Persistent drying in the tropics linked to volcanic forcing

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Climate projections for the future indicate a regional contrast in tropical hydrologic trends between areas that are slated to dry and those that will become wet[1]. While much of the tropical ocean under the Intertropical Convergence Zone (ITCZ) is projected to see an increase in rainfall, a wide area of Central America and surrounding oceans is expected to experience severe drying. Approximately half the world's population lives in the tropics, and future changes in the hydrologic cycle will impact not just fresh water supplies but also energy production in areas dependent upon hydroelectric power. It is vital that we understand tropical forcing mechanisms and the eventual hydrologic response in order to better assess projected future precipitation trends and variability and to potentially customize solutions for particular regions. Paleoclimate proxies are a valuable source of information for this purpose as they provide long times series that pre-date and complement the present, often short instrumental time series. Here we present paleoprecipitation data from a

speleothem deposit located in Mesoamerica that reveal large multidecadal declines in regional precipitation whose onset coincides with large volcanic eruptions during the 19th and 20th centuries. These new observations may indicate a previously unknown pattern of the regional climate response to external radiative forcing.

Speleothems are increasingly used as terrestrial archives of past climate and environmental change because they often provide long, continuous, high-resolution time series that can be precisely dated by uranium-series isotopic analyses and are generally unaffected by post-depositional diagenetic alteration. The data for this study derive from a stalagmite (GU-Xi-1) collected 250 m inside the large cavern of Xibalba in the Campur Formation[2] located in the Maya Mountains of Guatemala near the Belize border (Fig 1., 16.5ºN, 89ºW). The in-cave elevation is 350 m, with a cave mean annual temperature of 23 °C. GU-Xi-1 was actively dripping at the time of collection, and chosen for its candle-shape form, its distance from outside atmospheric influences, and its location of 30 meters above the nearby modern river level; the karst surface is generally 100-150 m above the cave passages (Supplementary Fig. 1). The specimen is 33cm tall but only the last 18 cm was used for this study. It possesses a rounded top and no "cup" that could imply drip erosion (Supplementary Fig. 2). Our age model (Supplementary Fig. 3 and Fig 3b) is highly constrained by nine U/Th multicollector inductively coupled plasma mass spectrometry dates (Supplementary Information Table S1).

The climate of Mesoamerica is characterized by a boreal summer/fall (June-October) rainy season and a relatively dry winter[3]. Low-level atmospheric circulation in the region is dominated by the northeast trade winds that bring moisture from the tropical Atlantic Ocean to rain over the peninsula. The largest amounts of annual precipitation in the region fall on the high mountain ranges of Guatemala to the southwest of the speleothem cave. Summer precipitation values in the Maya Mountains reach upwards of 400 mm/month, but are approximately half that amount in the area of our cave. A strong inverse correlation between speleothem $\delta^{18}O$ and tropical precipitation intensity[4] has previously been observed for the region[5] and is clearly demonstrated in a plot of speleothem $\delta^{18}O$ and precipitation data from nearby Belize City over the interval of instrumental overlap (Fig. 2).

The complete three-century precipitation record is characterized by interannual-to subdecadal variability superimposed on several distinct multidecadal drying episodes (Fig. 3). Because of its location, Mesoamerica may be particularly sensitive to hydrologic fluctuations, responding to climate variability occurring in both the tropical Atlantic and the Pacific Oceans on a broad range of timescales[6] (Supplementary Fig. S4). Today, year-to-year rainfall variability in the Guatemala mountain regions is correlated with the thermal gradient between sea surface temperatures (SST) in the western tropical Atlantic and eastern tropical Pacific, with the Atlantic playing a more important role in the interaction[3]. Colder (warmer) than normal tropical Atlantic SSTs, which are consistent with a stronger (weaker) and more southward (northward) displaced Atlantic subtropical high, lead to drier (wetter) than normal conditions in Central America[7,8]. Similarly, anomalously warm (cold) eastern equatorial Pacific SSTs, e.g., during El Niño (La Nina) events, forces an equatorward (northward) displacement of the east Pacific ITCZ and contributes to drying (wetting) in most of Central America[9-10] (Supplementary Fig. S4). The east Pacific ITCZ influences precipitation in Mesoamerica throughout the year. In summer, the ITCZ migrates to its northern position, which reaches about 10°N on the Pacific-side of Central America and is associated with widespread rainfall over the region[11].

As indicated above, the most prominent aspects of our reconstruction are the occurrences of three distinct multidecadal drying trends during the 19th and 20th centuries (Fig. 3). Based on the modern relationship between $\delta^{18}O$ and regional precipitation anomalies[12], the speleothem data indicate an approximately 25% decrease in precipitation between 1815 and 1845 C. E., another comparable precipitation decrease between 1883 and 1925 C. E., and a smaller decrease from 1963 to the present. The drying steps are separated from one another by brief intervals of precipitation recovery in mid-century. Another record from Mesoamerica displays similar drying steps in the 19th century and 20th centuries (Supplementary Fig. S5) suggesting a broader regional phenomenon.

The three pronounced decreases in regional precipitation are associated with periods of volcanic activity clusters each of which lasted several decades (Fig. 3). Each cluster of these volcanic activities is associated with at least one highly explosive (forcing > 0.50 W/m^2) tropical volcanic eruption. The most prominent of these were El Chichon in 1809 and Tambora in 1815 (cluster 1), Krakatoa in 1883 (cluster 2), Agung in 1963 and Pinatubo in 1991 (cluster 3). Tambora, Krakatoa, and Pinatubo were the largest tropical volcanic eruptions of the last 250 years. Precipitation decreased throughout the periods of strong volcanic activity clusters such that there appears to be a volcanic cumulative effect on precipitation during these intervals. Precipitation only recovered when volcanic activity diminished, but not to previous levels as there is a multicentennial background drying trend in Mesoamerica that began 1000 YBP[5,13]. There could be many explanations for the long-term drying trend, but the most recent drying may be a result of the extension of the mid-summer drought[14]. A pronounced high pressure in the subtropics, centered on the Caribbean region is significantly positively correlated with the speleothem $\delta^{18}O$ (Supplementary Fig. S4, note the figure displays the correlation with (-1)×$\delta^{18}O$) and is part of a correlation pattern resembling the positive phase of the North Atlantic Oscillation (NAO)[15]. Notably, tropical region volcanoes tend to produce a positive wintertime NAO[16] response in the Northern Hemisphere winter.

Aerosol effects remain poorly understood in global climate models[17] but their long-term modulation on climate is essential for the predictability of decadal to multidecadal variability[18]. Our study suggests that volcanic stratospheric aerosols have been an important forcing agent in the tropical Atlantic during the last millennium along with solar variability, changes in greenhouse gas concentrations, and land cover changes[19,20]. Recent millennium model runs forced with reconstructed volcanic and solar variations have produced a global climate response to a significant extent, but a robust response is still lacking[18, 21-24]. Major volcanic eruptions lead to a pronounced North Atlantic cooling[18, 25] with greatest cooling in the summer months and have a tendency to induce a pronounced subtropical high and a positive NAO[18,25]. Using an Earth system model with dynamical stratosphere-troposphere interactions[18] shows that volcanoes play a dominant role in pacing AO/NAO affecting the multidecadal variability via the oceans and the tropical sea surface temperatures, and thus potentially modulate Caribbean rainfall. A pronounced subtropical high leads to stronger than normal tropical Atlantic trade winds[26], and consequently to reduced rainfall in Mesoamerica (Supplementary Fig. S4). Our new stalagmite data support this possible scenario relating volcanic eruptions to precipitation: the onset of drier conditions on multidecadal to centennial timescales falls together with the clustering of major eruption events (1815-1845; 1883-1925; 1963-2000) during the last 300 years. The relatively quiet phase prior to 1812 is associated with relatively wet conditions in the stalagmite record.

Our observations relating large volcanic eruptions to decreased precipitaion lends support to emerging evidence from global models regarding the sensitivity of the world's other monsoons to radiative forcing[27,28]. Of particular interest is the indication that the introduction of sulphate aerosol into the stratosphere through explosive eruptions leads to a serious reduction in monsoonal precipitation. Our results in combination with studies of global stream flow after large volcanic eruptions[29] imply that certain regions are highly sensitive to volcanic forcing arguing against geoengineering proposals to mitigate anthropogenic warming by releasing sulphate aerosols into the stratosphere[30].

METHODS SUMMARY

We collected the GU-XI-1 stalagmite from the Xibalba cave located in the Guatemala/ Belize border. The stalagmite was cut into two sections and a 1 cm-thick slab was produced from one of the sections. Nine ^{230}Th dates were analyzed in the upper 175mm of GU-XI-1 (Supplementary Figs. 2; 3, Table 1), resulting in an age control point approximately every 30 years in the speleothem slab. The age model for the speleothem is based on a parabolic curve fit to the ^{230}Th dates. We used the resulting polynomial equation to convert each sample depth to calendar ages from the speleothem, which we used for our age model. 595 samples each containing about 200 micrograms of powder were continuously milled at 0.3mm intervals along the stalagmite growth axis resulting in annual to subannual resolution for our stable isotope data.

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Author contributions AW, TM, YK, and DB conceived the project. AW, YK, DB and GL wrote most of the paper. AB, GH, JEM, SB, LB, and HC performed the experiments and analytical work.

Figure Captions

Figure 1. Location map of Mesoamerica and our speleothem site.

Figure 2. Comparison of speleothem $\delta^{18}O$ (this study, solid line) and Belize City, Belize, June to November precipitation anomalies (deviation from climatology, dashed line). Data for Belize-City precipitation is from the National Oceanic and Atmospheric Administration, monthly Global Historical Climatology Network (GHCN, see: http://www.ncdc.noaa.gov/ghcnm/). Precipitation data were filtered with a one path of the binomial, 2nd-order filter that emphasizes periods longer than 5 years.

Figure 3. (A) Volcanic radiative forcing from 1700-2000 C. E. after[19] Light-red boxes encapsule volcanic eruption clusters noted in the manuscript. (B) Speleothem GU-Xi-1 $\delta^{18}O$ for the same time period as (A). Interpolated annual $\delta^{18}O$ is shown by blue circles, and the solid line represents a nine-point moving average of the annualy-interpolated data. Multidecadal drying events are coincident with volcanic eruption clusters 1, 2, and 3.

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