonomical resolution of pollen counts from modern surface sediments (Whitmore et al. 2005).

3 Methods

3.1 Transfer-function development and climate reconstruction

In addition to the previous qualitative interpretations (Grimm et al. 1993, 2006) we use numerical methods to quantitatively reconstruct past climate changes based on the Lake Tulane pollen records. Regional pollen-based climate inference models were developed using an extensive compilation of (bio)climatic data (Whitmore et al. 2005) and pollen counts from surface sediment samples (Whitmore et al. 2005; Donders et al. 2005a). Our selection covers wide temperature and precipitation gradients (tropical to warm-temperate) across the SE USA (Fig. 1; Supplemental material S1). In attempt to increase the predictive power of the inference models (Table 1), we limited wide-ranging genera (e.g. *Carya, Quercus, Pinus*) to species with shorter environmental variables by excluding surface sediment samples from more temperate areas. The individual explanatory power of 36 (bio)climatic parameters was assessed using canonical correspondence analysis (CCA)(Supplemental material S1). The ecologically and statistically most significant parameters, mean summer precipitation (P_{JJA}) and mean November temperature (T_{NOV}), were tested and selected as predictands for the pollen-climate inference models (Table 1; Supplemental material S1). Inference models were derived by partial least squares (PLS) and weighted-averaging PLS (WA-PLS) with bootstrap cross-validated prediction errors. These methods have been used successfully for pollen-climate inferences (e.g. Finsinger et al. 2007) and are considered robust methods (Birks 2004), especially for predictions within the calibration range. To assess the reliability of the reconstruction and detect possible problematic intervals, a goodness-of-fit statistic was calculated for P_{JJA} and $T_{\mathrm{NOV.}}$ For each variable the squared residual distance was calculated using a CCA with a single environmental variable, providing an estimate of the fit of the environmental variable with the calibration data.

3.2 Climate model sensitivity experiments

We performed climate model sensitivity experiments with the Earth-system model of intermediate complexity (EMIC) PUMA-2 (Fraedrich et al. 1998, 2005a, b) to investigate the sensitivity of the land-surface climate in Florida to SST anomalies in the (extra) tropical North Atlantic, Caribbean Sea, and GoM. PUMA-2 is a general circulation model (GCM) with relatively low

Table 1 Pollen–climate inference model performance for winter and summer precipitation (P_{win}, P_{sum}), and November temperature (T_{nov})

	$P_{\mathrm{djf\ (winter)}}$ (mm/season)	$P_{\mathrm{JJA\ (summer)}}$ (mm/season)	T_{NOV} (°C)
% Variance	10.8	9.8	11.8
Model type	WA-PLS	PLS	WA-PLS
Gradient length	1.576	1.846	1.557
# Components	2	2	2
RMSEP	31.32	39.7	1.9
R^2 boot	0.76	0.66	0.62
# Outliers removed	3	2	2
RMSEP % range	11.9	17.9	15.3

computational demand, yet simulates an atmospheric response to SST forcing comparable to the more complex ECHAM4 (Romanova et al. 2006; Grosfeld et al. 2007, 2008). To represent details of the Florida region, the model is used in a T42 spectral triangular resolution with 10 vertical layers. We performed four climate model simulations: a last glacial maximum (LGM, 21 ka) reference (EMIC-LGM) with prescribed LGM boundary conditions for SSTs, solar insolation and atmospheric CO_2 concentrations (200 ppmv) and three climate sensitivity simulations with idealized SST anomalies (Table 2). In the sensitivity simulations, we altered only the prescribed SSTs to constrain potential source areas for the land-surface temperature and precipitation anomalies seen in Florida during H-events. Each simulation is run for 40-years and started from an atmosphere at rest. Because SSTs are prescribed, the model's spin-up time requires at most 20 years. To reduce model noise, climatology is calculated as an average of the last 20 years of each simulation.

Monthly LGM SSTs and sea-ice boundary conditions are based on the GLAMAP dataset (Schäfer-Neth and Paul 2003), glacial ice cover, orography, sea level, and coastlines follow Peltier (1994), and LGM vegetation is based on Crowley (1995) and Martin (1998) (Fig. S4). In the EMIC-H0 simulation (Fig. 2a), SST boundary conditions were based on the assumption that, relative to LGM conditions, a decrease in northwards heat transport resulted in a zonal average SST cooling (of maximum 6°C) in the extra-tropical North Atlantic during the last H-event (after Bond et al. 1992, 1993). The EMIC-H1 simulation (Fig. 2b) represents, besides North Atlantic cooling, increased low latitude summer insolation resulting in a maximum 2°C zonal average warming of the equatorial surface waters (after Schmidt et al. 2004; Ziegler et al. 2008). The EMIC-H + simulation (Fig. 2c) additionally includes increased zonal heat transport from the tropical East Atlantic, through the Caribbean Sea into the GoM, representing an intensification of the Loop Current. SSTs in EMIC-H + simulation increase 1–2°C close to Florida (after Flower et al. 2004), relative to the LGM simulation (see Supplemental material S2 for details on simulations).

4 Results

4.1 Pollen-inferred climate reconstruction

Inference model data show that during the TP1-TP6 phases, coeval with strong Greenland stadials, mean summer precipitation (P_{JJA}) increased by 0.5–0.9 mm/day, while November temperature (T_{NOV}) increased by 2.0–3.0°C (Fig. 3). Reconstruction results from two independent datasets from Lake Tulane are highly consistent and offsets between records do not exceed the bootstrapped prediction errors (Table 1; Supplemental material S1, Fig. S3). The Lake Tulane signals for 0–13 ka agree with the reconstruction from nearby Lake Annie (Supplemental material S1, Fig. S3).

Remarkable features at both sites are the consistently dry/cool conditions in the Allerød and warm/wet conditions during (part of) the Younger Dryas (YD). Increased wetness during the Middle Holocene is consistent with independent reconstructions from South Florida (Donders et al. 2005b). A coastal pollen record from Tampa Bay (Willard et al. 2007) partly confirms this result, showing wet conditions during H1 and a stepwise change during the YD that mirrors the changes seen in the Tulane 06 record, but not the Tulane 93 and Lake Annie records. The length of the wet phase in the YD is therefore unclear. The middle Holocene temperature increase is remarkably high compared to the glacial-interglacial transition. Early Holocene vegetation stands out as an intermediate phase in the record (Grimm et al. 2006), with abundant *Quercus* and some *Ambrosia,* but low heath and intermediate *Pinus* abundance. In the calibration dataset, *Ambrosia* is generally more abundant in temperate areas due to forest clearance and land disturbance, which possibly skews the reconstruction to somewhat lower winter temperatures during the LGM and early Holocene. Figure S3 shows the goodness-of-fit with 90% percentile cutoff values. Only the lowest T_{NOV} reconstruction values between 21 and 20 ka BP are uncertain since the transfer model does not perform well in that interval. Our reconstruction data are reliable during the TP1-TP6 phases. Warming during these phases is also indicated qualitatively by lower *Ambrosia* abundances, because warm winters inhibit *Ambrosia* to germinate effectively (Bazzaz 1974).

Table 2 Description of the climate model simulations, SST boundary conditions and reference to the SST reconstruction on which the simulation is based

Simulation	SST boundary conditions	Reference
EMIC-LGM	GLAMAP monthly	Schäfer-Neth and Paul (2003)
EMIC-H0	As EMIC-LGM with North-Atlantic cooling	Bond et al. (1992, 1993)
EMIC-H1	As EMIC-H0 with increased low latitude summer insolation	Bond et al. (1992, 1993, 2004), Ziegler et al. (2008)
EMIC-H+	As EMIC-H1 with Loop Current intensification	Flower et al. (2004)

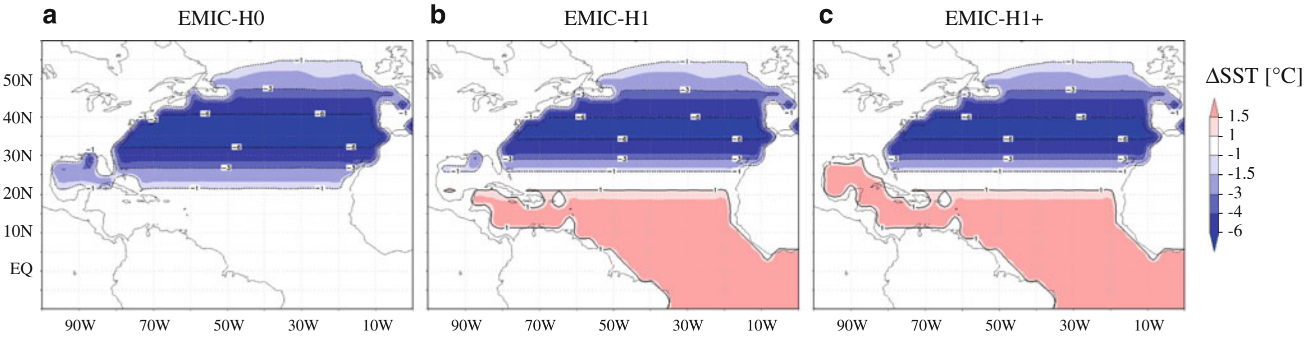

Fig. 2 Boundary conditions for the EMIC-H0, EMIC-H1 and EMIC-H+ climate sensitivity simulations, relative to those used in the EMIC-LGM control simulation

Age uncertainties of the Lake Tulane record (Grimm et al. 2006) are larger than the NGRIP ice core record (Svensson et al. 2008), but in TP-0–2 do not exceed 1.5 ka, and only for TP-5 and 6 exceed the duration of the event. Especially for the pine phases TP1-3 we can confidently state that they correlate to Greenland Stadials (Fig. 3) that include a Heinrich event, since the latter have been correlated independently to the Greenland ice cores (Stoner et al. 2000). The warm/wet TP2 and TP4 phases start well before and extend beyond H2 and H4, respectively. Despite uncertainties in both the Heinrich ages and the Lake Tulane chronology (see Stoner et al. 2000; Grimm et al. 2006), this long duration seems robust. Confining the duration of TP2 and TP4 events exactly to H2 and H4 would require an unrealistic threefold increase in sedimentation rate during the pine phases. See also Grimm et al. (2006) for a more extended discussion on the age uncertainties of the Lake Tulane record.

4.2 Climate sensitivity to Atlantic SSTs

Our climate sensitivity experiments indicate that the climate in Florida is sensitive to changes in both low- and high-latitudinal (North) Atlantic SSTs. Figure 4 shows modeled land-surface temperature and precipitation (anomalies) for Florida (averaged over 75–88°W to 25–30°N). Summer precipitation varies strongly between experiments; while winter is consistently modeled as dry and summer as wet (Fig. 4a, b), the EMIC-H+ simulation shows the strongest seasonality. All simulations produce a drier climate compared to the pollen-inferred reconstructions [P_{JJA} of 5–6 mm/day based on pollen, and 1.4 (EMIC-LGM), 0.8 (EMIC-H0), 1.2 (EMIC-H1) and 1.7 mm/day (EMIC-H+) simulated] and peak precipitation is delayed by 1 month. Only the EMIC-H+ simulation explains the magnitude of the pollen-inferred P_{JJA} increase from LGM to H1. This increase in summer precipitation is related to a localized northward shift of the ITCZ during summer (see Supplemental S3 material, Fig. S6).

Land-surface temperatures vary little between the experiments (Fig. 4c, d). Compared to the EMIC-LGM simulation, all EMIC-H experiments show positive temperature anomalies at the onset of winter and are generally colder during spring, summer, and fall. The largest positive temperature anomaly (1°C) is simulated in the EMIC-H+ simulation for December. All simulations produce a warmer climate compared to the pollen-inferred reconstructions [T_{NOV} of 16–17°C based on pollen, and 18 (EMIC-LGM), 18 (EMIC-H0), 19 (EMIC-H1) and 19°C (EMIC-H+) simulated]. Relative to the EMIC-LGM simulation, the EMIC-H1 and EMIC-H+ simulations show a positive temperature anomaly in November (1°C), while the EMIC-H0 simulation shows little change. The results indicate that a warming of the equatorial Atlantic and the GoM is needed to explain the pollen-inferred increase in summer precipitation and November temperature during North-Atlantic cold spells.

5 Discussion

5.1 Source of heat and moisture anomalies

To explain the observed increases in precipitation and temperature in Florida, we hypothesize that the GoM warmed during North Atlantic colds spells and that this warming is potentially related to increased Loop Current (Hofmann and Worley 1986; Poore et al. 2004). Grimm et al. (2006) observed a general inverse correlation to Greenland stadials and the Lake Tulane pollen record, both on independent chronologies. With the quantitative temperature data from Lake Tulane and update to the fully layer-counted NGRIP chronology used in Fig. 3, this conclusion is strengthened here. However, different SST records do not show a clear and unequivocal regional low-latitude warming (Fig. 3).

At present, the Loop Current is controlled by an interplay between regional surface winds and water flow from

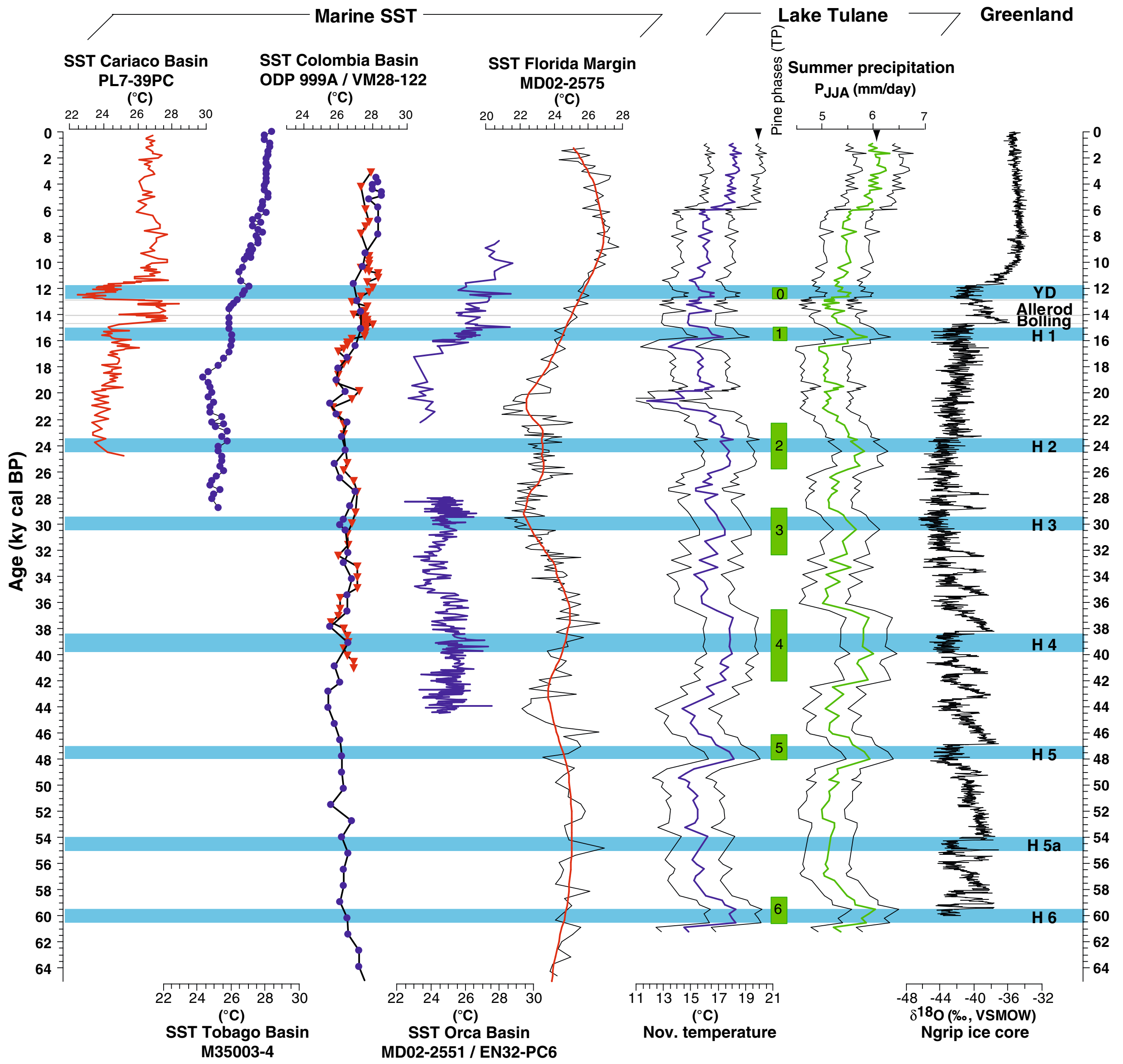

Fig. 3 Paleoclimate reconstructions from Lake Tulane based on the pollen climate inference models for the last 60 kyr. The Lake Tulane chronology is based on 55 AMS ^{14}C ages that were calibrated with the intcal04 (Reimer et al. 2004) for ages younger than 20,000 ^{14}C yr BP, and with the Fairbanks et al. (2005) calibration curve (based on paired AMS ^{14}C/U-series dating of corals) for ages 20,000–40,000 ^{14}C yr BP. Phases TP5 and TP6 are not independently dated but correlated to H5 and H6, analogous to the observed correlation of TP1–TP4 with H1–H4 (see Grimm et al. 2006 for more details). Arrows indicate present day climatic values at Lake Tulane. Data is compared to the regional marine SST records from the Cariaco Basin (Lea et al. 2003), Tobago Basin (Rühlemann et al. 1999), Colombia Basin (Schmidt et al. 2004), Orca Basin (Hill et al. 2006; Flower et al. 2004) and Florida Margin (Ziegler et al. 2008). *Blue bars* indicate maximum calendar age ranges of North Atlantic iceberg-rafted debris (*IRD*) deposition, following Stoner et al. (2000). Depending on the record used, the exact timing and duration of Heinrich events vary (Rashid et al. 2003). We consider the estimates based on correlation between paleomagnetic intensity measured in sediment records close to Greenland and cosmogenic isotopes fluxes measured in the GISP2 Greenland ice core record (Stoner et al. 2000) as most reliable, and use these for data comparison. Heinrich event ages, and hence the Lake Tulane record below TP4, have been updated to the new Greenland Ice Core Chronology 2005 (*GICC05*), which is based on layer counting of the NGRIP ice core back to 60 ka (Rasmussen et al. 2008; Svensson et al. 2008)

the Caribbean Sea through the Yucatan Channel (Johns et al. 2002; Romanou et al. 2004; Cherubin et al. 2005). These studies indicate that a northerly ITCZ position during summer enhances the intrusion of the Loop Current because the associated (south)easterly trade winds enhance the northwestward advection of warm surface waters.

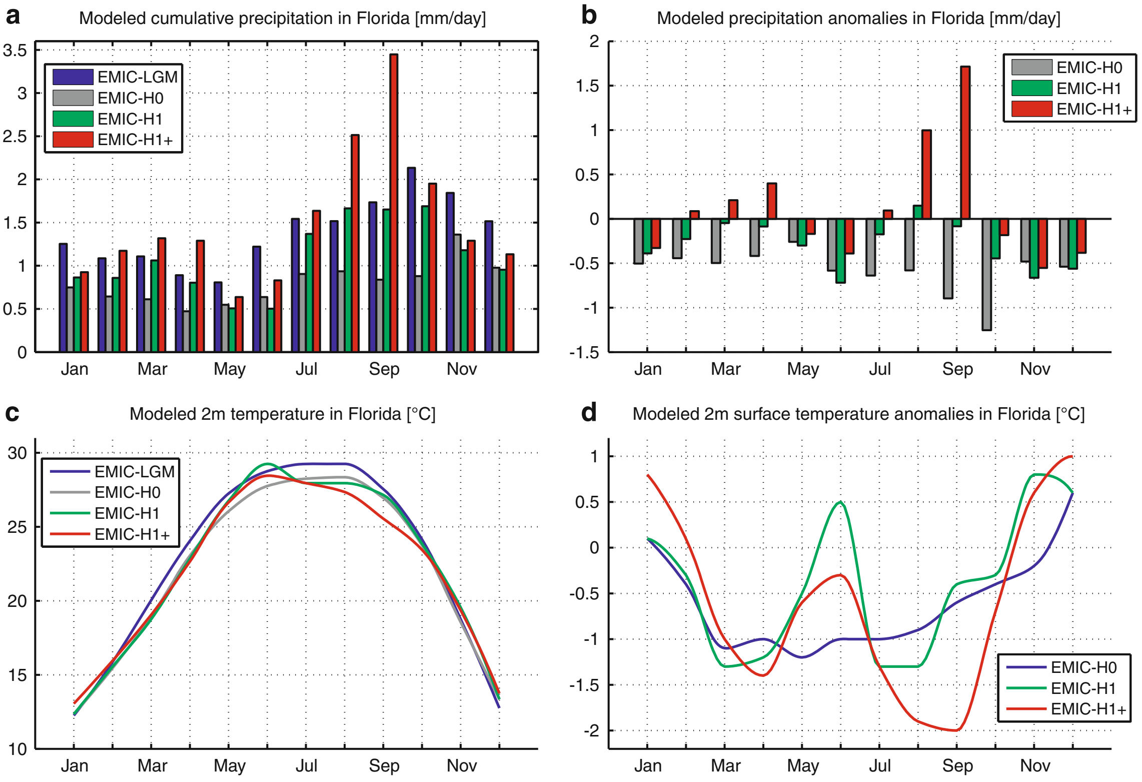

Fig. 4 Simulated land surface temperature and precipitation for the Florida region. Simulated monthly precipitation (**a**) and precipitation anomalies relative to LGM simulation (**b**) are averaged over the larger Florida region (75–88°W to 25–30°N) including grid-cells over water. Simulated monthly land surface (2 m) temperature (**c**) and temperature anomalies relative to LGM simulation (**d**) are averaged over terrestrial grid-cells in the Florida region (75–88°W to 25–30°N)

Hodell et al. (1991) and Poore et al. (2004) indicate that during the Holocene the Loop Current was mainly controlled by the effect of summer insolation on ITCZ position. Nürnberg et al. (2008) reconstructed SSTs and sea surface salinities in the northeastern GoM (Florida margin) over the past 400 kyr. Their results reveal that Loop Current intrusion was modulated by the northward extend of the AWP and freshwater discharge from the Laurentide Ice Sheet. All these studies indicate a positive relation between a northerly ITCZ position and Loop Current intrusion. Observational evidence suggests that the ITCZ moved south during periods of North Atlantic cooling (Wang et al. 2005; Stott et al. 2002; Burns et al. 2003; Muller et al. 2008). These observations are supported by simulations with various climate models (Zhang and Delworth 2005; Stouffer et al. 2005). If the ITCZ was indeed displaced south over the western Atlantic region, this would cause a decrease in summer trade winds and a reduction of the associated advection of warm surface waters through the GoM. However, based on the coincidence between our climate model simulations and pollen-based climate reconstructions, we infer that heat transport up to and through the GoM potentially increased, suggesting an increase in summer trade winds and a northerly position of the ITCZ over the region.

We explain this apparent contradiction by an increase in heat transport up to and through the GoM forced by increased summer trade winds driven by a steepened equator–pole temperature gradient during North Atlantic cold spells. Ziegler et al. (2008) indicate that summer expansion of the AWP is generally insensitive to extratropical North Atlantic cooling. A persistent AWP, combined with a warm GoM should therefore allow for a northerly ITCZ position over the eastern tropical North Atlantic during boreal summer and could provide moisture and heat to Florida. The highest SST increase during H1 is seen in the central GoM (Flower et al. 2004) (Fig. 1, 3), which is directly influenced by the warm waters of the Loop Current (DeHaan and Sturges 2005). Koutavas et al. (2002) found evidence for decreased trade-winds with a lower equator–pole temperature gradient during LGM based on reduced upwelling offshore Peru. Conversely, increased equator–pole temperature gradient enhanced Hadley circulation during North Atlantic cold spells (Jain et al. 1999; Trenberth et al. 2000; Clement et al. 2004). The increase in Hadley circulation possibly led to an increase in easterly trade winds over the western equatorial North Atlantic in summer (Zhang and Delworth 2005), thereby enhancing Loop Current intrusion into the GoM and warming the surface waters around the Florida peninsula.

The observed increase of summer precipitation and November temperature in Florida could therefore represent an increase in summer trade winds and reflect the persistence of the AWP and increased Loop Current during North Atlantic cold spells (Nürnberg et al. 2008; Ziegler et al. 2008). It contrasts the presumed same-sign synchronicity of low and high latitude climates during the late Glacial as observed in a planktic foraminiferal Mg/Ca record from the Cariaco Basin on the northern Venezuelan shelf (Lea et al. 2003). Analogous to well-known precipitation decrease at Cariaco during stadials (e.g. Haug et al. 2001; González et al. 2008), the SST cooling has been explained by invoking a mean southward migration of the ITCZ (Lea et al. 2003), which should reduce summer precipitation in Florida (e.g. Chen and Gerber 1992; Enfield et al. 2001). However, the Cariaco SST decrease during the YD is large (3–4°C) relative to other records from the AWP (Fig. 3), and probably shows a winter upwelling signal in a restricted marine basin (Ziegler et al. 2008). Moreover, marine records from the western tropical Atlantic show SST increases (Tobago Basin), and terrestrial wet conditions with SST and sea surface salinity increases (offshore NE Brazil) during H1 and the YD (Rühlemann et al. 1999; Jennerjahn et al. 2004; Weldeab et al. 2006). These reconstructions are best explained by a more southward ITCZ position during stadial (boreal) winters. Farther north, reconstructed summer SSTs also show conflicting patterns. In the central GoM a clear warming during H1 is present (Flower et al. 2004), while summer SSTs from the Florida margin (MD02-2575) do not show consistent warming during YD and H-events (Ziegler et al. 2008). However, the pre-Holocene long term temperature trends between MD02-2575 and Lake Tulane correspond remarkably well (Fig. 3).

Ziegler et al. (2008) explain contrasting regional paleo SST patterns by invoking a strongly seasonally biased climate response to North Atlantic cold events in the tropical Atlantic. Their GoM SST signal is controlled by boreal summer insolation that displaces the northern limit of the AWP, while it is relatively insensitive to the millennial-scale YD and H-events that primarily affect boreal winter conditions. Because our Lake Tulane record represents summer-precipitation changes, the variable duration of TP phases might be determined by summer insolation influencing the northern extent of the AWP. This hypothesis is supported by the results of our climate model sensitivity analysis, which indicates that the climate in Florida is relatively insensitive to extra-tropical North Atlantic cooling if the AWP is present. Rather, the clear warm/wet phases during H-events and YD result from heat flow from the AWP into the GoM by summer trade wind forcing.

5.2 Sensitivity of simulated land surface temperatures

Altough variation in the simulated T_{NOV} anomalies in Florida among the EMIC-H0, -H1, and -H+ simulations is limited, their offsets with the EMIC-LGM simulation is considerable. This contrast indicates that both extratropical North Atlantic cooling and low latitudinal Atlantic warming contribute to the temperature increase. Winter warming of Florida in the EMIC-H simulations relative to the EMIC-LGM simulation coincides with a decrease in winter precipitation in the region (Supplemental material S3). The simulated T_{NOV} increase could therefore partly be explained by alterations in the surface energy balance related to a decrease in soil moisture and cloudiness (Wild and Ohmura 1999).

The absolute difference between our pollen-inferred and modeled November temperature could be caused by the constant solar forcing prescribed in our model simulations. Insolation changed considerably between the LGM and the last Heinrich event and has an important effect on tropical climate (Clement et al. 2004). Winter insolation decreased by approximately 30 W/m^2 and summer insolation increased by a similar value (Berger and Loutre 1991). Taking into account the decrease in winter insolation would potentially allow for a better match between the pollen-inferred and modeled November temperatures. This account however, would blur the results of the sensitivity analysis and was therefore omitted.

6 Conclusions

Increases in summer precipitation and November temperatures in Florida coincided with episodes of extreme cooling in the North Atlantic during Heinrich events and Younger Dryas, the latter of which may contain both a warm/wet and cold/dry subphase. These reconstructed climate changes are best explained by a warming of the surface waters of the tropical Atlantic and the Gulf of Mexico. Surface waters in the Gulf of Mexico potentially warmed by an intensified Loop Current facilitated by a persistent Atlantic Warm Pool and increased easterly trade winds during summer. The inter-tropical convergence zone was generally displaced south of Florida during the glacial and its summer position was controlled by insolation changes and the extent of the Atlantic Warm Pool. These controls on the inter-tropical convergence zone may have influenced the duration of the lake Tulane pine phases which are associated with wet summer conditions.

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