**Constraints on the Magnitude of the Deglacial Migration of the ITCZ in the Central Equatorial
Pacific Ocean.**

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Abstract

Accurate paleo-latitudinal reconstructions of the Intertropical Convergence Zone (ITCZ) are necessary for understanding tropical hydroclimate and atmospheric circulation. Paleoclimate models and records suggest that as global temperatures increase, the ITCZ should migrate towards the warmer hemisphere. Many uncertainties remain regarding the magnitude of this migration, and few studies have focused on the Central Equatorial Pacific (CEP). Here, we use eolian dust records recovered from three locations in the CEP to address changes in dust provenance across the paleo ITCZ since the last glacial maximum (LGM). Radiogenic isotope compositions of Nd and Pb show that dust delivered to the CEP was sourced mainly from two regions: East Asia and South America. From these data we deduced that since Marine Oxygen Isotope Stage 2 (MIS2) the ITCZ has migrated north to its modern position, being displaced by as much as 7° , to as little as 2.5° , degrees. We find that the ITCZ migrated further north during the early Holocene (~ 9 kyr), reaching its position furthest north during the mid-Holocene warm interval (~ 7 kyr), based on an increase in South American dust at the northernmost sites.

1. Introduction

The Intertropical Convergence Zone (ITCZ) is a key component of the Hadley Cell circulation; in the Pacific Ocean it lies north of the Equator. The ITCZ is a zone of low atmospheric pressure dominated by convective storm systems where trade winds converge (Philander et al., 1996). Given that dust is effectively scavenged by precipitation, the precipitation maximum associated with the ITCZ acts as a strong barrier to inter-hemispheric dust transport (Rea, 1994). ITCZ paleo-latitude can be used to monitor the extent of the interhemispheric thermal gradient (Chiang and Friedman, 2012), and provides insights into the degree of inter-hemispheric thermal asymmetry in the past. Studying ITCZ paleo-latitude and the sensitivity of the ITCZ to global temperature changes is critical since half the global population

resides in tropical hydroclimates which are dominated by the Hadley cell circulation and impacted by changes in tropical precipitation (Schneider et al., 2014).

Paleo-records indicate that the paleo-ITCZ migrates towards the hemisphere experiencing relative warming (Schneider et al., 2014). The development of an interhemispheric thermal gradient is part of a teleconnection of extra-tropical cooling in the tropical rainfall climate (Chiang and Friedman, 2012). Independent lines of evidence – modelling (Broccoli et al., 2006; Chiang and Bitz, 2005) and paleoclimate observations (Koutavas and Lynch-Stieglitz, 2004) – have shown a link between northern hemisphere cooling and a global southward shift of the ITCZ. However, the mechanism of this connection is not properly understood.

Over the Pacific Ocean the location of the ITCZ varies seasonally between 9°N during the boreal summer and 2°N during the boreal winter (Schneider et al., 2014). Locally, at 160°W, the ITCZ is more narrowly defined, with an annual range between 8°N and 5°N (Adler et al., 2003). The modern location of the zonally averaged annual maximum precipitation more closely follows the maximum precipitation during July-August-September (Adler et al., 2003), when the ITCZ is near its northernmost position. Only a few studies have looked at the changes in the mean position of the ITCZ in the Pacific Ocean, with most focused on the Eastern Equatorial Pacific (EEP). These studies, as summarized by Koutavas and Lynch-Stieglitz (2004), have found that there is a link between increased Northern Hemisphere cooling and a southward displacement of the ITCZ at the EEP during the Last Glacial Maximum.

The direction of migration of the average position of the ITCZ, i.e., a southward shift during Northern hemisphere cooling, seems relatively consistent in both models (Broccoli et al., 2006; Donohoe et al., 2013) and paleodata (Haug et al., 2001; Koutavas and Lynch-Stieglitz, 2004; McGee et al., 2014). The magnitude of the variations, however, can vary substantially.

McGee et al. (2014) calculated a less than 1° shift in ITCZ position over glacial-interglacial transitions, while a more recent study using ^{230}Th fluxes, found as much as a 7° shift at Heinrich stage 11 during the penultimate deglaciation within the Central Equatorial Pacific (CEP) (Jacobel et al., 2016).

Continental mineral dust which accumulates in pelagic sediments provides the only direct information about paleo-atmospheric circulation (Rea, 1994). This dust is mostly sourced from the world's deserts and arid areas, which are located at lower latitudes in the descending branch of the Hadley circulation (Grousset and Biscaye, 2005). In addition to being a recorder of climate change, atmospheric dust directly impacts the Earth's radiative balance by affecting the scattering and absorption of solar radiation (Mahowald et al., 2006).

A combination of different radiogenic isotopic signatures can be used to differentiate between dust source areas because the heterogeneities in exposed rocks can be highlighted in eolian material (Grousset and Biscaye, 2005). Radiogenic isotopic compositions of dust may vary with particle size, but are not altered during transport. Specifically, although Sr isotope ratios can be biased within varying grain size fractions of dust, the isotope ratios of Nd and Pb do not seem to be sensitive to grain size fractionation processes (Grousset and Biscaye, 2005). The $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ isotope ratios vary significantly in dust source areas based on crustal lithology and age (see summary in Grousset and Biscaye, 2005).

The purpose of this research is to investigate the possible changes in the position of the Intertropical Convergence Zone (ITCZ) in response to climate during the past 30 kyr. This time period includes critical moments in Earth's recent climate history including the Last Glacial Maximum (LGM), the deglacial to Holocene transition, and the Holocene thermal maximum. Here, we combine Nd and Pb isotope ratios in an attempt to robustly interpret changes in dust

provenance through time in sediment cores retrieved across a central equatorial Pacific transect that covers the modern extent of the ITCZ. Given that dust is effectively scavenged by precipitation, we interpret changes in hemispheric provenance as displacement of the ITCZ through time. Samples were collected from three piston cores recovered from near the Line Islands ridge. They represent a seven-degree-latitude north-south transect across the modern position of the ITCZ near 160°W. The Line Islands are an ideal location for this study because at this longitude the ITCZ is well defined and has little deflection due to continental masses.

2. Methodology

2.1 Site and sampling

In May 2012, cruise MGL1208 aboard the R/V Marcus Langseth investigated a portion of the Line Islands dominated by a relatively broad volcanic ridge (100–300 km in length; Lynch-Stieglitz et al., 2015). Here, we have selected sediment samples retrieved during that cruise from three piston cores along a North-South Transect, ML1208-37BB (37BB) at 7.04°N, 161.63°W, ML1208-31BB (31BB) at 4.68°N, 160.05°W, ML1208-18GC at 0.59°N, 156.66°W, and ML1208-17PC (17PC) at 0.48°N, 156.45°W, and (Fig. 1). Detailed descriptions of the core sites are available in Lynch-Stieglitz et al. (2015), as well as in a cruise report (Lynch Stieglitz et al., 2012). The most northern core (MGL1208-37BB) coincides with the northern extent of the ITCZ in boreal summer (at 7°N) and our most southern core (MGL1208-17PC) is below the boreal winter position of the ITCZ (at 0.5°N).

The cores record low sedimentation rates, but these cores were chosen because they had some of the highest sedimentation rates from the Line Island transect cores collected. MGL1208-17PC (0.48°N, 2926 m water depth) has an estimated sedimentation rate at the MIS 3/4 boundary of about 3.0 cm/kyr (Lynch-Stieglitz et al., 2015). MGL1208-31BB (4.68°N, 2857 m water

depth) has an average sedimentation rate of about 3.7 cm/kyr (Lynch-Stieglitz et al., 2015).

Lastly, the northernmost core MGL1208-37BB (7.04°N, 2798 m water depth) has the lowest sedimentation rate of 1.54 cm/kyr (Lynch-Stieglitz et al., 2015).

The cores were sampled at 4-cm and 5-cm intervals, allowing for a maximum temporal resolution of approximately one sample every 1000 years for the two southern cores, and one sample every 2500 years for the northernmost core. The identification of the age-depth relationships was developed based on planktonic foraminifera oxygen isotope stratigraphy, as well as carbon-14 dated samples (Lynch-Stieglitz et al., 2015).

2.2 Radiogenic isotope analysis

All work was performed in the clean laboratory of the Williams Radiogenic Isotope Geosciences Facility at Texas A&M University. In order to analyze Pb and Nd isotopes, we first isolated the operationally-defined detrital fraction of the sediment. The first step was to wet-sieve the sediments and isolate the <63µm size fraction. The sieved sediments were then treated to chemically separate the detrital portion based on a sequential extraction procedure presented in (Xie and Marcantonio, 2012) and outlined as follows. The carbonate fraction was digested with a gentle acid to avoid leaching the clay. Ten per cent acetic acid buffered with sodium acetate was added to the sample until no more visible fizzing occurred upon addition of acid. After this step, we leached the authigenic Fe-Mn oxyhydroxide portion of the samples using 0.02 M hydroxylamine hydrochloride with 25% acetic acid. Finally, the samples were placed overnight in a water bath at 80°C with 2M KOH to remove biogenic opal. Once the operationally-defined aluminosilicate fraction was isolated, the samples were dried at 60°C and weighed before being fully digested.

Detrital fractions of the sediment were digested with high-purity concentrated acids. First the samples were placed in a mixture of HF-HNO₃ (5:2) at 120°C for two days. This step was repeated once. Then, the samples were digested with aqua regia at 80°C until dry.

The dissolved samples were first run through an anion exchange (AG1X8, 200-400 mesh), hydrobromic acid column to separate Pb. The Rare Earth Elements (REEs) were collected during the rinse step of the Pb columns and additionally passed through RE Spec (Eichrom) columns to purify the REE fraction. The REE fraction was then loaded onto Ln Spec (Eichrom) columns to purify and separate the Nd from the rest of the REEs. Finally, the isotopic composition of the samples was analyzed for Nd and Pb by Thermal Ionization Mass Spectrometry (TIMS) at Texas A&M University.

Pb was loaded onto rhenium filaments with silica gel and was measured in static mode. Pb isotopes, expressed as the ratio of the radiogenic isotope (²⁰⁶Pb, ²⁰⁷Pb, or ²⁰⁸Pb) to the non-radiogenic isotope (²⁰⁴Pb), were corrected for mass fractionation (0.1%/amu) based on multiple runs of the NIST981 Pb standard. The procedural Pb blank, analyzed with a ²⁰⁵Pb spike, was found to be less than 50 pg, and no blank corrections on the measured ratios were necessary.

Nd was loaded onto rhenium filaments and measured in static mode as the Nd⁺ ion. ¹⁴³Nd/¹⁴⁴Nd ratios were corrected for any Sm interference on mass 144 by monitoring mass 147. ¹⁴³Nd/¹⁴⁴Nd ratios were normalized to ¹⁴⁶Nd/¹⁴⁴Nd = 0.7219. Standard JNdi-1 was run throughout this study and gave a mean value of ¹⁴³Nd/¹⁴⁴Nd = 0.512101 ± 4 ppm (1σ, n= 34). No further corrections were made to the Nd data in this study. ¹⁴³Nd/¹⁴⁴Nd ratios in this study are expressed as ε_{Nd} values (Equation 1), where (¹⁴³Nd/¹⁴⁴Nd)_{CHUR} = 0.512638 is the ¹⁴³Nd/¹⁴⁴Nd ratio of the Chondritic Uniform Reservoir (i.e. Bulk Earth).

$$\epsilon_{Nd} = \left\{ \frac{\left(\frac{{}^{143}Nd}{{}^{144}Nd} \right)_{Sample}}{\left(\frac{{}^{143}Nd}{{}^{144}Nd} \right)_{Bulk\ Earth}} - 1 \right\} \times 10^4 \quad (\text{Equation 1})$$

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150 3. Results

151 3.1 Isotope results

152 The overall range in the $^{208}\text{Pb}/^{204}\text{Pb}$ ratio for all of the samples analyzed is between 37.8 a
 153 39.2, while that for the $^{206}\text{Pb}/^{204}\text{Pb}$ ratio is between 17.8 and 18.9 (Fig. 2; Table S1,
 154 supplementary information). The widest range in Pb isotope values is seen at site 31BB (4.5°N).
 155 At 31BB, the greatest difference in Pb isotope values is found between the glacial samples at
 156 MIS2 (Marine Oxygen Isotope Stage 2) and the Holocene samples. Samples from sites 17PC and
 157 37BB have narrower ranges of Pb isotope values as well as smaller differences between the
 158 Holocene and Glacial samples. There is a difference in the amplitude of the $^{206}\text{Pb}/^{204}\text{Pb}$ and the
 159 $^{208}\text{Pb}/^{204}\text{Pb}$ ranges; however, the trends with time are similar (Fig 2). $^{207}\text{Pb}/^{204}\text{Pb}$ ratios have the
 160 smallest range (Table S1) and, yet, mimic the temporal trend in both $^{206}\text{Pb}/^{204}\text{Pb}$ and the
 161 $^{208}\text{Pb}/^{204}\text{Pb}$ ratios. Due to the strong consistency of the Pb isotope ratios between samples from
 162 site 18GC and 17PC, figures 2 and 3 present the equatorial Pb data as a single composite
 163 (Supplemental section S2).

164 Nd isotope ratios, expressed throughout this study as ϵ_{Nd} , range from -0.2 to -13.3 (Fig. 2,
 165 Table S1, supplementary information). Most of the variation is related to location of the core.
 166 17PC, the equatorial core, has the most positive Nd isotope ratios ($\epsilon_{Nd} = -7.4$ to $\epsilon_{Nd} = -0.2$), while
 167 the northern cores, 31BB ($\epsilon_{Nd} = -12.1$ to $\epsilon_{Nd} = -5.1$) and 37BB ($\epsilon_{Nd} = -13.3$ to $\epsilon_{Nd} = -8.3$) have Nd
 168 isotope ratios that are more negative. We do not include the three data points closest to the top of

core 31BB, because there is evidence that this part of the core is reworked (Lynch-Stieglitz et al.)Table S1; Supplemental Data). We, therefore, only include points from 15 cm and below for this core.

4. Discussion

4.1 Dust sources to the CEP

In order to trace ITCZ migration we differentiated between possible southern and northern hemisphere sources, based on published Nd and Pb isotope ranges in regional studies (potential source ranges shown in Figures 2 and 3). We can sort our data into four different dominant dust source regions, three southern hemisphere South American regions and one northern hemisphere East Asian end member. How delivery of material from these sources varies through time is explored in section 4.3.

Recent work has signaled western South America, through circulation of the SE trade winds, as a main source of dust to the Eastern Equatorial Pacific (e.g. Xie and Marcantonio, 2012, Pichat et al., 2014). The detailed characterization of sources within South America is based on the composition of volcanic and basement rocks on the western part of the continent as characterized and compiled by Mamani et al. (2008) and Mamani et al. (2010), as well as analysis of some suspended riverine sediments in Patagonia (Gaeiro et al., 2007). $^{206}\text{Pb}/^{204}\text{Pb}$ ratios range from 17.5 – 19.0; and ϵ_{Nd} ranges from 4 to – 12. This approach is appropriate since chemical or physical weathering does not further fractionate the Pb and Nd isotope signatures of detrital sediment (Grousset and Biscaye, 2005). Furthermore, in South America, Nd isotope work conducted on detrital-rich margin sediments shows that the Nd signal is dominated by the crystalline rocks of the continent (Jeandel et al., 2007).

In our data we can see the dominant isotopic signature of two sections of the Andes Cordillera, ranging from 16°S to 43°S, the Central Volcanic Zone and the South Volcanic Zone. The Central Volcanic Zone (CVZ), lying between 16° S and 27° S, can be subdivided into two critical regions, north and south. The *Northern Central Volcanic Zone* (N-CVZ), also known as the Arequipa Domain extends from 16° S to 21° S and is characterized by the least radiogenic Pb isotope ratios and medium to low ϵ_{Nd} values ($^{206}Pb/^{204}Pb$ ratios of 17.50 to 18.45; $^{208}Pb/^{204}Pb$ ratios of 37.63 to 38.66; ϵ_{Nd} values between -5.5 and -8; Mamani et al., 2008, Mamani et al., 2010). We suggest that the northern CVZ is the dominant source of dust to 4.5° N (core 31BB) during MIS2, and to 7° N (core 37BB) during the mid-Holocene (Fig. 2).

The *Southern Central Volcanic Zone* (S-CVZ), also known as the Antofalla domain, ranges from 22° S to 27.5° S and is dominated by more radiogenic Pb isotope ratios and higher ϵ_{Nd} values ($^{206}Pb/^{204}Pb$ ratios of 18.50 to 19.00; $^{208}Pb/^{204}Pb$ ratios of 38.86 and 39.00; ϵ_{Nd} isotope values between -3 and -6; Mamani et al., 2008, Mamani et al., 2010). The southern CVZ is likely the dominant source of dust to the equator (cores 17PC and 18GC) during MIS2 and until the mid-Holocene (Fig. 2).

In contrast the *Southern Volcanic Zone* (SVZ), which was estimated by Pichat et al. (2014) to be the main source of dust to the EEP through the deglacial, lies further south and extends from 33° S to 43° S. The SVZ is characterized by $^{206}Pb/^{204}Pb$ ratios of 18.5 to 18.7 and $^{208}Pb/^{204}Pb$ of 38.3 to 38.6 (Pichat et al., 2014), and relatively radiogenic neodymium isotope values from -2 to +2 (Gaiero et al., 2007). We suggest that the SVZ is the dominant source of dust to the equatorial site (17PC) during the mid-Holocene (Fig. 2).

Our northern hemisphere end member is dominated by an Asian Loess signal, most closely identified with the fine-grained fraction of sediments from the Chinese Loess Plateau

($^{206}\text{Pb}/^{204}\text{Pb}$ ratios between 18.82 and 18.98, and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios between 39.04 and 39.20; Sun and Zhu, 2010; ϵ_{Nd} values that range between -10 and -11.5; Rao et al. 2008, Wang et al. 2007, Zhang et al. 2015). Our Asian end-member is consistent with the findings of Pb isotope ratios in the detrital component of North Pacific sediments (Jones et al., 1994, 2000). Asian Loess is the main source of dust to 7° N (37BB) through MIS2 until the mid-Holocene, and to 4.5° N (31BB) during MIS2 (Fig. 2).

Much of the geochemical variation in dust from East Asia is captured in the signature provided by $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratios (Zhang et al., 2015). Unfortunately, we could not analyze our samples for $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratios because research shows that within 5° of the equator separated detrital material is easily contaminated with detrital barite (Xie and Marcantonio, 2012). This barite, characteristic of high-productivity areas (Paytan et al., 1996), is enriched in seawater Sr, which overwhelms the total detrital Sr isotope signature. In contrast, Xie and Marcantonio (2012) demonstrated that the ϵ_{Nd} values of detrital material in the EEP was free of barite influence, most likely due to the low relative concentration of neodymium in barite relative to dust (Martin et al., 1995). Similarly, leaching experiments by Pichat et al. (2014) concluded that there is little variation in the isotopes of Pb between different leached phases of the sediment, and that the bulk sediment record of Pb isotopes closely matches that of the eolian input, showing that barite contamination is not a major concern for the isotopic composition of residual Pb. Therefore, the Pb and Nd isotope ratios of our operationally-defined detrital components are sufficient to differentiate between the two main sources of dust (Asian Loess and South American volcanics) delivered to the CEP (Fig. 3).

4.2 Particulate matter from the Pacific Equatorial Undercurrent

Material from Papua New Guinea (PNG) can be carried to the CEP by the Equatorial Undercurrent (EUC). Particulate and dissolved traces have been found as far east as 140°W (Ziegler et al., 2008). The EUC flows eastward along the equator within a narrow latitudinal band of $\pm 2^\circ$, weakening dramatically outside of this range (Lukas and Firing, 1984). In this study, the only core that can be potentially influenced by particulate material from the EUC is 17PC (at 0.5°N). PNG materials are very radiogenic with respect to Nd and less radiogenic with respect to Pb ($\epsilon_{Nd} = +8$ to $+9$; $^{206}Pb/^{204}Pb = 17.5-18.5$; $^{208}Pb/^{204}Pb = 37.25-38.50$; Kennedy et al., 1990, Part et al., 2010). Work by Costa et al. (2016) on these Line Islands cores, spanning the same time frame studied here, suggests a very limited influence of the EUC in the detrital fraction of sediment from these cores. They base this suggestion on their estimated levels of productivity during the LGM that are low, despite dust fluxes that are 2-3 time higher during the same time period. Costa et al. (2016) suggest that a limited EUC influence, might be attributed to a decreased riverine discharge associated with regionally dry conditions in PNG (Reeves et al., 2013). Here, we offer further evidence for limited influence of EUC particulates on the detrital component of sediments of the CEP, as *both* our Pb and Nd isotope ratios are consistent with a South American provenance, and show no evidence for PNG material. More specifically, we attribute the higher ϵ_{Nd} values in core 17PC during the mid-Holocene, to an increased influence of dust from the Southern Volcanic Zone (Gaiero et al., 2007). Moreover, for a given $^{206}Pb/^{204}Pb$ isotope ratio, the $^{208}Pb/^{204}Pb$ ratio in our samples is far too radiogenic, and thus inconsistent with a PNG provenance.

4.3 Provenance changes over time

Based on both the Pb and the Nd isotope values, the provenance of the dust in the northernmost core (37BB) at 7.04° N is consistent with Asian Loess from the early Holocene

throughout MIS2 (Fig. 2). While there is some overlap in the Pb isotope range of Asian Loess and the S-CVZ, the ϵ_{Nd} values in our samples ($\epsilon_{\text{Nd}} = -8.3$ to -11.8) have a clear Asian loess dominance (Zhang et al., 2015). The most recent sample from 37BB, at 6.6 kyr BP has a more radiogenic Nd isotope value ($\epsilon_{\text{Nd}} = -6.6$) suggesting a provenance change to a southern hemisphere source, either the N-CVZ or the S-CVZ (Fig. 2).

The core at 4.5° N (31BB) records the most change through time with respect to Pb isotope ratios (Fig. 2). Values before the Holocene are consistent with a Northern Hemisphere provenance, interpreted here as derived from Asian Loess (Sun and Zhu, 2010). The Nd isotope values during this period are mostly in the upper range of Asian Loess (Zhang et al., 2015), but are very distinct from either the S-CVZ (Mamani et al., 2008) or the SVZ (Gaiero et al., 2007) (Fig. 2). During the Holocene the provenance of the dust has a signature consistent with the Southern Hemisphere, specifically dominated by the N-CVZ in South America (Mamani et al., 2010) (Fig. 2).

The provenance of the dust in the equatorial core (17PC) is more consistent with a S-CVZ source through most of the study period. For the same core, during the latter half of the Holocene there is a progressive increase in the neodymium isotope ratios from $\epsilon_{\text{Nd}} = -3.9$ at 8.9 kyr BP to $\epsilon_{\text{Nd}} = -1.1$ at 3.7 kyr BP, and little change in the Pb isotope ratios over the same time period. We suggest this variation is due to an increase in dust that is sourced from the SVZ (Fig. 2).

Taking into account both the Pb and Nd isotope ratios, it is possible to group the provenance of the dust at these study sites into four groups (Fig 3). Three are Southern Hemisphere sources in South America (the S-CVZ, the N-CVZ, and the SVZ) and one is a Northern Hemisphere source (Asian Loess). Figure 3 more clearly illustrates the shift in the

provenance of dust in core 31BB (4.5° N) between the glacial and the deglacial. More importantly, our radiogenic isotope data identify changes in source provenance regardless of whether or not there are changes in dust flux. Indeed, along the same 7-degree transect, Costa et al. (2016) found that the variability of dust flux within the Holocene, or the glacial, period across the transect is negligible when compared to the more than doubling of dust fluxes between the same time periods (Costa et al., 2016). One might expect that a transition between northern and southern hemisphere dust delivery would be associated with a sharp decrease in dust flux at varying times and positions within the transect, but these fluxes remain constant across the entire 7-degree transect during the same time slices. On the other hand, in the equator core studied here, Jacobel et al. (2016) argued for displacement of the ITCZ using evidence for changes in dust flux at the penultimate termination, during which differences between northern and southern hemisphere dust fluxes are greater than within the Holocene or the glacial periods.

4.4 ITCZ migration

Studies of the past 30 kyr from different regions tend to agree with a southern displacement of the ITCZ at the LGM, providing evidence for reduced precipitation, a weakened summer monsoon and increased winter trade winds in the Northern hemisphere, and increased precipitation in central South America and Northern Australia (McGee et al., 2014 and references therein). In the Atlantic Ocean, researchers studying shifts in past sea-surface salinities and temperatures have estimated a 7° meridional southward shift of the ITCZ during the LGM compared to its modern mean position (Arbuszewski et al., 2013).

As the ITCZ acts as a barrier for inter-hemispheric dust deposition, meridional changes in dust provenance help us to locate the paleo-position of ITCZ (Fig. 4). Samples from 17PC consistently have a South American provenance throughout the Holocene and the Glacial

(mostly S-CVZ, but a hint of SVZ in latest Holocene; Figures 2 and 3). Site 31BB shows the most heterogeneity in the provenance of dust, with glacial samples having provenance dominated by Asian Loess, and Holocene samples showing dust provenance consistent with the N-CVZ. For site 37BB at 7.04°N there are only nine data points in the studied time period (i.e., past 30 kyr), and this is mostly due to the very low sedimentation rate (1.54 cm/kyr, Lynch-Stieglitz et al., 2015). Between 10 kyr BP and 28.4 kyr BP, the Nd and Pb isotope systematics suggest an Asian Loess provenance (Figures 2 and 4). However, the Nd isotope ratio measured at site 37BB for the most recently deposited sediment (6 kyr BP) suggests a Southern Hemisphere source ($\epsilon_{Nd} = -6.6 \pm 0.3$), consistent with published work hypothesizing that the ITCZ migrated further north during the mid-Holocene, and then migrated south to its modern position (Arbuszewski et al., 2013; Donohoe et al., 2013; McGee et al., 2014). We do not have data for locations between 4.5°N and 0.5°N and, hence, cannot further constrain the ITCZ shift to better than between 2.5° and 7° in the CEP (Fig. 4).

Work by Xie and Marcantonio (2012) did not find evidence of Asian Loess dust in the EEP, but these authors did suggest that the ITCZ shifted further north during the deglacial, in agreement with our data. Models suggest that the greatest displacement of the ITCZ happens during Heinrich stadials (Chiang and Bitz, 2005). This interpretation has support from Jacobel et al. (2016) based on ^{232}Th dust fluxes that indicate a displacement of the ITCZ south of the equator during Heinrich 11 at the termination of the penultimate glacial. Unfortunately, we do not have the spatial, nor the temporal, resolution to determine whether the position of the ITCZ was further south during Heinrich 1 (~17 kyr) than that during the Last Glacial Maximum (21 kyr). Nevertheless, we suggest that the ITCZ did not migrate south of 17°PC during the past 30 kyr, as we do not see a substantial excursion in the Nd isotope record that would be associated

with an influx of dust of Asian provenance if the ITCZ had migrated below 17°PC. Given the robustness of the Nd and Pb isotope tracing capabilities in the CEP, we will focus future work on Heinrich stadial 11, to address and test the intriguing hypothesis put forward by Jacobel et al. (2016) which suggests a southward displacement of the ITCZ during a stadial event of the penultimate deglaciation.

4.5 Changes to the Southern Hemisphere Branch of the Hadley Cell

As with the position and changes to the ITCZ, the scientific community has been equally puzzled by the behavior of the Southern Hemisphere westerly winds (SWW) during glacial and interglacial stages (Kohfeld et al., 2013). Like the ITCZ the SWW are an important driver of climate change, and large-scale ocean circulation (Toggweiler and Samuels, 1995). Moreover, changes in the position and strength of the SWW might affect the ventilation of the Southern Ocean and, consequently, have a role in triggering glacial terminations through changes in the global carbon cycle (e.g. Anderson et al., 2009; Anderson and Carr, 2010). Deciphering the relationship between the ITCZ and the SWW could lead to clues that are crucial in determining changes to the southern hemisphere branch of the Hadley Cell through time. There is disagreement among scientists about the behavior of global SWW on glacial-interglacial timescales (Kohfeld et al., 2013), but we believe that contrasting our findings with recent work in the EEP (Pichat et al. 2014) can bring new light to these discussions.

Pichat et al. (2014) interpreted changes in the Pb isotope ratios of the detrital component through time in core ODP849 (at 110° W, 0.1° N) as reflecting changes in the contribution of dust to the EEP by the S-CVZ and the SVZ, with material from the SVZ dominating the Holocene dust flux. These changes suggest that during MIS2 the SWW were further north, thus allowing dust loading from further North in South America, and then migrated further south

during the last termination. Our equatorial record from site 17PC similarly shows a S-CVZ source of South American dust during MIS2. Although there is a migration toward a more southerly provenance for dust from the SVZ later in record, the shift does not occur until the mid-Holocene (Fig. 2).

To summarize, during the LGM, the more northerly South American provenance of dust (i.e., S-CVZ) delivered to the equator in the CEP (our work here) and the EEP (Pichat et al., 2014) suggest a scenario in which the SE trade winds are shifted equatorward. In tandem with the northward shift in South American dust sources at equator core during MIS2, there is a southward shift in ITCZ as documented by the Asian dust signals at site 31BB. Taken together, these shifts imply a constriction of the southern hemisphere trade wind belt (and Hadley Cell) towards the equator (from the N and the S).

A poleward migration of trade winds is suggested by the more southerly sources of South American dust (i.e., SVZ) determined during the deglacial in the EEP (Pichat et al., 2014) and the mid-Holocene in the CEP (our work here). In addition, during the Holocene, South American dust is delivered further north to site core 31BB (4.5° N) implying a northward displacement of the ITCZ. Later, during the mid-Holocene, South American dust is implicated even further north at site 37BB (7° N; Fig 4). Taken together, the data for the equatorial Pacific suggest that during the Holocene, there is a northward migration of the ITCZ that is contemporaneous with an expansion of the trade wind belt toward the pole. A contraction (MIS2) and expansion (Holocene) of the Hadley Cell likely coincide with a northward and southward migration, respectively, of the SWW. Researchers studying Holocene sediments from the Atlantic Ocean have also shown a simultaneous poleward displacement of the SWW (Voigt et al., 2015), and a northward shift in the ITCZ (Arbuszewski et al., 2013) from the early to the mid-Holocene.

These findings are not in agreement with model results, which suggest that during the LGM, due to the smaller inter-hemisphere temperature contrast, the Hadley Cell should, in fact, expand, and then contract during the Holocene (Rind and Perlwitz, 2004).

4.6 Large meridional displacements of the ITCZ: models versus observations

McGee et al. (2014) estimated that displacements of ITCZ migration larger than 1° can only happen in limited regional settings. Our work suggests that the ITCZ at the CEP was at least 2.5° degrees further south during MIS2 than during the early Holocene— south of core 31BB (4.5° N), but north of core 17PC (0.5° N) during the glacial, and north of core 31BB but south of 37BB (7° N) during the Holocene (Fig. 4). Such displacements are significant, although less than those estimated in the Atlantic (range of $\pm 7^\circ$) between the LGM and the Holocene (Arbuszewski et al., 2013).

Most paleo-records that document changes in the position of the ITCZ base their interpretations on proxy records that either reflect changes in the location of maximum precipitation (e. g. Wang et al., 2001) or sea surface temperature (e. g. Koutavas and Lynch-Stieglitz, 2003). These records are often land based. For example, Wang et al.'s (2001) record from Hulu Cave speleothems correlates the predicted changes in precipitation with a migration of the ITCZ. Haug et al. (2001) used titanium concentrations in Cariaco Basin sediments as a proxy for increased riverine discharge, itself a symptom of an ITCZ migration. Importantly, it is not possible to discount the possibility that measured changes in precipitation can be due to a shift in the position of the ITCZ or to a change in its rainfall intensity (Schneider et al., 2014). Our estimates, however, are not based on, or altered by, precipitation amount, and we can therefore decouple the location of the mean ITCZ with potential changes in ITCZ intensity (and thus precipitation amount) between the LGM and the Holocene.

McGee et al. (2014) estimated the position of the ITCZ based on estimates of tropical SST gradients and the modelled relationship between the paleo ITCZ position and SST changes. Their models generally were in agreement with a migration of the ITCZ toward the warmer hemisphere. However, the model was not consistent with the large ITCZ displacements interpreted by the paleo-record observations (e.g. Arbuszweski et al. 2013). They attributed the discrepancy between their estimates and larger published shifts to a decoupling of precipitation records from the ITCZ position, or to zonal heterogeneity. The latter allows for very large local changes in the ITCZ along some longitudes, as long as changes at other longitudes are near zero. Previous models have argued that changes to the ITCZ position must be zonally homogenous (Frierson and Hwang, 2012), but we suggest that there is indeed some heterogeneity, at least between different oceans, as our estimates of migration at the CEP are smaller than previous observations in the Atlantic during the same time period ($\sim 7^\circ$; Arbuszweski et al., 2013).

Other studies using dust provenance in the Pacific, but in the EEP, have found conflicting information regarding the magnitude of the migration of the ITCZ. A Nd isotope study of dust provenance by Xie and Marcantonio (2012) did not find evidence for a significant displacement of the ITCZ between the LGM and the Holocene, contradicting the SST data for a similar location (e.g. Koutavas and Lynch-Stieglitz, 2003). However, a similar study in the EEP using Pb isotope ratios by Pichat et al. (2014) did associate changes in the dust provenance in the EEP to a southward retreat of the SWW during the Holocene, which might be concurrent with a northward migration of the ITCZ as suggested in this study.

Work by Donohoe et al. (2013) demonstrates that the relationship between the cross-equatorial heat transport and the position of the ITCZ is robust, as reflected by both models and observations. However, the relationship between the location of maximum precipitation, and the

change in the SST gradient is more variable. Modeled work has shown that different climate states have varying relationships between the latitudinal change in the ITCZ position and the change in the tropical SST gradient (Donohoe et al., 2013; McGee et al., 2014). We suggest that dust provenance records can be used as an independent constraint for ITCZ paleo-position, and together with SST observations, a more precise quantitative relationship between changes in tropical SST gradients and the location of the ITCZ can be calculated for each climate state. This would allow researchers to use SST gradients, for which there is more abundant information, to more accurately calculate the position of the ITCZ. Unfortunately, there are no current estimates for the change in the SST gradient in the CEP between the Holocene and the LGM.

5. Conclusion

The ITCZ is an important hydroclimate element that affects the lives of billions of people, and understanding its sensitivity to hemispheric temperature gradients is critical to accurately predicting its behavior in the future. This work has shown that it is possible to successfully use radiogenic isotopes (Pb and Nd) to fingerprint the potential sources of dust, and trace ITCZ migration in the CEP during the past 30 kyr. The radiogenic isotope evidence, combined with other literature data (Jones et al., 1994, 2000), as well as robust atmospheric circulation models (e.g., Mahowald et al., 2011), has allowed us to narrow potential dust sources to the CEP as being either from Asia or South America. The most northern core (37BB) reflects a dust signal dominated by Asian loess, as most starkly reflected in the Nd isotope data. The equatorial core (17PC) has a dust provenance dominated by South American sources (S-CVZ and SVZ), while the middle core (31BB) at 4.5°N incorporates dust sources from both Asian and South America (N-CVZ).

These changes in dust provenance that the ITCZ has shifted south of its modern position by least 2.5 °, but less than 7 °, during the last glacial cycle. The direction of this shift is consistent with previous work, both in modelling (Broccoli et al., 2006; Chiang and Bitz, 2005) and observations (Arbuszewski et al., 2013; Koutavas and Lynch-Stieglitz, 2003; McGee et al., 2014). The magnitude of the shift, however, is much larger than the global estimated change of less than 1° (McGee et al., 2014), and further work is needed to explain the discrepancy between modelled estimates of ITCZ position and observations.

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Figure Captions

Figure 1. Bathymetric map with the location of the sediment cores from cruise MGL-1208. The yellow stars are the cores used in this study: 17PC--0.5° N, 18GC--0.6°N, 31BB--4.5° N, and 37BB--7° N. The red dots mark cores with oxygen isotope data discussed in Lynch-Stieglitz et al. (2015) while the white dots are cores with multi-sensor track (MST) data only. Modified from Lynch-Stieglitz et al. (2015).

Figure 2. a) $^{208}\text{Pb}/^{204}\text{Pb}$, b) $^{206}\text{Pb}/^{204}\text{Pb}$, and c) Nd isotope ratios plotted against time for all cores (17PC*, blue; 31BB--4.5° N, red; and 37BB--7° N, green). MIS 1 (Holocene) and MIS 2 (shaded) time periods are based on planktonic foraminifera $\delta^{18}\text{O}$ (shown only for core 17PC in panel d) and radiocarbon analyses (Lynch-Stieglitz, 2015). 17PC* is a composite equatorial core consisting of samples from core 17PC at 0.5° N and 18GC at 0.6° N (see section S1). The error bars represent standard errors. Possible dust source interpretations are marked by dashed lines. The South Central Volcanic Zone (S-CVZ, yellow) and the North Central Volcanic Zone (N-CVZ, orange) Pb and Nd ranges are from Mamani et al. (2010), and references therein. For the South Volcanic Zone (SVZ, pink) the Pb isotope range is based on Pichat et al. (2014) and references therein, and the Nd isotope range is from Gaiero et al. (2007). The Pb isotope ranges for Asian loess (dark green) are from Sun and Zhu. (2010), while the Nd values for Asian Loess from Zhang et al. (2015).

Figure 3. $^{206}\text{Pb}/^{204}\text{Pb}$ versus ϵ_{Nd} for all three sites (17PC--0.5° N, blue circles; 31BB--4.5° N, red squares; and 37BB--7° N, green triangles). The error bars represent standard errors. Filled shapes are Holocene samples, and open shapes are glacial samples. Possible dust source interpretations

are marked by dashed lines and the shaded areas. Note that the largest temporal shift occurs between Holocene and glacial samples in 31BB. The South Central Volcanic Zone (S-CVZ, yellow) and the North Central Volcanic Zone (N-CVZ, orange) Pb and Nd ranges are from Mamani et al. (2010), and references therein. For the South Volcanic Zone (SVZ, pink) the Pb isotope range is based on Pichat et al. (2014) and references therein, and the Nd isotope range is from Gaiero et al. (2007). The Pb isotope ranges for Asian loess (dark green) are from Sun and Zhu. (2010), while the Nd values for Asian Loess from Zhang et al. (2015).

Figure 4. ITCZ migration over time. All data points are marked along the dashed lines representing the core latitude. The arrows show the minimum ITCZ displacement (solid line) and the maximum ITCZ displacement (dashed line) for each time period. The blue arrows indicate a southern shift and the red arrow a northern shift (without an upper constraint). The color of each data point indicates the provenance interpretation: Asian Loess (dark green), North Central Volcanic Zone (N-CVZ; orange), South Central Volcanic Zone (S-CVZ; yellow), South Volcanic Zone (SVZ; pink). The pink area shows the boreal summer ITCZ position over the CEP, as recorded by the local annual maximum precipitation, in the global precipitation climatology product (GCP) version 2.2 from NOAA (Adler et al., 2003).

Figure 1

Figure 2

Figure 3

Figure 4