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Reply to comment by Paul H. Glaser et al. on "Donders, T.H. 2014. Middle Holocene humidity increase in Florida: Climate or sea-level. Quaternary Science Reviews 103: 170–174"

Glaser et al. have commented on my recent publication which is a reinterpretation of existing pollen data from the Florida peninsula using a transfer function, testing a hypothesis based on earlier results from a ~5000 year long peat-based pollen record (Donders et al., 2005a). That record, from Fakahatchee Strand in southwestern Florida (Fig. 1), noted a stepwise transition to longer hydroperiods in the Middle and Late Holocene (Donders et al., 2005a). We hypothesized that the changes resulted from increases in El Niño-driven dry season (winter) precipitation, effectively lengthening the hydroperiod and changed wetland conditions in South Florida.

Wetland vegetation distribution is strongly influenced by local variations in topography and hydrology (Kushlan, 1990; Willard et al., 2001), and pollen records from wetland sediments reflect a combination of local hydrology and regional climate. Because of the possibility that hydrologic patterns observed in the Fakahatchee Strand record were influenced by its proximity to shoreline, and therefore sea-level rise, the Donders (2014) paper applied a pollen-based transfer function to previously published lake records from the Florida peninsula to determine whether the pattern observed in Fakahatchee Strand represents a local or regional pattern. Pollen records from this north-to-south transect of lakes, located in central Florida, should not be directly influenced by mid-to Late Holocene changes in sea level, and they are believed to primarily represent regional, rather than local, vegetation patterns. In that paper, I observed that results from transfer function analyses indicated that a progressive increase in summer precipitation during the Late Holocene, with progressively wetter conditions from north to south, consistent with the pattern of intensification of ENSO during that time.

The comment by Glaser et al. on the Donders (2014) paper criticizes the use of pollen records from lakes north of the Lake Okeechobee to interpret changes in the Everglades wetland. They also note that the study relied on the pollen transfer function without considering the impacts of fire and sea level change. I agree that we should never blindly follow transfer function results, but the comment focuses on paleoclimate patterns in the Everglades wetland itself, rather than the broad regional scale that the Donders (2014) paper aimed to examine.

As will become clear in the comment and my reply, published pollen records from the Everglades all consist of wetland peats and marls, which represent both local small catchment conditions and regional climate variability, and these records therefore are inherently variable (Willard and Bernhardt, 2011). Because of the low topographic gradient of southern Florida, the Everglades hydrology was supplied principally by sheet flow from Lake Okeechobee (which is why any southern Florida hydrology record heavily depends on climate conditions north of/at Okeechobee). This implies that there is a regional aspect to the local hydrological conditions, since all local hydrological conditions are essentially sheet flow controlled. Based on this line of reasoning, I upscaled the interpretation of an essentially local record from Fakahatchee in the Donders et al. (2005a) study. The aim of the Donders (2014) study, on which Glaser et al. have commented, was to test this hypothesis by applying a pollen-based transfer function to reconstruct Holocene patterns of summer precipitation across the peninsula.

Fakahatchee Strand is dominated by a broad, elongated karst structure with dominant swamp cypress vegetation and long hydroperiods (Donders et al., 2005b). In support of the upscaling approach, in an ultra-high resolution vegetation reconstruction of the last 130 years at Fakahatchee, we detected the clear modern signature of El Niño-Southern Oscillation (ENSO) forcing in annual-scale variations of the pollen data (Donders et al., 2013). An earlier sensitivity test showed that the 20th century canalization lowered local water tables, shortening the hydroperiods, which was clearly detectable in the pollen composition of a subrecent peat section from Fakahatchee (Donders et al., 2005b).

The modern impact of ENSO in the southeastern USA is stronger in the south (Larkin and Harrison, 2005) (Fig. 1), which is why records further south should show a progressively stronger response to ENSO intensification after 5 ka (Moy et al., 2002). To test this, and exclude the potential bias from local peat records, I examined subtle changes in pollen records from more regionally representative lake records across the Florida peninsula and used a reasonably objective measure to interpret them (a transfer function). The results showed the predicted response. Because no lake records spanning the middle to Late Holocene have been published, the southernmost portion of the state is not included in the study. However, the overall pattern of a middle to Late Holocene progressive change to wetter conditions is clear and consistent with the ENSO-control hypothesis outlined in Donders et al. (2005a). This does not mean that other climatic forcing factors, such as solar insolation, or processes such as sea-level change did not influence

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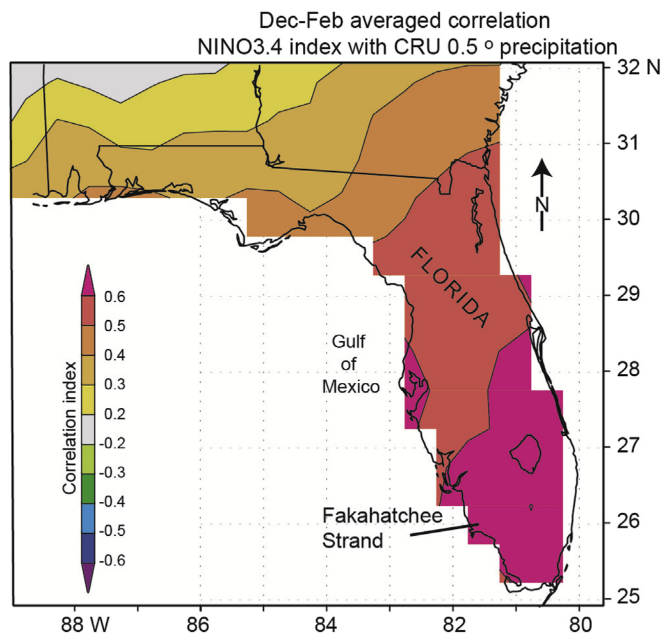

Fig. 1. Location of the Fakahatchee Strand in Florida. Gridded overlay shows average winter (DJF) correlation between precipitation and the NINO3.4 index (performed by KNMI climate explorer, after Van Oldenborgh and Burgers, 2005), based on station data containing >50 years.

regional precipitation and hydrology, but the available lake records are consistent with the ENSO forcing pattern.

This scenario does not agree with the North East Shark River Slough (NESRS) reconstruction as published earlier by Glaser et al. (2013). While suggested by Glaser et al. in their comment, direct comparison to the Caribbean region in support for their observed Late Holocene drying is problematic since the Caribbean area is mainly ITCZ controlled, while Florida is also influenced by Atlantic Meridional overturning circulation intensity (i.e. North Atlantic teleconnections, see Grimm et al., 2006; Donders et al., 2011) and winter jet stream impacts (which in turn are ENSO controlled; Vega et al., 1998; Enfield et al., 2001; Larkin and Harrison, 2005; Donders et al., 2013).

The Glaser et al. comment focuses primarily on Everglades wetland records, and the Donders (2014) paper intentionally presented evidence *outside* of the potentially variable south Florida peat records (which indeed suffer from the shortcomings described by Glaser et al.) to see if the larger pattern of the inferred hydrological change from Fakahatchee holds. The transfer function was not applied to the Fakahatchee record because of possible interaction with sea level, fire regimes and the restricted size of the basin. The sediment accumulation rate of the Fakahatchee site is indeed variable, but this does not directly imply episodes of significant drought. We noted changes of up to a factor two in accumulation rates from recent peat records 20 m apart due to slight microrelief variations that resulted in differential decomposition and compaction (Donders et al., 2004). However, the pollen evidence from Fakahatchee clearly shows a deepening of the local water table toward the present-day *Taxodium* swamp forest state, and is validated with numerous surface samples (Donders et al., 2005a). Glaser et al. comment that rising sea level could have influenced the vegetational changes at the Fakahatchee site, which is possible. The Donders (2014) study was designed to exclude effects of local variability and sea level change from the analysis.

Glaser et al. correctly note that most Everglades records are limited by their maximum age and age control. Most of the records span only the 2500 years or so, and few extend beyond 3000 BP (see Willard et al., 2001, 2006 and Bernhardt and Willard, 2009). Those that do extend before 3000 BP include those that imply wetter conditions (Fakahatchee Strand), those that imply drier conditions (NESRS site of Glaser et al., 2013; Gumbo Limbo tree island wet head; Site 5, Willard et al., 2001), and those showing no apparent hydrologic change (02-5-21-5 site of Bernhardt and Willard, 2009) between ~3000 and 2500 BP. Although the Glaser et al. (2013) study bases its age model on a series of dates on snail shells in the marl and one date on a snail at the base of the core, age models for most other records are based on a few radiocarbon dates on bulk peats and were generally not intended for developing high-resolution records for the entire late Holocene. These records clearly show that Everglades wetland records show local variability and need to be looked at in concert for climate reconstructions, while interpretation of synchronous timing should be approached cautiously. Especially their initiation is largely sea level controlled (Willard and Bernhardt, 2011; Dekker et al., 2015), which is why I took a *different* approach in the paper under discussion.

The *Pinus* increase and lithological change in Florida reported in Glaser et al. (2013) is probably an expression of locally drier conditions, although the study contains no statement of calibration with vegetation or surface samples to present conditions, and provides no supporting autecological sources to sustain the interpretation, apart from references on Amaranthaceae. The strength and regional implication of the *Pinus* increase is, in my view, strongly dependent on the prior vegetation conditions and site type. The long pollen stratigraphy from Lake Tulane shows that, based on the leaf macrofossil record, high *Pinus* phases occur together with high lake levels (Grimm et al., 2006), but a "moist" interpretation of *Pinus* depends entirely on the context and in the case of the Tulane record is relative to the dry upland scrub oak communities. The marl prairie communities are typically dominated by *Pinus* pollen (Bernhardt and Willard, 2006), and in that case represent the drier endmember within the Florida wetland types. Given that the preceding vegetation was very high in Amaranthaceae, a taxon which in Florida lowland is known to indicate seasonal drying (Willard et al., 2001, 2007; Bernhardt and Willard, 2009), the change to *Pinus* together with background increases in hammock taxa *Myrica*, Cupressaceae (most likely *Taxodium* in this part of Florida), and *Alnus* therefore cannot be straightforwardly interpreted as a climatically significant regional drying signal. Sparse prairies are strongly nutrient depleted (Gaiser et al., 2011) and therefore marl deposition can outpace organic (peat) deposition. Hydroperiod and water depth certainly affect this, but it is not the only factor, and certainly the seasonality of changes has needs to be taken into account. Also the gradual movement of tree islands, and changes in orientation of ridge and slough patterns can cause apparent hydroperiod and water depth changes (Bernhardt and Willard, 2009). Furthermore, the distinction between what is local and regional as presented by Glaser et al. (2013), is rather arbitrary as the majority of plants occur both locally and regionally.

Regarding the role of fire, the Fakahatchee peat record has no charcoal present (Donders et al., 2005a,b), which is unsurprising given that a stand of closed swamp forest is waterlogged and very unlikely to burn (Austin et al., 1990). Hence, based on that record no regional interpretation of fire frequency can be given, a point that was brought up in the original publication (see supplementary information; Donders et al., 2005a). It further implies that the extent of fire occurrence is also heavily controlled by hydroperiod.

There is no doubt that pollen-based transfer functions need improvement and careful interpretation; they currently are limited by available records from core tops and surface samples collected for various purposes (See Whitmore et al., 2005; Donders et al., 2011). However, they provide a quantitative means to reconstruct past climate that can be used in combination with more qualitative methods. Although there appears to be a contradiction in the direction of hydrologic change in the observed pollen sequences from Fakahatchee and NESRS, the common timing suggests the impact of some external forcing. As suggested by Glaser et al. (2013), an increase in El Niño activity after 2700 cal BP, could have caused a decline in hurricane frequency (see also Donnelly and Woodruff, 2007) and simultaneously increased winter-season precipitation (Enfield et al., 2001; Larkin and Harrison, 2005). Such an increase lengthens hydroperiod as it is this normally dry season that controls the effective inundation period (Donders et al., 2013). Maximum water depth however, is not necessarily affected as this is mostly summer precipitation controlled and dependent on the position of the Bermuda High, which might explain some of the observations at NESRS.

Additional research is needed to test the various hypotheses. For example, shallow marine sediment cores could be collected that record long-term patterns of Everglades outflow, thereby integrating a greater catchment area in the absence of lakes in south Florida, and provide the opportunity to compare marine and terrestrial responses. New terrestrial and marine records should be collected for high-resolution analysis, focusing on finer sampling and dating. More attention to seasonal aspects of the environmental shifts also may provide the key to solving the apparent contradictions. I would invite Glaser, coauthors, and other colleagues to collaborate and develop strategies to improve our understanding of the full range of processes that influence local and regional wetland variability in South Florida.

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