

# **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<sup>1</sup>. 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**

30 **speleothem deposit located in Mesoamerica that reveal large multidecadal declines in**  
31 **regional precipitation whose onset coincides with large volcanic eruptions during the**  
32 **19<sup>th</sup> and 20<sup>th</sup> centuries. These new observations may indicate a previously unknown**  
33 **pattern of the regional climate response to external radiative forcing.**

34 Speleothems are increasingly used as terrestrial archives of past climate and  
35 environmental change because they often provide long, continuous, high-resolution time  
36 series that can be precisely dated by uranium-series isotopic analyses and are generally  
37 unaffected by post-depositional diagenetic alteration. The data for this study derive from a  
38 stalagmite (GU-Xi-1) collected 250 m inside the large cavern of Xibalba in the Campur  
39 Formation<sup>2</sup> located in the Maya Mountains of Guatemala near the Belize border (Fig 1.,  
40 16.5°N, 89°W). The in-cave elevation is 350 m, with a cave mean annual temperature of 23  
41 °C. GU-Xi-1 was actively dripping at the time of collection, and chosen for its candle-shape  
42 form, its distance from outside atmospheric influences, and its location of 30 meters above  
43 the nearby modern river level; the karst surface is generally 100-150 m above the cave  
44 passages (Supplementary Fig. 1). The specimen is 33cm tall but only the last 18 cm was  
45 used for this study. It possesses a rounded top and no “cup” that could imply drip erosion  
46 (Supplementary Fig. 2). Our age model (Supplementary Fig. 3 and Fig 3b) is highly  
47 constrained by nine U/Th multicollector inductively coupled plasma mass spectrometry  
48 dates (Supplementary Information Table S1).

49 The climate of Mesoamerica is characterized by a boreal summer/fall (June-October)  
50 rainy season and a relatively dry winter<sup>3</sup>. Low-level atmospheric circulation in the region is  
51 dominated by the northeast trade winds that bring moisture from the tropical Atlantic Ocean  
52 to rain over the peninsula. The largest amounts of annual precipitation in the region fall on

53 the high mountain ranges of Guatemala to the southwest of the speleothem cave. Summer  
54 precipitation values in the Maya Mountains reach upwards of 400 mm/month, but are  
55 approximately half that amount in the area of our cave. A strong inverse correlation between  
56 speleothem  $\delta^{18}\text{O}$  and tropical precipitation intensity<sup>4</sup> has previously been observed for the  
57 region<sup>5</sup> and is clearly demonstrated in a plot of speleothem  $\delta^{18}\text{O}$  and precipitation data from  
58 nearby Belize City over the interval of instrumental overlap (Fig. 2).

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

76 As indicated above, the most prominent aspects of our reconstruction are the  
77 occurrences of three distinct multidecadal drying trends during the 19<sup>th</sup> and 20<sup>th</sup> centuries (Fig.  
78 3). Based on the modern relationship between  $\delta^{18}\text{O}$  and regional precipitation anomalies<sup>12</sup>, the  
79 speleothem data indicate an approximately 25% decrease in precipitation between 1815 and  
80 1845 C. E., another comparable precipitation decrease between 1883 and 1925 C. E., and a  
81 smaller decrease from 1963 to the present. The drying steps are separated from one another by  
82 brief intervals of precipitation recovery in mid-century. Another record from Mesoamerica  
83 displays similar drying steps in the 19<sup>th</sup> century and 20<sup>th</sup> centuries (Supplementary Fig. S5)  
84 suggesting a broader regional phenomenon.

85 The three pronounced decreases in regional precipitation are associated with periods of  
86 volcanic activity clusters each of which lasted several decades (Fig. 3). Each cluster of these  
87 volcanic activities is associated with at least one highly explosive (forcing > 0.50 W/m<sup>2</sup>)  
88 tropical volcanic eruption. The most prominent of these were El Chichon in 1809 and  
89 Tambora in 1815 (cluster 1), Krakatoa in 1883 (cluster 2), Agung in 1963 and Pinatubo in  
90 1991 (cluster 3). Tambora, Krakatoa, and Pinatubo were the largest tropical volcanic eruptions  
91 of the last 250 years. Precipitation decreased throughout the periods of strong volcanic  
92 activity clusters such that there appears to be a volcanic cumulative effect on precipitation  
93 during these intervals. Precipitation only recovered when volcanic activity diminished, but not  
94 to previous levels as there is a multicentennial background drying trend in Mesoamerica that  
95 began 1000 YBP<sup>5,13</sup>. There could be many explanations for the long-term drying trend, but  
96 the most recent drying may be a result of the extension of the mid-summer drought<sup>14</sup>. A  
97 pronounced high pressure in the subtropics, centered on the Caribbean region is significantly  
98 positively correlated with the speleothem  $\delta^{18}\text{O}$  (Supplementary Fig. S4, note the figure

99 displays the correlation with  $(-1) \times \delta^{18}\text{O}$  and is part of a correlation pattern resembling the  
100 positive phase of the North Atlantic Oscillation (NAO)<sup>15</sup>. Notably, tropical region volcanoes  
101 tend to produce a positive wintertime NAO<sup>16</sup> response in the Northern Hemisphere winter.

102 Aerosol effects remain poorly understood in global climate models<sup>17</sup> but their long-  
103 term modulation on climate is essential for the predictability of decadal to multidecadal  
104 variability<sup>18</sup>. Our study suggests that volcanic stratospheric aerosols have been an important  
105 forcing agent in the tropical Atlantic during the last millennium along with solar variability,  
106 changes in greenhouse gas concentrations, and land cover changes<sup>19,20</sup>. Recent millennium  
107 model runs forced with reconstructed volcanic and solar variations have produced a global  
108 climate response to a significant extent, but a robust response is still lacking<sup>18, 21-24</sup>. Major  
109 volcanic eruptions lead to a pronounced North Atlantic cooling<sup>18, 25</sup> with greatest cooling in the  
110 summer months and have a tendency to induce a pronounced subtropical high and a positive  
111 NAO<sup>18,25</sup>. Using an Earth system model with dynamical stratosphere-troposphere  
112 interactions<sup>18</sup> shows that volcanoes play a dominant role in pacing AO/NAO affecting the  
113 multidecadal variability via the oceans and the tropical sea surface temperatures, and thus  
114 potentially modulate Caribbean rainfall. A pronounced subtropical high leads to stronger than  
115 normal tropical Atlantic trade winds<sup>26</sup>, and consequently to reduced rainfall in Mesoamerica  
116 (Supplementary Fig. S4). Our new stalagmite data support this possible scenario relating  
117 volcanic eruptions to precipitation: the onset of drier conditions on multidecadal to centennial  
118 timescales falls together with the clustering of major eruption events (1815-1845; 1883-1925;  
119 1963-2000) during the last 300 years. The relatively quiet phase prior to 1812 is associated  
120 with relatively wet conditions in the stalagmite record.

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

129

## 130 **METHODS SUMMARY**

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

141

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

155

## 156 **Figure Captions**

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

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

165

166 Figure 3. (A) Volcanic radiative forcing from 1700-2000 C. E. after<sup>19</sup> Light-red boxes  
 167 encapsule volcanic eruption clusters noted in the manuscript. (B) Speleothem GU-Xi-1  $\delta^{18}\text{O}$   
 168 for the same time period as (A). Interpolated annual  $\delta^{18}\text{O}$  is shown by blue circles, and the  
 169 solid line represents a nine-point moving average of the annually-interpolated data.

170 Multidecadal drying events are coincident with volcanic eruption clusters 1, 2, and 3.

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