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A severe drought during the last millennium in East Java, Indonesia

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ABSTRACT

The Little Ice Age (LIA) is characterized by widespread northern hemisphere cooling during a period of reduced radiative forcing. Sediment records from three crater lakes indicate that the most severe drought of the last 1200 years struck East Java at the end of the LIA. We use ^{14}C and U-series dating applied to carbonate geochemical records from Lakes Lading, Logung, and Lamongan to demonstrate this drought occurred at 1790 Common Era (CE) ± 20 years. Drought occurred during a period of strong El Niño events and Asian monsoon failures in the late 1790s, yet our records indicate that drought conditions persisted well beyond this decade and reached peak intensity in East Java ca 1810 CE ± 30 years. The continuation of severe drought into the 1800s may have resulted from the large volcanic eruptions that occurred in 1809, 1815 and 1835 CE, which likely caused brief, abrupt decreases in Indo-Pacific Warm Pool (IPWP) sea surface temperatures (SSTs), reducing local convection in East Java. Alternatively, broad changes in atmospheric circulation, such as a slowing of the Pacific Walker Circulation in response to decreased solar radiation during the LIA, could have produced several decades of drought in East Java. However, there is a lack of clear supporting evidence for such a change based upon paleohydrological records from the opposite ends of both the Indian and Pacific ocean zonal circulation systems. Based on the available evidence, we suggest severe multidecadal drought in East Java throughout the turn of the 19th century was driven by locally reduced convection resulting from a combination of heightened El Niño activity and volcanic eruptions.

1. Introduction

1.1. Background

Convection over the Indo-Pacific Warm Pool (IPWP) is a major source of atmospheric water vapor and is a vitally important component of the global hydrological cycle (Pierrehumbert, 2000). Emerging records from the IPWP indicate significant hydroclimate changes over the past millennium, which could have important consequences for tropical precipitation and global climate (Crausbay et al., 2006; Griffiths et al., 2009; Oppo et al., 2009; Sachs et al., 2009; Tierney et al., 2010; Rodysill et al., 2012; Konecky et al., 2013). Conflicting trends in reconstructed IPWP hydrology during the Little Ice Age (LIA) call into question how patterns of rainfall and drought respond to extended decadal to millennial-scale periods of warming and cooling. For example, isotopic records from the Makassar Strait and East Java indicate convective activity increased over southern Indonesia through much of the past millennium, yet decadal variations in these records exhibit significant temporal differences in hydrologic extremes (Oppo et al., 2009; Tierney et al., 2010; Rodysill et al., 2012; Konecky et al., 2013).

The Makassar Strait experienced the coldest temperatures of the past millennium circa 1700 CE (Oppo et al., 2009). While cool sea surface temperatures should reduce regional convective activity, lake sediments in East Java record the most severe droughts during the LIA from 1450 to 1650 Common Era (CE) and from 1790 to 1860 CE (Crausbay et al., 2006; Rodysill et al., 2012). These differences could arise from the diverse controls on the intensity of convection in the IPWP, which include changes in the mean position of the Inter-tropical Convergence Zone (ITCZ), changes in IPWP SSTs, and Walker Circulation strength associated with the El Niño-Southern Oscillation (ENSO) or the Indian Ocean Dipole (IOD). Understanding

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the regional hydrology in the IPWP during the LIA could illuminate how convective intensity responds to changes in the global climate system, and how IPWP variations in turn affect global-scale climate processes. Here we present a new record of drought from crater lake sediments in East Java and synthesize ages of droughts in nearby crater lakes that provide strong evidence for a major drought in East Java during the LIA.

1.2. Regional setting

Our study site is located between the tropical Indian and Pacific Oceans on the island of Java, Indonesia, just south of the IPWP (Fig. 1A). Seasonal rainfall variations in Java are controlled by the Austral summer monsoon, which brings heavy precipitation from the northwest, and the dry southeasterlies of the Austral winter monsoon (Fig. 1C). Interannual variations in rainfall are influenced by the strength of the monsoons and the phase of ENSO, where anomalous cold SSTs, weaker Walker Circulation, and decreased vertical convection over the IPWP during El Niño events prolong southeasterly flow over Java, lengthening the dry season and causing drought (Hendon, 2003).

Lake Lading (8°0.53′S, 113°18.75′E) is a closed basin lake situated on the southwest side of Gunung Lamongan, a historically active volcano in Eastern Java (Carn and Pyle, 2001; Fig. 1B). This ~200-m-diameter maar crater-lake is 8.6 m deep and sits at an elevation of 324 m in mafic volcanic bedrock (Carn and Pyle, 2001). Observations of water balance and salinity of East Java lakes have shown that lakes in this region are sensitive to seasonal changes in climate (Green et al., 1976), and sediment records from nearby crater lakes have demonstrated that these lakes can preserve a record of climate-driven salinity variations in their lithology and geochemistry covering at least the past 1400 years (Crausbay et al., 2006; Rodysill et al., 2012).

2. Materials and methods

We recovered two cores from the deepest part of Lake Lading using a Bolivia corer in July 2008 in offset, overlapping drives to minimize coring hiatuses. Resistant beds (tephras) below 2.5 m prevented penetration with the Bolivia corer, so a Livingstone coring system was used to recover an additional 3.6 m of sediment. The upper 42 cm of surface sediment was collected with a hand-held Uwitec™ gravity corer and extruded in the field in 1-cm increments with a modified Verschuren (1993) extruder to preserve chemical and physical sediment properties. The cores were split and macroscopically described at Brown University using the methods of Schnurrenberger et al. (2003). These cores were spliced into one composite section by visually correlating distinctive laminae and beds and distinctive geochemical variations.

The core chronology was assembled using ^{210}Pb dating methods to constrain ages in the upper meter of core, and ^{14}C ages on six plant macrofossils and one bulk sediment sample in the lower sections. ^{210}Pb activity was measured using alpha spectroscopy at Flett Research Laboratories, and a constant rate of supply model was used to determine ^{210}Pb ages (Appleby and Oldfield, 1978; Appleby, 1997). Four ^{14}C dates were measured on plant material from cores that were collected from Lading in 1998 (Crausbay, 2000); sample depths corresponding to these dates were correlated to our cores using a combination of visual correlation of distinctive laminae and magnetic susceptibility profiles. An additional three ^{14}C dates were sampled directly from our cores to constrain correlation of the previously measured ^{14}C dates and to fill in gaps in the age model. These samples were analyzed at the Woods Hole Oceanographic Institution's National Ocean Sciences AMS Facility. All of the ^{14}C ages were calibrated to calendar years using the IntCal09 model from Calib 6.0 (Table 1; Stuiver and Reimer, 1993). Two ~20-cm-thick volcanic ash beds were treated as instantaneous events, so we removed them from the composite depth before calculating the age model. The age model and model error approximations were derived using a mixed-effect regression model applied to both ^{210}Pb and calibrated ^{14}C ages (Heegaard et al., 2005).

We developed continuous profiles of the elemental chemistry of our cores using an ITRAX corescanner with a Mo X-ray source at 1-cm resolution with a 120-s dwell time at the University of Minnesota Duluth's Large Lakes Observatory. We also measured the

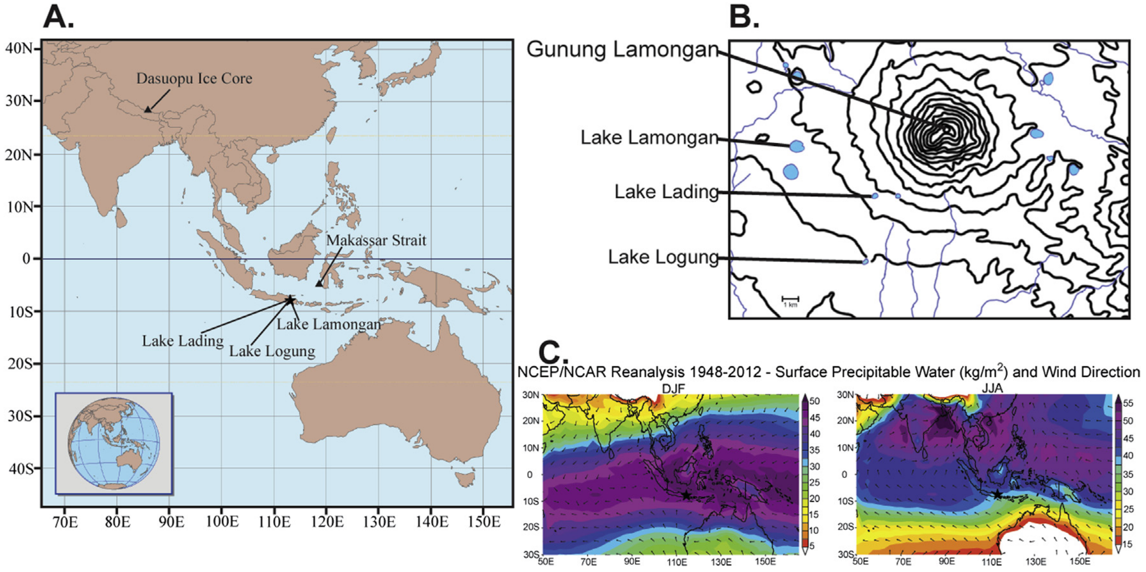

Fig. 1. Location of our study sites and seasonal precipitation maps. **A**: Regional map highlighting the location of our study sites (star) and the Dasuopu ice core and Makassar Strait SST records mentioned in the discussion section (triangles). **B**: Contour map of Gunung Lamongan volcano in East Java with Lakes Lading, Logung, and Lamongan depicted as light blue circles. Black lines are 100 m contours. **C**: Seasonal precipitable water in kg/m^2 and wind direction at 1000 mb in Java during austral summer (left) and austral winter (right). Cooler colors represent a greater amount of precipitable water. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)