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Climate-related response of dust flux to the central equatorial Pacific over the past 150 kyr

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ABSTRACT

High resolution paleoclimate records from low latitudes are critical for understanding the role of the tropics in transmitting and generating feedbacks for high-latitude climate change on glacial–interglacial and millennial timescales. Here we present three new records of $^{230}Th_{xs,0}$-normalized ^{232}Th-derived dust fluxes from the central equatorial Pacific spanning the last 150 kyr at millennial-resolution. All three dust flux records share the "sawtooth" pattern characteristic of glacial–interglacial cycles in ice volume, confirming a coherent response to global climate forcing on long timescales. These records permit a detailed examination of millennial variability in tropical dust fluxes related to abrupt perturbations in oceanic and atmospheric circulation. Increases in dust flux in association with at least six of the longest Greenland stadials provide evidence that abrupt, high-latitude climate oscillations influenced the atmospheric aerosol load in the equatorial Pacific, with implications for both direct and indirect effects on the tropical energy balance. Our latitudinal transect of cores captures shifts in the position of the Intertropical Convergence Zone (ITCZ) in response to variations in the interhemispheric thermal gradient associated with cooling in Greenland and bipolar seesaw warming in Antarctica. These observations demonstrate that changes in the energy and hydrologic balance of the tropics were repeated features of the penultimate deglaciation, last glacial inception and last glacial cycle, and highlight the role of the tropical atmosphere as a dynamic and responsive component of Earth's climate system.

1. Introduction

Windblown mineral dust plays a critical role in the climate system through its alteration of radiative forcing, surface albedo, significance as cloud and ice condensation nuclei, and ability to enhance biological sequestration of carbon (review in Mahowald et al., 2014). Long, high-resolution records of mineral dust flux exist from sites in Antarctica (Lambert et al., 2012) and Greenland (Ruth et al., 2007), but no equivalent reconstructions exist from the tropics where the atmospheric load of dust can be especially important due to high incoming solar radiation and large convective potential. Previous work has reconstructed dust fluxes in the tropics at low resolution (Anderson et al., 2006; McGee et al., 2007), and has been critical in establishing that global dust fluxes demonstrate coherent cyclicity over at least the last 500 kyr (Winckler et al., 2008). Despite these advances, the temporal and spatial resolution of existing tropical dust flux records has limited our ability to draw conclusions about low latitude climate responses and feedbacks. For example, the identification of millennial stadial events in equatorial dust fluxes has been challenging due to insufficient data resolution. Abrupt dust flux changes that would be smoothed out by bioturbation in low sedimentation rate environments, or hidden in noisy proxy reconstructions are important for interpreting the far-field implications of high latitude climate shifts with significant consequences for tropical radiative balance. Additionally, although geographically proximal dust flux reconstructions have the potential to inform our understanding of spatially variable dust removal processes, the temporal span of such records is limited (McGee et al., 2007). Multiple archives yielding proxy data with high temporal resolution and a low signal to noise ratio have the potential to reveal information about regional climate variability. The value of this type of approach was recently demonstrated using dust flux records to identify major shifts in tropical hydrology at the termination of the penultimate glacial period (Jacobel et al., 2016). Reconstructing records of tropical dust fluxes over glacial cycles at sub-millennial scale resolution is important as we try to un-

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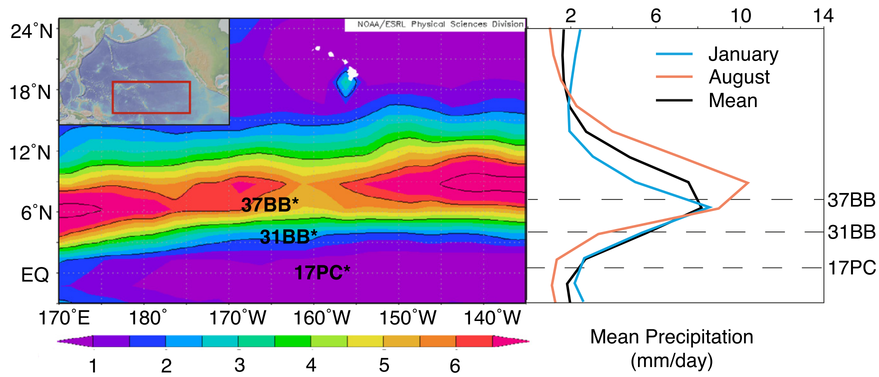

Fig. 1. Map of study area. ML1208 core sites 37BB, 31BB and 17PC (black stars) are shown relative to Hawaii (white islands), and mean annual precipitation in mm per day (colors) at left of figure. Inset shows the location of this map (red rectangle) in the broader context of the Pacific Ocean. Panel at right indicates the mean annual distribution of precipitation (black line) at 160°W as well as the long term mean precipitation during the months of January (blue line) and August (orange line). Basemap generated using the global precipitation climatology product (GPCP) version 2.2 and histograms generated using Climate Prediction Center long term mean data, both from National Oceanic and Atmospheric Administration's (NOAA's) Physical Sciences Division, Earth System Research Laboratory. Inset generated in GeoMapApp. Figure and caption modified from Jacobel et al. (2016). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

derstand linkages between high and low latitude climate and the mechanisms of climate forcing and feedbacks.

In tropical ocean basins far from continental sources, the most important removal mechanism for dust is wet deposition by the Intertropical Convergence Zone (ITCZ), which efficiently scavenges particles from the atmospheric column (McGee et al., 2007; Schlosser et al., 2014) and acts as a barrier to interhemispheric dust transport (Xie and Marcantonio, 2012; Pichat et al., 2014). The mean position of the ITCZ is often identified via satellite imagery as the latitude at which precipitation, and consequently wet-deposition of aerosols (Schlosser et al., 2014), is at an annual maximum. The ITCZ forms where northern and southern hemisphere trade winds converge and convection occurs. On long timescales, the mean position of the ITCZ is responsive to the latitude of Earth's thermal equator (Schneider et al., 2014) with the ITCZ shifting towards the differentially warming hemisphere. This behavior has been demonstrated in model simulations and paleoclimate reconstructions for glacial–interglacial climate shifts (Chiang et al., 2003; Arbuszewski et al., 2013), abrupt stadial events (Wang et al., 2004; Chiang and Bitz, 2005; Jacobel et al., 2016), and even changes during the historical period arising from hemispherically asymmetric aerosol loading (Ridley et al., 2015). This interplay of forces influencing ITCZ position adds complexity that makes a simple determination of ITCZ sensitivity to thermal perturbations difficult, hindering our predictive capabilities.

Addressing questions about past ITCZ shifts and their causes is important not only in establishing the range of responses to asymmetric climate forcing, but also because perturbations of the ITCZ may act to alter global atmospheric circulation patterns. Modeling work has shown that changes in ITCZ latitude influence the position of the Southern Hemisphere Westerlies (Lee et al., 2011), a key component of the Southern Ocean deglacial upwelling hypothesis (Anderson et al., 2009). Recent work has indicated that a southward shift of the Pacific ITCZ at least 4.5 degrees south of its present day latitude accompanied the deglacial stadial event that punctuated the penultimate deglaciation (~150–120 ka) (Jacobel et al., 2016). This shift of the ITCZ may have driven significant changes in global atmospheric circulation patterns, contributing to the conditions required for deglaciation. In sum, existing evidence suggests the position of the ITCZ is a key indicator of and intermediary player in global climate change, making long, high spatiotemporal resolution records of its behavior essential in developing a comprehensive picture of past climate.

Here we present high-resolution records from a latitudinal transect of three sediment core sites in the central Equatorial Pacific to constrain ITCZ movement and position via the quantification of dust fluxes from the penultimate deglaciation, through the last glacial inception, last glacial maximum and last deglaciation. Our records are the first to constrain equatorial Pacific dust fluxes at sub-millennial resolution over this entire time period, allowing us to examine the sensitivity of both tropical dust fluxes and the ITCZ to a range of perturbations, occurring over a variety of timescales. Here we focus our discussion on the last glacial inception and the last glacial period ~120–20 ka, as we have previously considered the penultimate deglaciation at high resolution (Jacobel et al., 2016) and a detailed comparison of the last two deglaciations (Terminations I and II) is forthcoming (Jacobel et al., in prep.).

2. Study area, sediment cores and age models

Three cores were selected for this study, forming a north-south transect in the central equatorial Pacific (cruise ML1208) (Fig. 1). All cores were taken near the Line Islands archipelago, a north-south trending chain of atolls. Core ML1208-37BB (hereafter 37BB) was recovered from 2,798 m of water at 7.04°N, 161.63°W, core ML1208-31BB (31BB) from 2,857 m of water at 4.68°N, 160.05°W and core ML1208-17PC (17PC) at 0.48°N, 156.45°W from a water depth of 2,926 m. Core sediments are composed primarily of foraminifer sands with correspondingly high calcium carbonate content. Site 37BB is located near the maxima in mean annual precipitation associated with the modern ITCZ (~7°N) (at 160°W), site 31BB is just south of both the boreal winter and mean annual precipitation maxima, and site 17PC is consistently south of the seasonally shifting ITCZ (Fig. 1).

Age models for the cores (Supplementary Fig. 1) are based on G. *ruber* (planktonic) foraminifera $\delta^{18}O$ isotope stratigraphies and radiocarbon dates (Lynch-Stieglitz et al., 2015), a portion of which were newly obtained for this study (Supplementary Note 1 and Table 1). Planktonic isotope stratigraphies were used to constrain chronologies beyond the range of radiocarbon via tuning to the LR04 benthic stack (Lisiecki and Raymo, 2005) using MonteXCM (Hoffman et al., 2015), making these chronologies distinct from those previously published by Lynch-Stieglitz et al., 2015. MonteXCM is a modified Monte-Carlo-enabled cross-correlation maximization scheme coupled with a random walk algorithm to assign age–depth relationships at control points based on the statistical match between the input data (planktonic $\delta^{18}O$) and a target chronology (the LR04 stack) within the analytical uncertainties of both data sets. Age control points from MonteXCM were passed into Bchron's 'Bchronology' function (Haslett and Parnell, 2008) to better constrain the age uncertainty associated with