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Rapid precipitation changes in the tropical West Pacific linked to North Atlantic climate forcing during the last deglaciation

Zhifang Xiong [a, b], Tiegang Li [a, b, *], Fengming Chang [c], Thomas J. Algeo [d, e], Peter D. Clift [f, g], Lisa Bretschneider [h], Zhengyao Lu [i], Xiao Zhu [c], Martin Frank [h], Peter E. Sauer [j], Fuqing Jiang [b, c], Shiming Wan [c], Xu Zhang [k], Shuangxi Chen [l], Jie Huang [c]

[a] Key Laboratory of Marine Sedimentology and Environmental Geology, First Institute of Oceanography, State Oceanic Administration, Qingdao 266061, China
[b] Laboratory for Marine Geology, Qingdao National Laboratory for Marine Science and Technology, Qingdao 266061, China
[c] Key Laboratory of Marine Geology and Environment, Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China
[d] Department of Geology, University of Cincinnati, Cincinnati, OH 45221-0013, USA
[e] State Key Laboratories of Biogeology and Environmental Geology, and Geological Processes and Mineral Resources, China University of Geosciences, Wuhan 430074, China
[f] Department of Geology and Geophysics and the Coastal Studies Institute, Louisiana State University, Baton Rouge, LA 70803, USA
[g] School of Geography Science, Nanjing Normal University, Nanjing 210023, China
[h] GEOMAR Helmholtz Centre for Ocean Research Kiel, Wischhofstrasse 1-3, 24148 Kiel, Germany
[i] Laboratory of Climate, Ocean and Atmosphere Studies, School of Physics, Peking University, Beijing 100871, China
[j] Department of Geological Sciences, Indiana University, Bloomington, IN 47405-1405, USA
[k] Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bussestrasse 24, D-27570 Bremerhaven, Germany
[l] Wuhan Center, China Geological Survey, Wuhan 430205, China

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ABSTRACT

The cause of rapid hydrological changes in the tropical West Pacific during the last deglaciation remains controversial. In order to test whether these changes were triggered by abrupt climate change events in the North Atlantic Ocean, variations in precipitation during the last deglaciation (18–10 ka) were extracted from proxy records of chemical weathering and terrigenous input in the western Philippine Sea (WPS). The evolution of chemical weathering and terrigenous input since 27 ka was reconstructed using the chemical index of alteration (CIA), elemental ratios (K/Al, TOC/TN and Ti/Ca), $\delta^{13}C_{org}$, terrigenous fraction abundance and flux data from International Marine Global Change Study Program (IMAGES) core MD06-3054 collected on the upper continental slope of eastern Luzon (northern Philippines). Sediment deposited during the Last Glacial Maximum (LGM) shows weathering equal to or slightly greater than Holocene sediment in the WPS. This unusual state of chemical weathering, which is inconsistent with lower air temperatures and decreased precipitation in Luzon during the LGM, may be due to reworking of poorly consolidated sediments on the eastern Luzon continental shelf during the LGM sea-level low-stand. Rapid changes in chemical weathering, characterized by higher intensity during the Heinrich event 1 (H1) and Younger Dryas (YD) and lower intensity during the Bølling-Allerød (B/A), were linked to rapid variations in precipitation in the WPS during the last deglaciation. The higher terrigenous inputs during the LGM relative to those of the Holocene were controlled by sea-level changes rather than precipitation. The terrigenous inputs show a long-term decline during the last deglaciation, punctuated by brief spikes during the H1 and YD related to sea-level rises and rapid precipitation changes in the WPS, respectively. The proxy records of chemical weathering and terrigenous input from eastern Luzon suggest high rainfall during the H1 and YD events, consistent with inferred rainfall patterns based on Fe/Ca records from offshore Mindanao. Rapid precipitation changes in the WPS did not coincide with migrations of the Intertropical Convergence Zone (ITCZ) but, rather, were related to state shifts of the El Niño-Southern Oscillation (ENSO) during the last deglaciation. Based on proxy records and modeling results, we argue that the Atlantic meridional overturning circulation (AMOC) controlled rapid

* Corresponding author. Key Laboratory of Marine Sedimentology and Environmental Geology, First Institute of Oceanography, State Oceanic Administration, Qingdao 266061, China.
E-mail address: tgli@fio.org.cn (T. Li).

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precipitation changes in the tropical West Pacific through zonal shifts of ENSO or meridional migration of the ITCZ during the last deglaciation. Our findings highlight the dominant role of the North Atlantic Ocean in the tropical hydrologic cycle during the last deglaciation.

1. Introduction

Tropical hydrology influences global climate via the meridional Hadley and zonal Walker circulations and their teleconnections with extratropical climate features (Chiang, 2009). Precipitation, an important hydrological parameter, underwent abrupt changes in the tropical Pacific Ocean and on adjacent maritime continents during the last deglaciation (18–10 ka) (note: all ages are given in "ka", i.e., thousands of years before present). During the Heinrich event 1 (H1; 16.4–14.7 ka) and the Younger Dryas (YD; 12.7–11.6 ka), marine and terrestrial records from north of the equator show decreased precipitation (Wang et al., 2001; Partin et al., 2007; Saikku et al., 2009), whereas those from south of the equator show increased precipitation (Tachikawa et al., 2011; Denniston et al., 2013). This interhemispheric anti-phased rainfall pattern has been attributed to meridional shifts of the Intertropical Convergence Zone (ITCZ), with heavy southern rainfall and light northern rainfall associated with its southward migration during the H1 and YD (Gibbons et al., 2014; McGee et al., 2014). In addition, rainfall patterns during the last deglaciation were also influenced by mode shifts of the El Niño-Southern Oscillation (ENSO), with heavy rainfall in the eastern tropical Pacific and light rainfall in the western tropical Pacific linked to a persistent El Niño state during the H1 and YD (Stott et al., 2002). Thus, the meridional migration of the ITCZ and the zonal migration of the ENSO have been routinely invoked to account for changes in precipitation patterns in the tropical Pacific during the last deglaciation.

As more high-resolution millennial-scale climate records have been generated, it has become increasingly difficult to consistently apply the conventional mechanisms of ITCZ meridional migration and ENSO zonal migration to explain changes in tropical Pacific precipitation during the last deglaciation. First, some recently generated precipitation proxy records have departed from the interhemispheric anti-phased pattern. For example, decreased rainfall in the southern tropics during the H1 and YD was indicated by global ice volume-corrected surface seawater $\delta^{18}O$ ($\Delta\delta^{18}O_{sw\text{-}iv}$) records from offshore southern Indonesia (Gibbons et al., 2014), and increased rainfall in the northern tropics by X-ray fluorescence (XRF)-based Fe/Ca ratios for sediment cores from offshore Mindanao (Philippines) (Fraser et al., 2014). Second, the relative importance of the ITCZ versus ENSO as a control on precipitation changes in the tropical Pacific during the last deglaciation is still unclear. Some studies have invoked solely the ITCZ (Leduc et al., 2009) or ENSO as a control (Stott et al., 2002; Jia et al., 2015), whereas others have suggested that both were important controls on rainfall during the H1 and YD (Levi et al., 2007). Third, some tropical sites have failed to yield evidence of significant precipitation changes during the H1 or YD despite large inferred meridional displacements of the ITCZ (Partin et al., 2007). Similar difficulties for employing ITCZ and ENSO mechanisms to interpret precipitation patterns are encountered at not only millennial timescales but also orbital and centennial timescales. Kissel et al. (2010) found opposing trends in precipitation between land and marine areas, with weak rainfall in the western Philippine Sea (WPS) and strong rainfall in East Asia during higher boreal summer insolation. Yan et al. (2015) suggested that in-phase moisture changes in the equatorial West Pacific reflected contraction rather than meridional migration of the ITCZ during the Little Ice Age. The proposed mode of ITCZ expansion and contraction, which is based on observational data and proxy records of rainfall (Denniston et al., 2016; Wodzicki and Rapp, 2016), has been related to the meridional moist static energy gradient (Byrne and Schneider, 2016). The differing conclusions of these studies show that interpretation of precipitation patterns in the tropical Pacific at multiple timescales is still under debate.

The correspondence of precipitation changes in the tropical Pacific with the $\delta^{18}O$ record of the Greenland icesheet, and its implication that North Atlantic climate controlled tropical precipitation patterns during the last deglaciation, have been noted in many studies (e.g. Mohtadi et al., 2011; Denniston et al., 2013; Mollier-Vogel et al., 2013). This relationship has been attributed to a slowdown or shutdown of Atlantic meridional overturning circulation (AMOC), reducing northward oceanic heat transport and triggering a steepening of the interhemispheric sea surface temperature (SST) gradient during the H1 and YD (see review in Mohtadi et al., 2016). Variation in the interhemispheric SST gradient altered heat redistribution between the tropics and high-latitude Northern Hemisphere, thus directly influencing tropical precipitation during the last deglaciation (McGee et al., 2014). In this scenario, the mean meridional position of the ITCZ was sensitive to the interhemispheric SST gradient, with its southward shift corresponding to a weak AMOC (Broccoli et al., 2006; Chiang and Friedman, 2012). ENSO also responded to variations in AMOC, but its responsive behavior has been a matter of debate. Some studies have inferred that weakening of AMOC resulted in increased ENSO variability (Merkel et al., 2010) whereas others have inferred reduced ENSO variability (Timmermann et al., 2005). What is generally agreed is that ITCZ migration and ENSO mode shifts are a feedback or response of the climate system to changing AMOC strength. From this perspective, rapid precipitation changes in the tropical Pacific during the last deglaciation are likely to have been due to forcings emanating from the North Atlantic region.

Uncertainties in reconstructing precipitation patterns in the tropical Pacific during the last deglaciation are due in part to the nature of the employed proxies. To date, reconstruction of paleoprecipitation has been based mainly on two types of proxies: (1) $\Delta\delta^{18}O_{sw\text{-}iv}$ calculated from planktonic foraminiferal $\delta^{18}O$, and (2) proxies for sediment discharge related to freshwater runoff. Sometimes, these two types of proxies yield conflicting information regarding precipitation in the same marine area, and even in the same sediment core. For example, $\Delta\delta^{18}O_{sw\text{-}iv}$ data from three sediment cores in the WPS indicated decreased rainfall during the H1 and YD, but Fe/Ca records from one of the cores point to increased rainfall (Stott et al., 2002; Bolliet et al., 2011; Fraser et al., 2014). Such conflicts may be due to differences in the nature of these proxies: $\Delta\delta^{18}O_{sw\text{-}iv}$ reflects salinity variation in the ocean surface layer, thus integrating large-scale hydrological changes including not only rainfall but also evaporation and advection or upwelling of watermasses (Ravelo and Hillaire-Marcel, 2007; Fraser et al., 2014; Gibbons et al., 2014), whereas proxies for sediment discharge are sensitive only to local freshwater runoff and, thus, appear to be more robust and direct proxies for precipitation.