

Possible evidence for wet Heinrich phases in tropical NE Australia: the Lynch's Crater deposit

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Abstract

Unarguably, one of the most significant paleoclimatological discoveries of the last two decades has been that of abrupt climate events (Dansgaard–Oeschger cycles and Heinrich events). Most evidence for these events has originated from the high-latitude Northern Hemisphere, with few records documenting the response of the low latitude Southern Hemisphere. Here we present new data from Lynch's Crater, a unique terrestrial record from NE-Australia that may show evidence for southward propagations of the Intertropical Convergence Zone (ITCZ) during abrupt climate perturbations as a result of alteration of the low latitude air masses. Proxies for precipitation/wetness indicate enhanced rainfall in the region during Heinrich events (H events 1–3) and the 8.2 ka Northern Hemisphere cold event. A fully coupled atmosphere/ocean climate model simulating a 1 Sv freshwater influx to the North Atlantic Ocean produces a scenario which agrees with the climate changes shown by the Lynch's Crater record. The model shows precipitation anomalies that include a southward migration of the ITCZ and a zonal shift in mid-latitude storm tracks over the Southern Hemisphere equatorial region. These data indicate large-scale shifts of the austral summer ITCZ position that is known to control monsoonal precipitation in NE Australia. This terrestrial record from Australia may demonstrate the involvement of the tropical western Pacific Ocean in ITCZ migrations during abrupt climate events of the last glacial period. Defining such past migrations offers insight into the importance and role of the equatorial region in global climate dynamics.

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1. Introduction

It is thought that the semi-periodic instability of ice sheets during the last glacial period resulted in abrupt and

massive iceberg discharges to the North Atlantic, periods that have been termed Heinrich events (H events) (Bond et al., 1993; Dansgaard et al., 1993; Broecker, 1994). This influenced the subsequent shutdown of the ocean conveyor system and forced dramatic drops in Northern Hemisphere temperatures. Co-existing with H events are Dansgaard–Oeschger (D–O) events, which are high-frequency climate oscillations with 1000-, 1450-, and 3000-year cyclicities (Bond et al., 1999). Together, H events and

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D–O cycles comprise “Bond Cycles”, each of which consists of a major D–O interstadial (warm period) followed by a series of shorter and less intense interstadials, and then by a long stadial (cold period) that is terminated by a H event (Alley, 2000). With other events such as the Younger Dryas (~11.5–12.5 ka ago) and the 8.2 ka event, Bond cycles are described as “abrupt climate cycles”. The majority of evidence for these events comes from the Northern Hemisphere, mostly from marine sediments and ice cores (Heinrich, 1988; Broecker, 1994; Alley et al., 2003). There is still a great deal of debate surrounding the origin and global extent of these events, for example their occurrence and extent in the Southern Hemisphere (Partridge, 2002; Sachs and Anderson, 2005) and more recently, the theory that the tropics is a key player in forcing these abrupt climate changes (McIntyre and Molino, 1996; Hendy and Kennett, 2000; Farmer and deMenocal, 2005; Kienast et al., 2006).

To date, most Heinrich event studies from the tropical Southern Hemisphere (Fig. 1) have focused on marine sediments from the Atlantic Ocean (Arz et al., 1998; Behling et al., 2000; Jennerjahn et al., 2004), and speleothem records from Brazil (Wang et al., 2004). Such records imply a direct relationship between a southern ITCZ migration over the equatorial Atlantic Ocean and increased precipitation in the Southern Hemisphere tropics during millennial scale Heinrich events. Paleoclimate records of the last glacial from Africa and South America (Gasse, 2000; Jennerjahn et al., 2004) show elevated precipitation, while records from China (Wang et al., 2001) show reduced precipitation in association with a southward migration of the ITCZ. The ITCZ is an equatorial region that encircles the Earth, where trade winds of the Northern and Southern Hemispheres converge (Wells, 1997). Intense humidity is responsible for almost perpetual thunderstorms within this zone and convection associated with the ITCZ is the primary supplier of precipitation to equatorial regions. Changes in the ITCZ location may result in severe wet and dry periods for intertropical landmasses (Broccoli et al., 2006). For this reason, short and long-term variations in the ITCZ position are of primary importance to nearby regions

where vegetation depends on the availability of water supplied by this system.

The Lynch’s Crater climate record, described herein from a peat core, exhibits new high-resolution geochemical evidence for the possible effects of Heinrich events and millennial-scale climate changes. Lynch’s Crater is located in tropical NE-Australia, which is influenced by the western Pacific Ocean austral summer monsoon system, the ITCZ and the austral winter SE trades. This study focused on several different proxies that are inferred to link environmental and climate change, in order to identify atmospheric and oceanic teleconnections between the North Atlantic and the Southern Hemisphere’s Western Pacific region.

2. Regional setting

Lynch’s Crater (17°37’S, 145°70’E) is situated at 760 m elevation on the undulating plateau of the Atherton Tableland, 30 km from the east coast of North Queensland, Australia (Fig. 1). The crater itself was formed by an explosive volcanic event ~250,000 years ago (Kershaw, 1978), it is approximately 600 m in diameter and contains over 60 m of lake and peat sediments. This study has focussed on the top of 1300 cm of the deposit.

At present, 80% of the mean annual rainfall in the area (2570 mm) falls during the austral summer months of November through March (www.bom.gov.au) as a result of seasonal ITCZ migration. Also of consequence is the South Pacific Convergence Zone (SPCZ) known as the largest and most persistent spur of the ITCZ (Linsley et al., 2006). The SPCZ is a 200–400 km broad zone of low-level wind convergence, high cloudiness, and enhanced precipitation stretching from the ITCZ near the equatorial Solomon Islands to Fiji, Samoa, Tonga and further southeast. The axis of maximum rainfall associated with the SPCZ is known to shift northeast during El Niño events and southwest during La Niña events (Salinger et al., 2001; Folland et al., 2002).

High rainfall in the Lynch’s Crater region allows for the present day growth of luxurious and diverse rainforest vegetation, and it previously favoured peat and lake

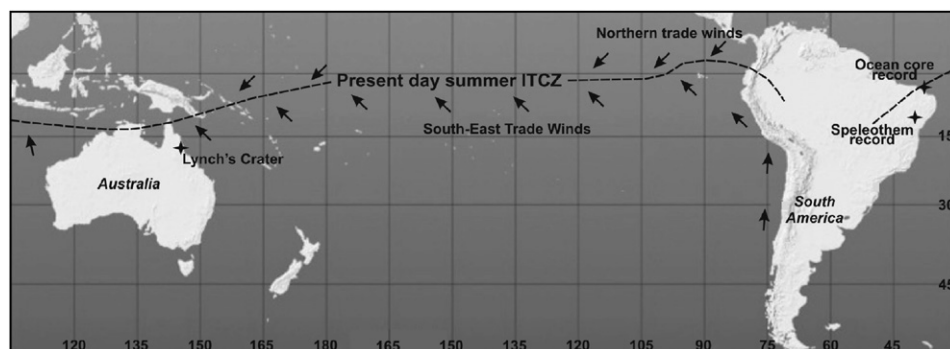


Fig. 1. Locations of records from Lynch’s Crater (this study), the tropical western Atlantic (Jennerjahn et al., 2004) and NE Brazilian speleothems (Wang et al., 2004). The present day summer position for the ITCZ with its associated atmospheric trade winds is indicated as dashed line.

sediment accumulation in depressional settings. Palynological work from Lynch's Crater has identified major vegetation changes in the last ~200,000 years (Kershaw, 1978, 1986). A peat humification study identified climate variations at millennial and orbital time scales over the last 50 ka (Turney et al., 2004) in response to variations in precipitation regimes. From ~50 ka, the pollen record reveals a progression from rainforest to an environment dominated by sclerophyll woodland towards the end of the Pleistocene that illustrates decreasing precipitation, and later, with higher precipitation, a mesophyll vine forest environment during the Holocene (Kershaw, 1978, 1986). The peat humification study showed a correlation between high degree of humification and millennial-scale dry periods that were interpreted as periods of frequent El Niño. The authors found that these dry periods were correlated with D–O warm events in the North Atlantic and additionally found climate cycles at semiprecessional timescales thought to represent dry Heinrich events. In this study we capitalise on a number of proxies from a continuous 1300 cm peat core obtained from Lynch's Crater in 2004. These proxies include geochemical, sedimentological and pollen proxies in order further assess past environmental conditions of this site.

3. Materials and methods

A 13 m long profile record was collected from the centre of Lynch's Crater in July 2003 using a D-section Russian corer. Cores were taken in 50 cm increments continuously from two holes 10 cm apart, so that disturbance is avoided. From 0 to 10 cm a monolith was cut from a hummock using a stainless steel knife and divided into 2 cm increments then packed in plastic bags. In the laboratory, samples at 10 cm increments were placed in plastic bags and freeze-dried. Twenty-one AMS radiocarbon dates were measured at the Australian Nuclear Science and Technology Organisation (ANSTO) and ^{14}C data were calibrated using both IntCal04 and Cariaco Basin datasets (Blockley et al., 2004) (Appendix 1). Bayesian analysis of the data established the robust chronology. Material was analysed for loss on ignition (LOI) after samples were ignited at 450 °C for 12 h to provide the "ash yield" (i.e. content of the inorganic material determined as: ash yield in wt% = 100%–LOI). Scanning electron microscopy (SEM) (JEOL JSM-5410LV) analysis was undertaken to identify the inorganic fraction (Appendix 2). X-ray fluorescence spectroscopy (XRF) was undertaken at the RIAIDT XRF Facility of the University of Santiago de Compostela, to determine Si and Al concentrations. The Si content was normalised to Al (Appendix 2) to approximate the Si content derived from diatom and sponge debris (assuming that diatom and sponge debris contain no Al) versus Si from other sources (atmospheric dust or terrigenous sediments). The proxy of the Si/Al ratio is used to identify more clearly the transitions between peat sections and layers with high biogenic silica contents. Total biogenic

opal content as a percentage of the ash yield was also determined with a single extraction of silica into 2 M Na_2CO_3 (Mortlock and Froelich, 1989) after which samples were run on a spectrophotometer at the University of British Columbia.

As a comparison to our proxies, we used the Cyperaceae (sedge) to Poaceae (grass) ratio from a previous study (Turney et al., 2004) to reveal temporal change in relative abundance and/or coverage of either sedges or grasses. Higher moisture availability at Lynch's Crater probably favour high Cyperaceae/Poaceae ratios, while lower ratios represent drier paleohydrological conditions. N15 isotope data was also used as another hydrological and nutrient proxy (Appendix 2). Nitrogen isotope analyses were obtained using a standard elemental analyser isotope ratio mass spectrometer (EA-IRMS). The mass spectrometer was used to combust organic material that in turn forms N_2 and CO_2 , which were measured on a Thermo Electron Delta C IRMS in a continuous flow mode at the SERC Stable Isotope Laboratory, Florida International University.

4. Results and discussion

In previous work (Muller et al., 2006, 2008), pH and ash yield were used to demonstrate that the top 150 cm of Lynch's Crater is ombrotrophic with a transition zone of ombrotrophic to minerotrophic conditions between 350 and 150 cm depth and minerotrophic conditions between 350 and 1300 cm. The peat lake interface exists further down in the deposit at ~1500 cm.

The peat stratigraphy has been previously described as mostly sapric in nature (Muller et al., 2006). Ash yield is lowest (2–5%) in the top 140 cm of the deposit, compared with other sections of the core, with a high value (31%) in the top 10 cm. Low ash yield is also observed between 900 and 1300 cm (<8%) in the lowermost section of the core and between 610–690 cm (8–10%) and 370–470 cm (7–10%). Within the low ash yield, sapric peat some distinct horizons show sharp increases in ash yield (Fig. 2). From the bottom of the core, sections with elevated ash yield are: 39–40.8 ka (11 wt%), 34–37 ka (18–25 wt%), 32–33 ka (21 wt%), 29–30 ka (25 wt%), 22–25 ka (11 wt%), 18–19 ka (11–13 wt%), 12.5–16.5 ka (18–53 wt%), 8.5 ka (8.5 wt%), and the surface layer (30 wt%). The sections between 34–37 ka and 12.5–16.5 ka are composed of multiple peaks. SEM analysis was required to determine if only mineral matter was present as inorganics may be composed of mineral matter and/or biogenic material. These analyses identified abundant biogenic silica components within these elevated ash-yield sections, namely freshwater sponge spicules (Family *Spongillidae*) and some well-preserved diatom frustules. These SEM analyses are presented in previous work (Muller et al., 2008). A periodic alteration in the Lynch's Crater swamp environment must have taken place in order to accommodate the presence of these layers of high biogenic silica within the peat. Sponge

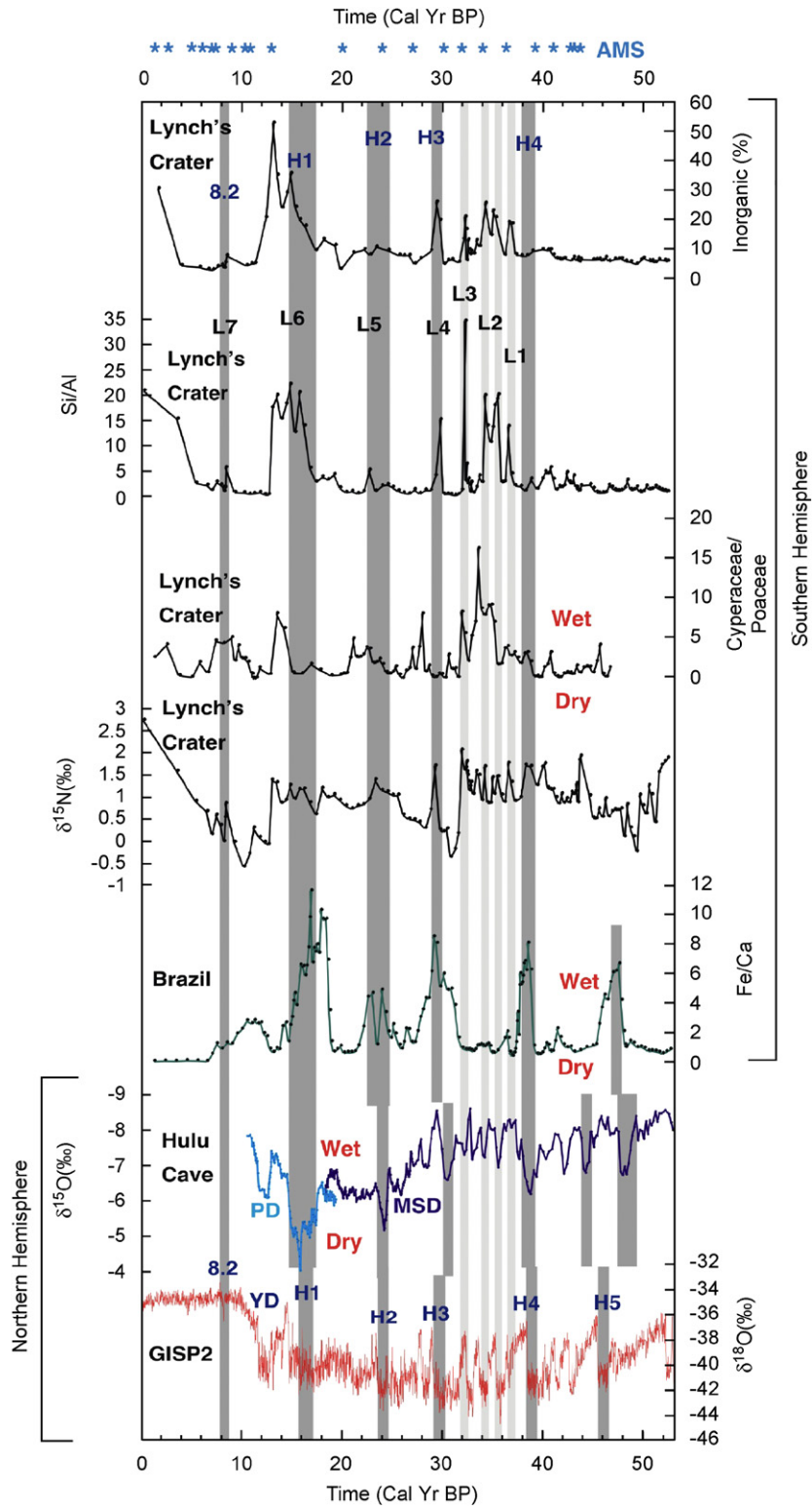


Fig. 2. Ash yield (inorganics), Si/Al ratio, Cyperaceae/Poaceae ratio (Turney et al., 2004) and $\delta^{15}\text{N}$ of bulk material show rapid changes of values that coincide at least with the timing of the 8.2 ka event, and Heinrich 1–3 events (H1–3). Layer 1–7 (L1–7) with high inorganic content and high Si/Al are illustrated. For comparison, the Fe/Ca precipitation proxy from ocean sediments offshore NE Brazil (in green) (Jennerjahn et al., 2004), the $\delta^{18}\text{O}$ isotope record of Hulu Cave speleothems (PD in blue and MSD in purple) (Wang et al., 2001), and the $\delta^{18}\text{O}$ GRIP ice core record (in red) (Dansgaard et al., 1993) are plotted.

and diatom proliferation is the likely result of increased precipitation that temporarily elevated the water level above the peat surface. Under such increased wetness, it is

possible that runoff from the crater wall catchment may have contributed superfluous nutrients to the crater swamp where periods of standing water masses fostered diatom

and sponge growth. This is documented in a case from a Malaysia where peat-forming environments have standing water for a few months of the year (Wüst and Bustin, 2003).

A marked change of biogenic silica productivity is also evident from the Si/Al ratio, which is strongly elevated in the sections with elevated ash yield. Low ash yield peat layers have Si/Al ratios of ~ 1 , whereas high ash yield layers have ratios between 7 and 35. Layer 3 has a Si/Al ratio of $\sim 35\%$, layers 1, 2, 4 and 6 have values of ~ 20 , while layers 5 and 7 have values of 6–7. Changes in terrestrial input composition may influence changes in Si/Al ratios, however, high Si/Al ratios indicate that these layers had a higher Si contribution (e.g. biogenic silica) than the average terrestrial component that accumulated at Lynch's Crater. The determined opaline silica content of selected samples further confirmed the presence of biogenic silica. Of the layers with high Si/Al ratios, opaline silica was as follows: 12% (L1), 20–44% (L2), 43% (L3), 31% (L4), 4% (L5), 54% (L6), respectively, for these periods. Opaline silica was not measured for L7 (limited sample material), but samples with low Si/Al ratio tested contained $< 1\%$ opaline silica and diatom/sponge debris was not confirmed during microscope analysis.

Other data for significant precipitation changes during the last glacial stem from pollen studies (Turney et al., 2004). Most layers with high ash yield and high Si/Al ratios coincide with high Cyperaceae/Poaceae ratios supporting increased soil moisture content during these periods (Fig. 2) and a change in the abundance of sedges versus grasses. In some cases, the Cyperaceae/Poaceae peaks are offset from the Si/Al peaks and display possible time lags (~ 1 ka). A similar time lag of vegetation changes in response to precipitation was also observed in the Brazilian marine sediment record (Jennerjahn et al., 2004). This could be a true time lag in Lynch's Crater, where the response time of the vegetation to wetting has been on the order of ~ 1 ka. However, it is also possible and probably more likely, that it is the result of an offset in the chronology of the core from this study and the Turney et al., core. A coupled precipitation–vegetation change as indicated by the Cyperaceae/Poaceae ratio may be expressed by the $\delta^{15}\text{N}$ data, where heavier $\delta^{15}\text{N}$ values are associated with elevated Cyperaceae/Poaceae ratios (Fig. 2). Variations are probably due to changing nitrogen sources. While fixation of atmospheric N ($\delta^{15}\text{N} = 0\%$) is a major N source of land plants, dissolved inorganic nitrogen (DIN, $\delta^{15}\text{N} \approx 5\text{--}10\%$) is the major N source for aquatic algae (e.g. Wada and Hattori, 1990; Middelburg and Nieuwenhuize, 2001). Aquatic plants discriminate against ^{15}N during DIN uptake leading to a lower $\delta^{15}\text{N}$ than in the DIN reservoir (Talbot and Laerdal, 2000). It is conceivable that during wet periods increased nutrient input promoted primary production of predominantly siliceous algae and sponges leading to the observed heavier $\delta^{15}\text{N}$ values. During dry periods, aquatic primary production was less significant and any N deposited would have been

predominantly derived from atmospheric fixation, resulting in the observed lighter $\delta^{15}\text{N}$ values. Although the $\delta^{15}\text{N}$ record cannot be fully explored at the moment due to its complexity typical for peat deposits (i.e. nutrient influx, vegetation type, water table fluctuations, decomposition processes, etc.), periodic changes seemed to be associated with marked environmental changes as indicated by other proxies.

In summary, the peat deposits of Lynch's Crater show several distinct layers (Fig. 2) with somewhat synchronous high ash yield, high Si/Al ratios, high Cyperaceae/Poaceae ratios and heavier $\delta^{15}\text{N}$ isotopes over the last 55 ka. The layers span the following periods: 29–30 ka, 23–24 ka, 14.5–16 ka, 12.5–13.5 ka, and 8.5 ka and within the limitations of our age model, that are in similar timing with Heinrich events 3, 2, and 1, the Boelling/Alleroed and the 8.2 ka event. These timings are all characterised in the Northern Hemisphere as abrupt climate events (Broecker, 1994; Alley and Ágústsson, 2005). The proxy analyses of the peats of Lynch's Crater indicate increased precipitation during these periods. This interpretation is in line with that of other records of the low latitudes from the Atlantic region, for example in speleothem growth phases from caves in NE Brazil (Wang et al., 2004) and terrigenous discharge events identified in ocean sediments, from offshore NE Brazil (Arz et al., 1998; Behling et al., 2000; Jennerjahn et al., 2004; Fig. 1). The increased tropical precipitation signal corresponds to that of abrupt climate events in the high latitudes.

Heinrich event 4 (recorded in both GISP2 and the Hulu Cave) shows only subtle change in the ash yield or Si/Al record of Lynch's Crater (Fig. 2) and is only represented by small changes in the pollen and $\delta^{15}\text{N}$ proxies. We do not have a robust explanation for why a strong H4 signal is absent from Lynch's Crater. In addition, it is not understood why the rapid oscillating climate changes after the termination of H4, that are also present in both GISP2 and Hulu Cave between 34 and 37 ka (light grey bars in Fig. 2) appear in Lynch's Crater. It is possible that these offsets are a limitation of the radiocarbon dating technique, where deeper, more decomposed peat material has incorporated younger carbon from root material, giving overall younger ages. It is also possible that these changes indicate that past ITCZ migrations are not solely related to Heinrich events and that other dry/cold periods (e.g. Bond-cycles) may have forced the ITCZ southward. In addition, we highlight that Heinrich events recorded in equatorial regions do not always occur in exact timing with abrupt events recorded in Greenland ice as equatorial regions are most likely recording triggers or feedbacks to the Northern Hemisphere high latitude events.

Our record demonstrates abrupt precipitation changes at Lynch's Crater over the last 55 ka and a possible link between the last three Heinrich events and some of the other rapid climate change events (e.g. between 34 and 37 ka ago), including the 8.2 ka cold event of the Northern Hemisphere. Concomitantly, we can attempt to determine

the impact of climate shifts in the Southern Hemisphere and more specifically the western Pacific Ocean during these millennial-scale climate perturbations. We estimate that the duration of environmental changes associated with the timing of Heinrich events are as follows: H3: ~ 1 ka, H2: ~ 2 ka, and H1 ~ 3 ka. The Holocene record of Lynch's Crater suggests that the 8.2 ka event lasted about 400 years and shows lowest ash yield, Si/Al ratios, Cyperaceae/Poaceae ratios and $\delta^{15}\text{N}$ isotopes relative to the other abrupt events described above. This is consistent with paleorecords and climate simulations that describe the climate anomalies of the 8.2 ka abrupt event as smaller, shorter-lived and less extensive than those of older origin (e.g. H1 event) (LeGrande et al., 2006).

Heinrich events are linked to large-scale ice discharge into the North Atlantic that disrupt the North Atlantic Thermohaline Circulation (LeGrande et al., 2006). Modelling studies consistently indicate a resulting slowdown in North Atlantic Deep Water (NADW) formation, the so-called "ocean conveyor" in response to this large freshwater forcing. Previous climate simulations of the 8.2 ka event used coupled general circulation models (GCMs) and showed a slowing down of NADW formation with subsequent cooling in the Northern Hemisphere and southward shift of the ITCZ in the ocean basins (LeGrande et al., 2006); this is consistent with our record which favours wet conditions at ~ 8.2 ka.

In this study a Heinrich-like event was simulated by adding 1 Sverdrup (Sv) of freshwater over 100 years to the North Atlantic, a Sv being the equivalent to 10^6 m^3 of water per second. The simulation resulted in global climate

responses that included widespread cooling in the Northern Hemisphere and alterations in precipitation patterns (Fig. 3). Specifically, precipitation anomalies include a southward migration of the ITCZ and a zonal shift in mid-latitude storm tracks (Broecker, 2006). The model shows that precipitation decreases in the northern subtropics and increases in the southern subtropics, which is consistent with paleoclimate records from northern South America. Our record of increased precipitation during Heinrich events at Lynch's Crater (17°S) also suggest that these periods coincided with a more southward migration of the ITCZ, which is consistent with modelling studies of a shutdown or slowdown of the ocean conveyor and with changes in intra-hemispheric temperature gradients.

Simulations of past ITCZ positions (Broccoli et al., 2006) indicate that increased temperature gradients between the Northern and Southern Hemispheres are the driving mechanism for its southern displacement and that the sea ice extent in the North Atlantic was a major factor influencing the position of the Atlantic ITCZ (Chiang and Bitz, 2005; Kienast et al., 2006). The trigger for the initial increase in this gradient is debatable and its relation to increased warming of the equatorial hemisphere or cooling of the Northern Hemisphere is still in question. Some studies have referred to the low latitudes as driving millennial-scale cycles by changing atmospheric and oceanic circulation patterns (Clement et al., 2001; Koutavas et al., 2002). Paleorecords from the Santa Barbara Basin suggest that the tropical ocean may have played an important role in high-latitude warming during the last glacial (Hendy and Kennett, 1999). Some climate model

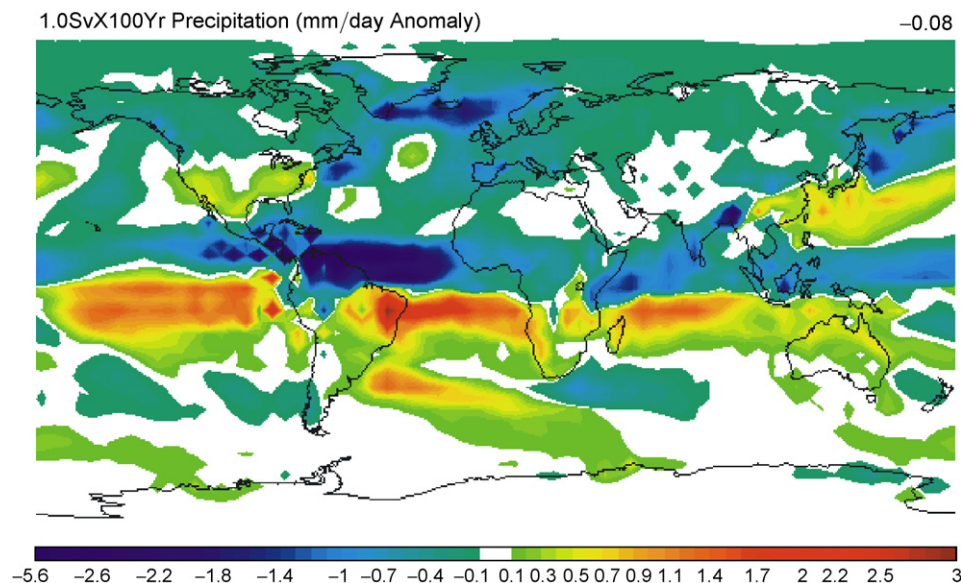


Fig. 3. Simulated precipitation anomalies for 1 Sverdrup ($10^6 \text{ m}^3/\text{s}$) freshwater forcing in the North Atlantic between 50 and 70°N over 100 years, roughly the equivalent of 9 m of sea level change; above is the average precipitation anomaly during the last 20 years of freshwater forcing. This simulation used GISS ModelE-R, a fully coupled atmosphere/ocean general circulation model (Goddard Institute for Space Studies ModelE). The ocean model is non-Boussinesq, mass conserving, and has a full free surface. Freshwater has a prescribed temperature of 0°C and salinity of 0 psu; it is added in a "natural" way, increasing the free surface and reducing salinity purely through dilution. No equivalent salt fluxes or flux adjustments were used. All boundary conditions and atmospheric composition are appropriate to the pre-industrial (circa 1880).

simulations have also identified the possible trigger for abrupt events as changes in mean sea surface temperatures in the tropical Pacific caused by variations in insolation (Clement et al., 2001). This all points to abrupt climate events such as Heinrich events having been triggered by “global warming” or shifts in climate systems that originated in the low latitudes.

Higher chronological resolution and a combination of different dating techniques of long paleoclimate records, such as Lynch’s Crater and other records that propose evidence of past ITCZ migrations would allow us to better address these questions. The role and migration of the ITCZ may be more important than previously thought and could play an important role in the current debate about climate change and ice sheet collapses.

5. Conclusions

The Lynch’s Crater peat record reveals new findings in the debate of abrupt climate change in the past. The data suggests the involvement of the tropical Pacific region during these abrupt events and may indicate an extended southward migration of the ITCZ during events such as H1–3. Although most models with freshwater forcing in the North Atlantic, including the one presented in this study (Fig. 3), show that the tropical Atlantic region responded with higher precipitation anomalies (e.g. Brazil with ~ 3 mm/day) than the tropical western Pacific (e.g. Australia with ~ 0.5 mm/day), the paleorecord of Lynch’s Crater indicates that past Heinrich events may have resulted in much higher precipitation changes in NE-Australia than the model prediction. This highlights the need for models that critically assess the Pacific ocean/atmosphere circulation and interaction during these abrupt climate events. The Lynch’s Crater record of possible past ITCZ migrations demonstrates the efficiency and rapidity of global interconnections between ocean and atmosphere, and from this we can only improve our current understanding of global climate dynamics.

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Appendix A. Supplementary materials

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.quascirev.2007.11.006.

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