Geology, published online on 6 September 2013 as doi:10.1130/G34718.1

Multidecadal rainfall variability in South Pacific Convergence Zone as revealed by stalagmite geochemistry

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ABSTRACT

Pacific decadal variability (PDV) causes widespread, persistent fluctuations that affect climate, water resources, and fisheries throughout the Pacific basin, yet the magnitude, frequency, and causes of PDV remain poorly constrained. Here we present an absolutely dated, subannually resolved, 446 yr stable oxygen isotope ($\delta^{18}O$) cave record of rainfall variability in Vanuatu (southern Pacific Ocean), a location that has a climate heavily influenced by the South Pacific Convergence Zone (SPCZ). The $\delta^{18}O$-based proxy rainfall record is dominated by changes in stalagmite $\delta^{18}O$ that are large (~1‰), quasi-periodic (~50 yr period), and generally abrupt (within 5–10 yr). These isotopic changes imply abrupt rainfall changes of as much as ~1.8 m per wet season, changes that can be ~2.5× larger than the 1976 C.E. shift in rainfall amount associated with a PDV phase switch. The Vanuatu record also shares little commonality with previously documented changes in the Intertropical Convergence Zone during the Little Ice Age or solar forcing. We conclude that multidecadal SPCZ variability is likely of an endogenous nature. Large, spontaneous, and low-frequency changes in SPCZ rainfall during the past 500 yr have important implications for the relative magnitude of natural PDV possible in the coming century.

INTRODUCTION

The South Pacific Convergence Zone (SPCZ), which extends more than 7000 km from Papua New Guinea to Tahiti, represents the largest perennial rainfall feature in the Southern Hemisphere (Trenberth, 1991; Vincent, 1994). Due to its large size, changes in the position of the SPCZ have far-reaching effects on global climate (Trenberth, 1991; Vincent, 1994; Deser et al., 2004; van Loon et al., 2007; Cai et al., 2012; Matthews, 2012; Widlansky et al., 2012), but most changes proximately affect the availability of potable water in island nations of the South Pacific. While such nations can anticipate seasonal to interannual changes in SPCZ-related rainfall, they are ill prepared to cope with decades-long periods of reduced rainfall resulting from long-term shifts in the position of the SPCZ (Deser et al., 2004; van Loon et al., 2007; Matthews, 2012). Such an SPCZ shift occurred in 1976–1977 (Folland et al., 2002; Deser et al., 2004) contemporaneous with, and linked to, climatic changes across the Pacific Ocean (Trenberth and Hurrell, 1994; Mantua et al., 1997). However, due to the short length of the instrumental record, the magnitude, frequency, and causes of such events are poorly constrained. Mechanisms suggested to account for Pacific decadal variability (PDV) include dynamic explanations involving subtropical cells (Gu and Philander, 1997; McPhaden and Zhang, 2002), tropical-extratropical feedbacks (Di Lorenzo et al., 2010), or oceanic integration of short-term atmospheric forcing (Newman et al., 2003; Clement et al., 2011), but there is no consensus on cause. Furthermore, the lack of information about the magnitude, frequency, and timing of decadal-scale climate variability (Lintner and Neelin, 2008) increases uncertainty in global climate model projections of future SPCZ behavior under global warming scenarios (Cai et al., 2012; Widlansky et al., 2012).

In an effort to fill the knowledge gap about PDV (Trenberth and Hurrell, 1994; Mantua et al., 1997; McPhaden and Zhang, 2002; Deser et al., 2004, 2012; Di Lorenzo et al., 2010; Clement et al., 2011) and SPCZ variability in the pre-instrumental period, we present a high-resolution stalagmite record of rainfall from Vanuatu that covers the past 446 yr. Annually banded corals have provided long records of past climate variability from the South Pacific (Linsley et al., 2000; DeLong et al., 2012); however, the coral proxy in this region mainly monitors changes in ocean advection linked to atmospheric variability, and is not a direct proxy for rainfall. Our Vanuatu stalagmite record is demonstrably linked to rainfall, and documents changes that are large, repetitive, and abrupt. These changes appear to arise without external forcing and are much larger than those of the past 100 yr.

STUDY SITE AND STALAGMITE RECORD

The wet season in Vanuatu normally extends from November through April, but rainfall is especially pronounced in December, January, and February (DJF) (Fig. 1). Seasonality of rainfall is high in areas extending from Vanuatu to Tahiti; Papua New Guinea and the Solomon Islands have low seasonality and can experience rainfall year-round. Qualitative analysis of monthly outgoing longwave radiation data (Fig. DR1 in

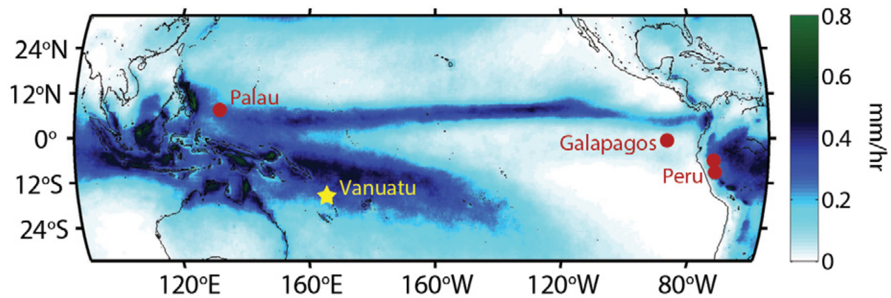

Figure 1. December-January-February (DJF) composite precipitation from 1998 to 2011 C.E., when South Pacific Convergence Zone (SPCZ) rainfall is at maximum (Tropical Rainfall Measuring Mission, TRMM 3B43, product; Kummerow et al., 2000), demonstrating the size and intensity of this convergence zone. Yellow star depicts the location of Vanuatu study site at edge of SPCZ. Red dots note locations of Intertropical Convergence Zone (ITCZ) proxy studies used in Figure 4.

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Data Repository item 2013318 | doi:10.1130/G34718.1

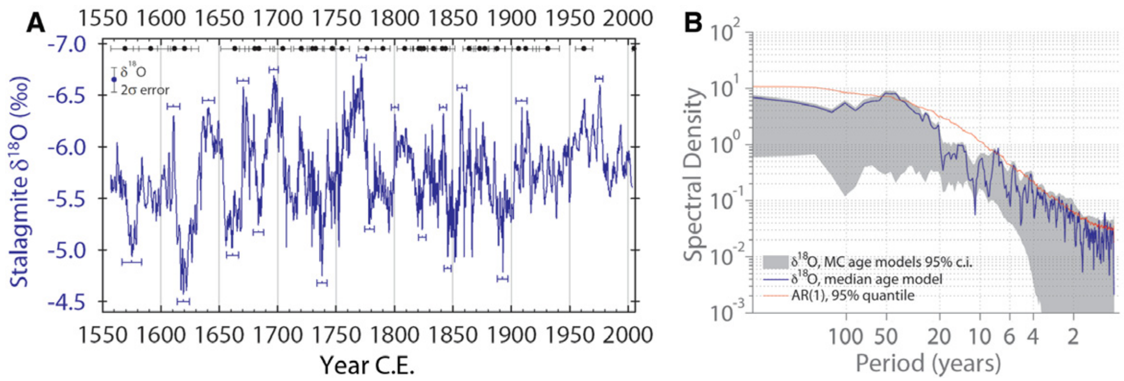

Figure 2. A: Time series of stalagmite δ^{18}O from Taurius Cave in Espiritu Santo, Vanuatu from 1557 to 2003 C.E. U-Th ages are represented by black points on top, with 2σ analytical error bar. Blue error bars along record are 2σ errors for individual δ^{18}O measurement calculated using 10,000 realizations of age models based on Monte Carlo approach, and are included to depict range of uncertainty associated with peak or valley (see the Data Repository [see footnote 1]). B: Multitaper method spectral analysis of time series using median age model (blue). Gray shading delineates 95% confidence interval (c.i.) obtained from 10,000 age model simulations. Peaks rising above 95% confidence limit [using an AR(1) (autoregressive) null hypothesis] include ~2–7 yr (El Niño–Southern Oscillation) and ~50 yr (multidecadal variability). MC—Monte Carlo.

the GSA Data Repository[1]) agrees with a more-detailed analysis of SPCZ modes of variability (Matthews, 2012); both suggest that Vanuatu receives more rain when the main axis of precipitation of the SPCZ is over Vanuatu, making this margin site a good proxy for SPCZ position (Lintner and Neelin, 2008).

We developed a U-Th-dated (Shen et al., 2012), 446 yr δ^{18}O cave stalagmite record of past rainfall variability from Espiritu Santo, Vanuatu (15.5°S, 167°E) to investigate low-frequency rainfall variability in the SPCZ (Fig. 2A; Fig. DR2). The average growth rate of the stalagmite is ~1.2 mm/yr, based on 31 U-Th dates (Fig. 2A; Fig. DR3 and Table DR1) and ^{210}Pb dating (Fig. DR4). Multiple lines of evidence are compatible with equilibrium precipitation of the calcite stalagmite with cave dripwater (Figs. DR5–DR7). The rapid growth rate of the stalagmite provides the opportunity to develop a subannually resolved record of rainfall variability. The record most likely captures the wet season when rainfall is high enough to recharge the aquifer and infiltrate the cave.

Modern rainfall and stalagmite δ^{18}O records agree that the period 1947–1976 C.E. was wetter than average in Vanuatu (Fig. 3A). This wet period corresponds to the PDV phase when the SPCZ shifts to the southwest over Vanuatu (e.g., Fig. DR1). On decadal time scales, we derive a conversion of a change in 1‰ stalagmite δ^{18}O per 1.4 m of rainfall per wet season (Fig. DR8). Vanuatu experiences dry conditions during El Niño events, when the SPCZ moves northeast, and wet conditions during La Niña events, when the SPCZ moves southwest. However, for this record a calibration between stalagmite δ^{18}O and rainfall at annual to interannual time scales is not possible due to the relatively low growth rate during the past 100 yr (~0.6 mm/yr), combined with 3–7 yr age uncertainties and the smoothing of high-frequency rainfall changes due to mixing in the karst bedrock. While little annual or interannual power is exhibited in the wavelet spectrum over the past ~100 yr, many significant El Niño–Southern Oscillation (ENSO) related peaks are in older portions of the record, when the growth rate was higher (Fig. DR9). Multi-taper method spectral analysis (Thomson, 1982) of the δ^{18}O time series reveals statistically significant concentrations of variance at the multidecadal (broad peak at ~50 yr) and ENSO (several sharp peaks at 2–7 yr) scales (Fig. 2B). Notably, the spectrum lacks power at the 10–20 yr scale, suggesting no direct response to the 11 yr solar cycle (Fig. 2B; Table DR2).

UNCERTAINTY ANALYSIS

We examine the sensitivity of our results to two leading sources of uncertainty: (1) age model errors, and (2) rainfall signal distortion induced by the karst-stalagmite system. We quantify the effect of age model errors by generating 10,000 alternate realizations of the age model (blue error bars in Fig. 2A; see the Data Repository), yielding uncertainty bands for the estimated spectrum (gray envelope in Fig. 2B); the results show that the median age model (the most probable, given the data) captures uniquely sharp peaks, which would otherwise get blurred by age errors.

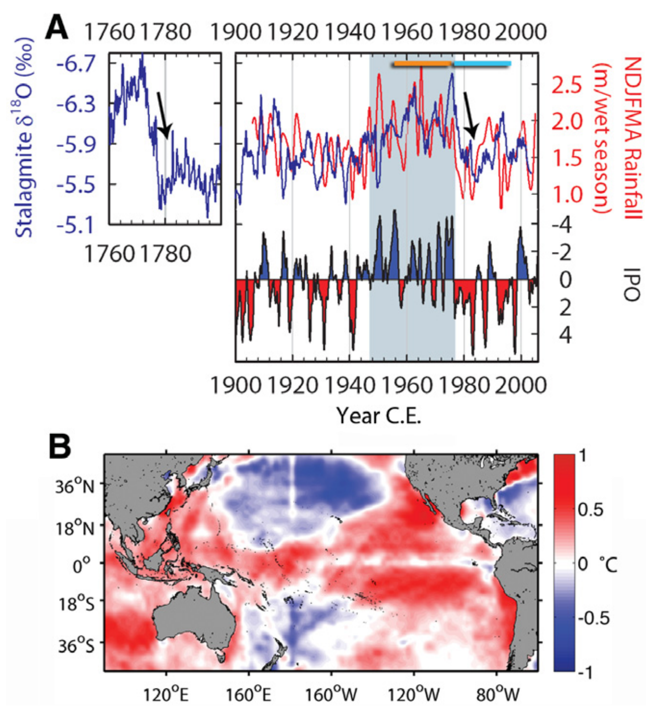

Figure 3. A: Most recent 100 yr of Vanuatu stalagmite δ^{18}O (blue) and November–April (NDJFMA) wet-season rainfall totals (red) from Pekoa Airport, Espiritu Santo, Vanuatu (upper two curves) and Interdecadal Pacific Oscillation index (IPO; Folland et al., 2002) (lower black curve). Blue shading spanning 1947 to 1976 C.E. highlights a period when the IPO is in the negative phase, during which the South Pacific Convergence Zone (SPCZ) shifts on average to the southwest, causing increase in rainfall over Vanuatu and more negative stalagmite δ^{18}O. Also depicted is large change in stalagmite δ^{18}O ca. 1775 C.E. (upper left blue curve) to illustrate magnitude of past variability in Vanuatu as compared to 1976 C.E. (arrows depict analogous phase changes). B: Difference in Hadley Center sea-surface temperature (SST) between 20 yr epochs 1977–1996 C.E. (light blue bar in A) minus 1957–1976 C.E. (orange bar in A). SST differences between central and eastern tropical Pacific versus northern and southern subtropics (horseshoe-like pattern) likely contribute to multidecadal Pacific decadal variability.

[1]GSA Data Repository item 2013318, site location, methods, sample description, and models, is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA. Geochemical data are available at the U.S. NOAA National Climatic Data Center (NCDC; http://www.ncdc.noaa.gov/paleo/paleo.html).

We quantify climate signal distortion via a box model of groundwater hydrology (Gelhar and Wilson, 1974) that provides an estimate of the power redistribution from the rainfall signal to the groundwater isotopic composition (Fig. DR10). The analysis suggests that flow through the karst bedrock acts as a low-pass filter, shifting power in the rainfall $\delta^{18}O$ spectrum from higher frequencies (annual to interannual) to lower frequencies (decadal and multidecadal). Although the lack of measurements of karst parameters (e.g., residence time, porosity) precludes a precise inversion of the original rainfall signal, we find that for plausible karst parameters the deconvolved rainfall signal exhibits statistically significant multidecadal variability (Fig. DR10). This demonstrates that the multidecadal variability in the stalagmite time series cannot arise solely from karst bedrock dynamics, and must instead result from hydroclimate variability, in this case, of SPCZ position and/or intensity. The ratio between frequency bands, however, is distorted in an unknown amount.

CLIMATE IMPLICATIONS

The rainfall reconstruction from the Vanuatu stalagmite provides context for the magnitude and timing of past PDV-driven changes in the SPCZ relative to modern changes. The widely recognized 1976–1977 climate shift, often considered a large perturbation to the tropical Pacific (Mantua et al., 1997; Folland et al., 2002; Deser et al., 2004), manifests in our Vanuatu stalagmite $\delta^{18}O$ record as a modest change (~0.7 m per wet season), less than half as large as other transitions, centered at 1613, 1653, 1705, and 1775 C.E. (≤ 1.8 m per wet season) (Fig. 3A; see the Data Repository), underscoring the value of assessing such shifts in paleoclimate records.

Paleoclimate proxy reconstructions of hydrology from the tropical Pacific, including those from Palau, the Galapagos Islands (Sachs et al., 2009), and Peru (Reuter et al., 2009; Bird et al., 2011), contain trends that support the hypothesis of a northward migration of the Intertropical Convergence Zone (ITCZ) from the Little Ice Age (LIA) to present (Fig. 4). The ITCZ shift is most likely a response to multiple factors affecting the inter-hemispheric heat gradient, including changes in solar output, explosive volcanism, and sea ice (Miller et al., 2012). While there is a small, significant trend in the Vanuatu proxy rainfall record from the LIA to present of ~0.2‰ ($p < 0.01$), it is an order of magnitude smaller than the multidecadal variability of ~1.2‰, resulting in an end-point–sensitive trend calculation. The LIA section of the Vanuatu stalagmite record is characterized by slightly drier than average conditions, suggesting that the SPCZ shifted slightly equatorward (northward) during the LIA. Hence, while the SPCZ and ITCZ are both prominent tropical convergence zones, they did not respond equivalently to external forcing over the past several hundred years.

Additional proxy evidence from the Asian Monsoon region supports the notion that the hemispheric heat gradient affects large-scale circulation patterns (Zhang et al., 2008). SPCZ proxy records that extend to the Medieval Climate Anomaly, and earlier in the Holocene, when seasonality was different than today, would provide further tests as to how background conditions may affect the SPCZ.

The magnitude and timing of peak rainfall intervals in our Vanuatu reconstruction correspond to times of both high (1630 and 1775 C.E.) and low (1670 C.E.) solar activity (Vieira et al., 2011). In addition, the lack of a measureable response to the 11 yr (Schwabe) solar cycle (Fig. 2B) suggests that SPCZ rainfall variability is independent of solar forcing. These observations are supported by the lack of consistent, significant correlations with solar reconstructions at known solar periodicities (Table DR2; see the Data Repository). This contradicts a previously identified relationship with solar variability in the 1978–2009 C.E. instrumental record of the SPCZ (van Loon et al., 2007; Meehl et al., 2009), which may be too short to detect significant associations. If solar forcing is not responsible for the observed multidecadal changes in SPCZ-related rainfall variability at Vanuatu in the past, what other mechanism or mechanisms might be responsible? One possibility is that variability in central and eastern tropical Pacific sea-surface temperature (SST) drives PDV (McPhaden and Zhang, 2002; Deser et al., 2004; Di Lorenzo et al., 2010; Clement et al., 2011), a notion supported by SSTs during the most recent PDV phases (a difference of two 20 yr means: 1977–1996 and 1957–1976 C.E.) when instrumental SST data quality for the region are high (Fig. 3B). The higher SSTs in the central and eastern tropical Pacific post-1976 would cause the SPCZ to

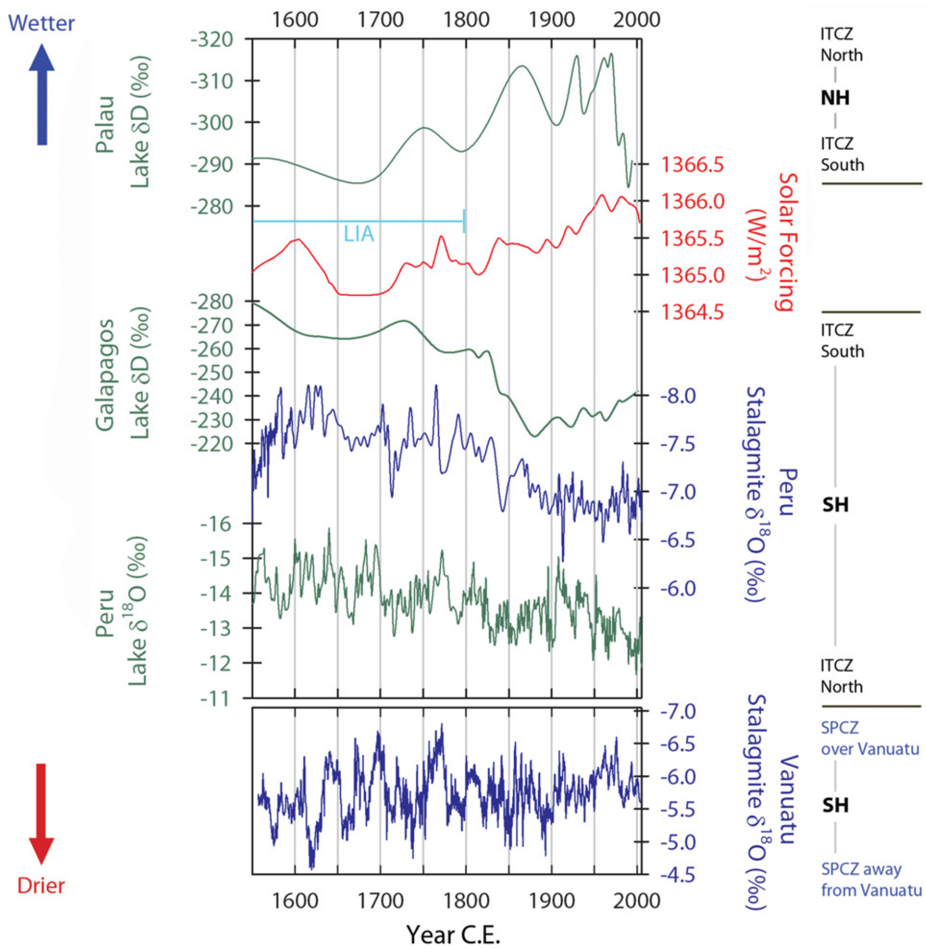

Figure 4. Comparison of Vanuatu stalagmite record of rainfall (bottom) with proxies of tropical Pacific precipitation from Palau (Sachs et al., 2009), Galapagos Islands (Sachs et al., 2009), and Peru (Reuter et al., 2009; Bird et al., 2011), as well as solar variability (Vieira et al., 2011) (red curve) to indicate timing of Little Ice Age (LIA). Vanuatu record during LIA contains prominent multidecadal variability and no northward migration trend. Other tropical Pacific proxy records capture inferred northward migration of Intertropical Convergence Zone (ITCZ) from LIA to present. Disparity between migration patterns, as well as character of multidecadal variability, suggests that South Pacific Convergence Zone (SPCZ) and ITCZ do not vary equally on decadal to centennial time scales. NH—Northern Hemisphere; SH—Southern Hemisphere.

shift equatorward, resulting in drier conditions at Vanuatu (Folland et al., 2002), somewhat akin to what occurs during an El Niño event. However, longer records are needed to determine whether the quasi-periodic ~50 yr oscillation in the Vanuatu record results from either random (Clement et al., 2011) or deterministic (Emile-Geay and Cane, 2009) processes.

The Vanuatu stalagmite record provides context for PDV during the past 100 yr: variability in the SPCZ was lowest during the instrumental era as compared to the past 440 yr. The long interval 1557–1850 C.E. is marked by a more regular, cyclic pattern in stalagmite $\delta^{18}O$ variability. In contrast, the past 100 yr of the stalagmite $\delta^{18}O$ record are characterized by a reduction in the amplitude of the 50 yr variability, and by a change in the baseline values of the dry intervals ($\delta^{18}O$ maxima) to more isotopically depleted values, whereas wet interval values remain relatively constant. The wettening of the SPCZ over the most recent century is consistent with the hypothesis that the hydrologic response to anthropogenic warming is one that accentuates hydrologic extremes, i.e., wet regions get wetter, dry regions get dryer (Held and Soden, 2006; Perkins et al., 2012). Whether the amplitude reduction in the past 100 yr of the stalagmite record results from anthropogenic or natural influences, the fact remains that the contribution of PDV to the current climate change is relatively limited. The multidecadal variability in the Vanuatu stalagmite record suggests that tropical Pacific dynamics contain a greater internal potential to alter South Pacific hydroclimate than seen in the modern era; this is a result with strong implications for water resource management of tropical island nations and for decadal climate predictability.

ACKNOWLEDGMENTS

We acknowledge Esline Garabiti of the Vanuatu Meteorological and Geohazards Department for assistance with permitting and allocation of field personnel. Peter Lulu of the Department of Water Resources, Vanuatu, provided invaluable field assistance and coordination with local chiefs and land owners. Chief Eric of Narango Village graciously allowed us to access and sample Taurius Cave. Marsten Tias provided assistance in the field. Nick Hayman provided assistance with X-ray diffraction analyses. Kaustubh Thirumalai provided assistance with calculations. Yuko Okumura provided helpful comments on the climate interpretation. Three anonymous reviewers and the editor provided constructive feedback on the manuscript. Financial support was provided by U.S. National Science Foundation award AGS-1003700, and Taiwan (Republic of China) National Science Council and National Taiwan University grants (101-2116-M-002-009 and 101R7625 to Shen).

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Manuscript received 8 May 2013
Revised manuscript received 15 July 2013
Manuscript accepted 19 July 2013

Printed in USA