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Persistent drying in the tropics linked to natural forcing

Amos Winter[1], Davide Zanchettin[2,3], Thomas Miller[1], Yochanan Kushnir[4], David Black[5], Gerrit Lohmann[6], Allison Burnett[7], Gerald Haug[8], Juan Estrella-Martínez[1], Sebastian F.M. Breitenbach[9,10], Luc Beaufort[11], Angelo Rubino[3], Hai Cheng[7,12]

1. University of Puerto Rico, Mayagüez, Puerto Rico 00681-9000, USA
2. Max Planck InstituteforMeteorology, Bundesstr. 53, 20157 Hamburg, Germany
3. University of Venice, Dorsoduro 2137, 30123 Venice, Italy
4. Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York 10964, USA
5. Stony Brook University, Stony Brook, New York 11790, USA
6. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, 27570Bremerhaven,Germany
7. University of Minnesota, Minneapolis, Minnesota 55455, USA
8. Swiss Federal Institute of Technology, Zurich 8092, Switzerland.
9. Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, UK
10. Sediment and Isotope Geology, Ruhr-University Bochum, Universitätsstr. 150, 44801, Bochum, Germany
11. CEREGE (CNRS-Université Aix Marseille), 13545 Aix en Provence, France
12. Xi'an Jiaotong University, Xi'an 710049, China

Approximately half the world's population lives in the tropics, and future changes in the hydrological cycle will impact not just freshwater supplies, but also energy production in areas dependent upon hydroelectric power. It is vital that we understand the mechanisms/processes that affect tropical precipitation and the eventual surface hydrological response to better assess projected future regional precipitation trends and variability. Paleoclimate proxies are well suited for this purpose as they provide long time series that pre-date and complement the present, often short instrumental observations. Here we present paleo-precipitation data from a speleothem located in Mesoamerica that reveal large multi-decadal declines in regional precipitation, whose onset coincides with clusters of large volcanic eruptions during the 19th and 20th centuries. This reconstruction provides new independent evidence of long-lasting

volcanic effects on climate and elucidates key aspects of the causal chain of physical processes determining the tropical climate response to global radiative forcing.

The climate of Mesomerica (Fig. 1a) is characterized by a boreal summer/fall (June-October) rainy season and a relatively dry winter[1]. Mesoamerica's rainfall is influenced by moisture originating usually from the vicinity of the Intertropical Convergence Zone (ITCZ) via transport into the monsoonal system over Belize, via the Caribbean low-level jet, and by localized convection. In summer, the ITCZ migrates to its northern position, its core stretching across the northern tropical Atlantic at ~10°N, into northern South America and from there turning north over Central America to the East Pacific, reaching to ~12°N and causing widespread rainfall over the land portion[2]. Because the two ITCZ segments respond to variations in sea-surface temperatures (SSTs) in both the tropical Atlantic and the Pacific Oceans, Mesoamerica is exposed to complex hydrological fluctuations on a broad range of timescales[3]. Year-to-year rainfall variability in the Guatemala mountain regions today is correlated with the gradient between SSTs in the western tropical Atlantic and eastern tropical Pacific[1]. 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[4,5]. Similarly, anomalously warm (cold) eastern equatorial Pacific SSTs, e.g., during El Niño (La Niña) events, force an equatorward (northward) displacement of the east Pacific ITCZ and contribute to drying (wetting) in most of Central America[6,7]. Observations also indicate an association between precipitation conditions over Mesoamerica and the phasing of the winter North Atlantic Oscillation (NAO)[8].

Timing and distribution of precipitation during the summer season is a critical issue for agricultural yields in Yucatán, and periods of drought vitally affect agriculture and, hence, local societies [new ref:]. Observational meteorological records indicate that droughts on the peninsula are much rare and tend to be more severe than wet periods [same ref as above]. However, the availability of continuous, long-term hydrological data beyond the few decades covered by the instrumental record is a necessary prerequisite to fully characterize regional hydrological variability and to uncontroversially address its dependence on large-scale climatic fluctuations, especially the identification of forcing mechanisms at the hemispheric to global scales. Speleothems are increasingly used as terrestrial archives of past climate and environmental change because they can provide long, continuous, precisely U-series dated and high-resolution time series, and are generally unaffected by post-depositional diagenetic alteration. Here we present results from a new 300 yr (1700-2000 C.E.) $\delta^{18}O$ reconstruction based on a speleothem from Mesoamerica demonstrating, for the first time, that natural external forcing can drive successive multi-decadal dry and wet phases in the tropics.

Results

Hydrological reconstruction and volcanic eruptions.

The data for this study derive from stalagmite GU-Xi-1 collected 250 m inside the large cavern of Xibalba in the Campur Formation[9] located in the Maya Mountains of Guatemala near the Belize border (Fig. 1a, 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, 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 (Fig. 1b). The specimen is 33 centimeters tall, but only the upper 18 centimeters are used for this study (Fig. 2a). Our age model (Fig. 2b) is highlyconstrained by nine U/Thmulticollector inductively coupled plasma mass spectrometry dates (Supplementary Table 1) and by the collection date in 2007.

The largest amounts of annual precipitation in the region fall on the high mountain ranges of Guatemala, southwest of the cave. Summer precipitation values in the Maya Mountains reach upwards of 400 mm/month, but are approximately half that amount in the study area. A strong inverse correlation between speleothem $\delta^{18}O$ and tropical precipitation intensity[10] has previously been observed for the region[11]. The speleothem $\delta^{18}O$significantly correlates (see methods) with precipitation from nearby Belize City over the instrumental period, when a lag of six years is imposed to the former (Fig. 3). The inverted correlation patterns of the speleothem $\delta^{18}O$ with the SST and sea-level pressure (SLP) fields over the Pacific and Atlantic sectors is consistent with corresponding patterns for observed precipitation (Fig. 4), supporting the robustness of the climatological scenario associated with interannual rainfall variability over the Yucatán.

The most prominent aspects of our reconstruction are the occurrences of three distinct multi-decadal drying trends during the 19th and 20th centuries (Fig. 5e). Based on the modern relationship between $\delta^{18}O$ and regional precipitation anomalies[12], the speleothem data indicate a 25% decrease in precipitation between 1810 and 1845 C. E., another comparable precipitation decrease between 1883 and 1925 C. E., and a third, smaller decrease from 1963 to the present. The drying steps are separated from one another by brief intervals of precipitation recovery in mid-century. Our and other available $\delta^{18}O$ records from Mesoamerica[13,14] correlate

with each other with variable strength during the reconstruction period (Fig. 6, Supplementary Figs. 1,2), in part reflecting large dating uncertainties in some of the reconstructions. The different reconstructions feature similar drying trends during the early and – less so – late 19th century, suggesting a broader regional phenomenon.

Our three pronounced decreases in regional precipitation coincided with clusters of strong tropical volcanic eruptions (Fig. 5a). The most prominent of these eruptions are the 1809 eruption of unknown location and Tambora in 1815 (cluster 1), Krakatau in 1883 (cluster 2), Agung in 1963 and Pinatubo in 1991 (cluster 3). Reconstructed precipitation decreases throughout each cluster such that the precipitation evolution during these periods is best described as a function of cumulative volcanic radiative forcing (Fig. 5b-d, Supplementary Figs. 3,4 and Supplementary Note 1). The different estimates of cumulative volcanic forcing provided in Fig. 5 exemplify the effects of uncertainties such as those in reconstructed aerosol optical properties used as volcanic forcing input to climate models, those arising from the presence of additional varying external forcing factors, and those inherent in the model-specific implementation of volcanic forcing.

The most recent volcanic cluster does not display a statistically-significant correlation between $\delta^{18}O$ and cumulative volcanic forcing, that we interpret as the result of the different background climate conditions and of interferences from other dominant forcing factors during the mid- to late-20th century. For the 19th century clusters, the drying trend only reverses when volcanic activity substantially weakens. The precipitation recovery is only partial, possibly as part of recurrent drying trends in Mesoamerica[11,15]. Aerosols are a known critical part of the overall anthropogenic as well as natural forcing of climate (the latter associated with aeolian dust and volcanic eruptions)[16-18]. We thus surmise that the decadal drying trends in the early

148 and late decades of the 19th century and during the second half of the 20th century are largely a
149 consequence of the clustered volcanic forcing, with the most recent period superposed on long-
150 term anthropogenic drying[19,20]. Periods of strong volcanic activity during the last millennium
151 also often coincide with periods of anomalous solar activity. This is the case, for instance, for
152 the first volcanic cluster that coincides with the prolonged period of weak solar activity known
153 as Dalton Minimum[21]. We can thus not attribute the reconstructed changes to volcanic forcing
154 alone.
155
156 **Dynamical interpretation of reconstructed changes**.
157 Based on the close agreement between the drying phases and the volcanic clusters, we
158 hypothesize that the eruption clusters played a primary role in these climatic changes by
159 inducing perturbations in patterns of SST variability that in turn crucially influence the Pacific-
160 Atlantic tropical SST gradient that dominate the Mesoamerican hydroclimate. Specifically, we
161 propose that the volcanic clusters influence the El Niño Southern Oscillation (ENSO) in the
162 equatorial Pacific and the long-term variations of tropical Atlantic SSTs, which is governed by
163 the Atlantic Multidecadal Oscillation (AMO)[22]. An increasing number of climate
164 reconstructions and simulations describe statistical and dynamical connections between
165 volcanic forcing and both ENSO[23]and AMO[24-26]. Indeed, drying (recovery) phases during the
166 volcanic clusters correspond to cold (warm) phases in a recent marine-proxy-based AMO
167 reconstruction[27] (Fig. 7a), while reconstructed data[28]suggest an increased role for ENSO in
168 Mesoamerican precipitation variability during the 20th century (Fig.7b). The preferred time
169 scales of significant coherence with the $\delta^{18}O$ signal differ between ENSO and AMO, as the
170 former index highlights interdecadal time scales (O(30 year)) while the latter highlights multi-

171 decadal time scales (O(50 year)), further suggesting that the linkages may reflect different
172 teleconnection mechanisms (see also Fig. 7c). Such differences in the relative roles of climatic
173 modes indicate that internal dynamics play a substantial role in communicating high
174 atmospheric evolution during the different volcanic eruption clustersto the surface. This
175 exemplifies the complexity of a dynamical interpretation, and hence attribution, of the
176 reconstructed changes in Mesoamerican precipitation. Moreover, reconstructions of climate
177 modes often lack robustness due to the inherent uncertainties implicated in reconstructing
178 large-scale features from a limited number of local climate proxies. This has been shown for
179 the NAO[29] that captures a dominant part of the short- and long-term variability of large-scale
180 atmospheric circulation over the North Atlantic, which is a known factor influencing
181 Mesoamerican precipitation (Fig. 4b,d) and is sensitive to volcanic forcing[30,31].
182 A warranted dynamical interpretation based on modeling results is also complicated by the
183 fact that last-millennium simulations from state-of-the-art global climate models do not show a
184 consistent response of Mesoamerican precipitation to strong volcanic activity (Fig. 8), failing
185 to robustly reproduce the patterns reconstructed from our speleothem. The discrepancy
186 between our reconstruction and the simulations can be ascribed to general deficiencies still
187 affecting the simulated representation of key chemical and physical processes related to aerosol
188 forcing, and to the consequent large uncertainties in the simulated climate response to volcanic
189 forcing[21,32]. Further possible explanations are the common model deficiencies concerning
190 regional precipitation variability at the decadal and multi-decadal time scales[33], which are
191 linked to poor and hence less robustly simulated representation of dominant modes of large-
192 scale climate variability and associated teleconnections including ENSO[34]and the AMO[35].
193 Large uncertainties also affect the reconstructed forcing[36]and we have very limited knowledge

194 about the background climate conditions at the time of volcanic eruptions that occurred prior to
195 the last half of the 20thcentury[26].
196
197 ## Discussion
198 The prolonged post-eruption drying conditions in Mesoamerica described by our new
199 speleothem-based data provide independent evidence that volcanic effects on tropical
200 climate persist well beyond the duration of the direct radiative imbalance[31]. We suggest that
201 volcanically-induced changes in dominant modes of large-scale, ocean-atmosphere coupled
202 variability is a likely physical mechanism contributing to such persistence. Further studies
203 are needed to clarify the dynamics governing the response. Still, our observation relating
204 clusters of large volcanic eruptions to prolonged decreased Mesoamerican precipitation
205 should expand the emerging discussion fostered by indications from global climate models
206 regarding the strong sensitivity of the world's other monsoons to external forcing[37,38]. Our
207 results, in combination with studies of global stream flows after large volcanic eruptions[39],
208 imply that certain tropical hydroclimates may be highly sensitive to volcanic forcing and,
209 more generally, to large stratospheric aerosols loading[20]. Global climate models have
210 become increasingly important to our physical understanding of such "global forcing to
211 regional response" connections. As discussed however, related uncertainties affecting the
212 simulated representation (or lack thereof) of key processes as well as the reconstructed
213 external forcing that is imposed on paleo-simulations remain considerable. We need to better
214 understand such critical aspects of reconstructed as well as simulated pre-industrial tropical
215 climate evolution in order to increase our confidence in projected future regional

precipitation trends and variability and to potentially customize solutions for particular regions.

Methods

Speleothemcharacteristics and analysis.We collected the GU-Xi-1 stalagmite in 2007 from the Xibalba cave located in a thick forest near the Guatemala/Belize border(Fig. 1b), and mapped its underground location relative to the surface. The ceiling height varies from 10 m to >40 m. The collection site lies well above the level of modern floods, which eliminates inaccuracies in dating due to possible initial detrital ^{230}Th. GU-Xi-1 was active and growing at the time of collection, with a columnar shape indicating it was a product of a single drip source.The stalagmite was cut into two sections and a 1 cm-thick slab was produced from one of the sections.

Age model. 200 mg of powder were collected with a hand-held dental drill from a polished slab section of GU-Xi-1along growth layers for dating. Nine ^{230}Th dates were analyzed in the upper 175 mm resulting in an age control point approximately every 30 years (Fig. 2a). We analyzed three samples for thorium and uranium isotopes separately on a Finnigan-MAT Element outfitted with a double focusing sector-field magnet in reversed Nier-Johnson geometry and a single Mas Com multiplier. We measured combined ionization plus transmission efficiency of 2.5 to 3‰ for uranium and 1.5 to 2‰ for thorium. Dating resolution using the machine was 40 to 80 years. Six more samples were analyzed with a Neptune ICP-MS MC, with a dating resolution of less than 4 years. Further details of instrumental procedures are explained in[40,41]. We obtained these dates with a magnetic sector inductively-

239 coupled plasma mass spectrometer at the University of Minnesota, Isotope Laboratory[42].
240 Chemical separation procedures followed those described in[43].The age model for the
241 speleothem is based on a parabolic curve fit to the ^{230}Th dates and the collection date (Fig. 2b).
242 Error bars are larger for the ages determined with a Finnigan-MAT Element compared to the
243 dating resolution obtained using the Neptune ICP-MS MC (Fig. 2b). We used Analyseries
244 (http://www.lsce.ipsl.fr/logiciels/index.php) to regress the U/Th ages with depth. We found
245 that the upper section of GU-Xi-1 grew according to a second-degree polynomial that was
246 parabolic (r=0.99). We removed any sampling bias with Analyseries using the integration
247 method to provide evenly spaced annual samples. We used the resulting polynomial equation
248 to convert each sample depth to calendar ages from the speleothem, which we used for our age
249 model.
250 Different possible age models have been tested (Supplementary Fig. 5), including StalAge[44],
251 COPRA[45], calcium (Ca) layer counting and the average between StalAge and the Ca count
252 methods (ChronMean).All the tested models agree closely with the timing of the drying event
253 observed from the stable isotope record associated with the Tamboraeruption. The largest
254 uncertainty is the timing of the Krakatau eruption. It should be noted that because GU-Xi-1
255 growth slowed down considerably towards the present (from 1915 to 2007 it grew 2.5 times
256 slower than from 1840 to 1871) any error for the more recent samples in assigning a depth to a
257 U/Th date is exacerbated. StalAge is a routinely usedalgorithm specifically designed for
258 speleothems. It takes into account outliers and age inversions using a Monte-Carlo simulation.
259 In our case, as we do not have outliers nor age inversions, it basically performs a linear
260 interpolation between age points. A similar age model[45] gives near identical results to that of
261 StalAge. Another approach is to count the annual laminations (clearly present in GU-Xi-1). We

are confident the laminations are annual because the number of laminations counted are within 97% confidence limits of the U/Th dates. The annual layers are tedious to count and also produce subjective counting errors. Another more objective method is to count the number of annual Ca peaks that clearly follow the annual banding. During summer more Ca is incorporated in the speleothems[46]. The results from this method are shown as the Ca counts chronology in Supplementary Fig. 1 and clearly lie to the right (younger) side of the age model especially from 1830 to the present. According to StalAge the "Krakatau" event (as seen in the stable isotopes) occurred in 1864 (about 20 years earlier) but according to the Ca counts the event occurred in 1910 (about 20 years later). StalAge based on U/Th dates may be biased towards recent samples because of the greater uncertainties (5 to 10% of the absolute age[47]) for younger speleothems with low U, thus limiting the possibility to correlate time-series based on speleothems with those based on instruments. A further approach is to take the mean of both the StalAge and the Ca count methods. The mean is shown as the "ChronMean" in Supplementary Fig. 5. The ChronMean model also smoothes any U/Th depth sampling error. The ChronMean is nearly identical to our parabolic fit for stalagmite GU-Xi-1 from 1750 onwards giving us confidence in our age chronology and timing of the isotopes events to the volcano chronology. Furthermore, there is supporting evidence that some stalagmites grow in a parabolic fashion. Parabolic growth of speleothems has been previously noted[48] and may be a natural function of conical growth. Finally, the similarity of our record withthat from another stalagmite from MesoAmerica[13] (Fig. 6) increases our confidence on the robustness of our age model.

Samples and $\delta^{18}O$ isotopic analysis. 582 samples were continuously milled along the stalagmite growth axis of GU-Xi-1 stalagmite using a digitally controlled micro-milling machine (SHERLINE 5410). Samples were milled at 0.3 mm intervals (Fig. 2a) giving a temporal resolution ranging between yearly at the top to seasonal at the bottom. Growth rate of the speleothem fluctuated from approximately 1 to 3 mm per year. The samples were analyzed using a continuous flow isotope ratio mass spectrometry (CF-IRMS[49])at the ETH Zurich, Switzerland. Details on the methodology are given in[49]. MS2 was used as in-house reference material (powdered Carrara marble, MS2[49]), with isotope ratios ($^{18}O/^{16}O$ and $^{13}C/^{12}C$) reported in standard Delta notation relative to the Vienna Pee Dee Belemnite (‰ VPDB) standard (see supplementary data 1). The external analytical precision for $\delta^{18}O$ is better than 0.06‰.

Amount Effect. The amount effect on stalagmites has been rigorously studied for Mesoamerica and has shown to be valid[11,12]. The comparison between precipitation and $\delta^{18}O$ in Fig. 3 indicates that the speleothem's oxygen isotopic properties capture the low-frequency variations of rainfall outside the cave, with the proportion of heavy isotope inversely proportional to the amount of precipitation.

Observational datasets. The precipitation data are from the University of East Anglia (UEA) - Climate Research Unit (CRU) gridded historical Time Series (TS) version 3.21 for 1901 to 2012 (for more information, see:http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__ACTIVITY_0c08abfc-f2d5-11e2-a948-00163e251233). The SST data are from the NOAA National Climate Data Center Extended Reconstructed Sea Surface Temperature (ERSST) analysis[50] version 3b averaged over the summer months between 1901 and 2012 in Fig. 4a, and between1880 and 2006 in Fig.

4c to fit with the length of the observed precipitation and $\delta^{18}O$ records, respectively. The SLP data are from the NOAA Environmental Research Laboratories Twentieth Century Reanalysis Project (TCRP)[51] version 2, covering the period between 1901 and 2006 in Fig. 4b and between 1880 and 2006 in Fig. 4d. The SLP data were averaged over the winter (December-March) preceding the summer, as this is when the atmosphere forces the SST pattern seen in Fig. 4a[8]. Support for the TCRP dataset was provided by the U.S. Department of Energy, Office of Science Innovative and Novel Computational Impact on Theory and Experiment (DOE INCITE) program, and Office of Biological and Environmental Research (BER), and by the National Oceanic and Atmospheric Administration Climate Program Office.

Data for Belize-City precipitation is from the National Oceanic and Atmospheric Administration, monthly Global Historical Climatology Network (GHCN: http://www.ncdc.noaa.gov/ghcnm/).

Simulated precipitation datasets. Time series of Yucatán precipitation covering the period 1700-2005 were obtained from an ensemble of climate model simulations from the repository of the Coupled Model Intercomparison Project 5 (CMIP5). For each model, the time series were created by merging the data from the last-millennium simulation (past1000, which ends in 1849) with the corresponding data from one of the historical simulations (starting in 1850). Yucatán is defined as the area between 91°W and 87°W and between 16°N and 22°N (all model data were interpolated to a 2°x2° grid before selecting the region).

Volcanic forcing estimates. Forcing estimates from ECHAM5/MPIOM[52] and Bergen Climate Model (BCM)[24] are derived from volcanic forcing-only and natural(volcanic and solar) last-

millennium simulations. Forcing estimates for CCSM4[53] are derived from the full-forcing last-millennium simulation available in the CMIP5 repository. Long-term influences from greenhouse gases in CCSM4 are accounted for by removing the fourth-order polynomial trend over the period 1750-2005. Natural forcing was then estimated based on clear-sky top-of-atmosphere radiative fluxes to discard cloud related feedbacks. The simulations use different reconstructions of aerosol optical properties for volcanic forcing: ECHAM5/MPIOM uses the reconstruction by[54]; BCM uses the reconstruction by[55]; CCSM4 uses the reconstruction by[56].Cumulative volcanic forcing is obtained by cumulatively adding the forcing of each volcanic event through time.

Statistical significance. Statistical significance for correlations accounts for the effective degrees of freedom based on autocorrelation following the method by[57]. The lag in Fig. 3 was determined based on a cross-correlation analysis between the two time series with lags varying between -10 and +10 years. The binomial smoothed 71-year precipitation record shown in Fig. 3 has 15 degrees of freedom, so that a correlation value of 0.43 is significant at the 95% level using a directional test (appropriate in this case as we can surmise that the precipitation is the driver of the $\delta^{18}O$ variations and not vice versa).

Wavelet analysis. Wavelet coherence spectra were calculated using the tool by[58]. For additional information, see:[59]. The power of the wavelet coherence spectrum can be interpreted as a measure of the strength of the local (in the time-frequency domain) correlation between the two time series.

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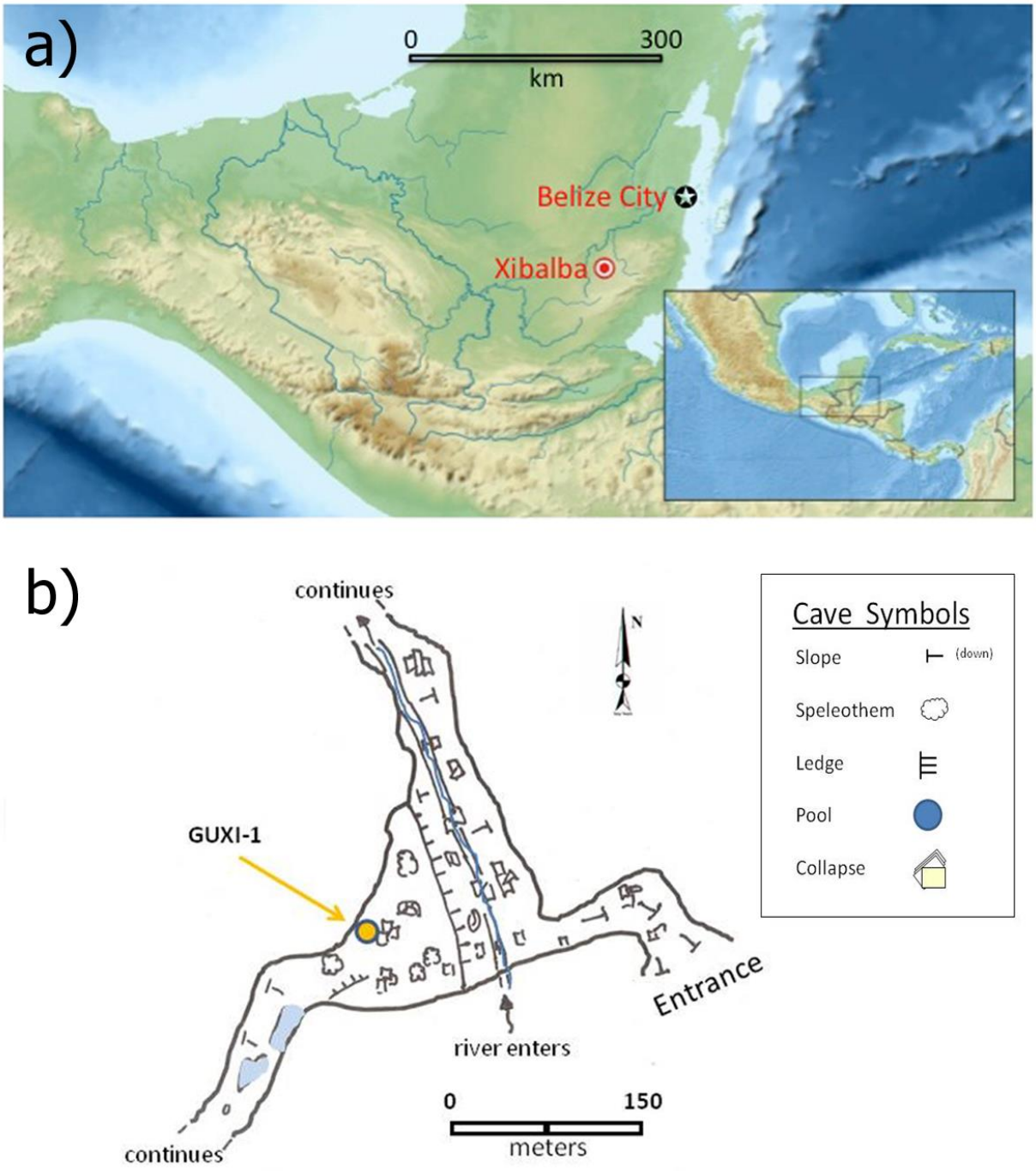
Author contributions AW, YK, and DB conceived the project. TM selected and retrieved the stalagmite, and mapped its locations with respect to the surface. AW, DZ, YK, DB, GL and AR wrote most of the paper. AB, GH, JEM, SB, LB, DZ and HC performed the experiments and analytical work.

Figure Captions



377

378 **Figure 1: Geographicalcharacteristics of the study area.**(**a**) Location map of Mesoamerica
379 and of the Xibalba cave; (**b**) Map of the speleothem site with major physical features of the
380 cave.

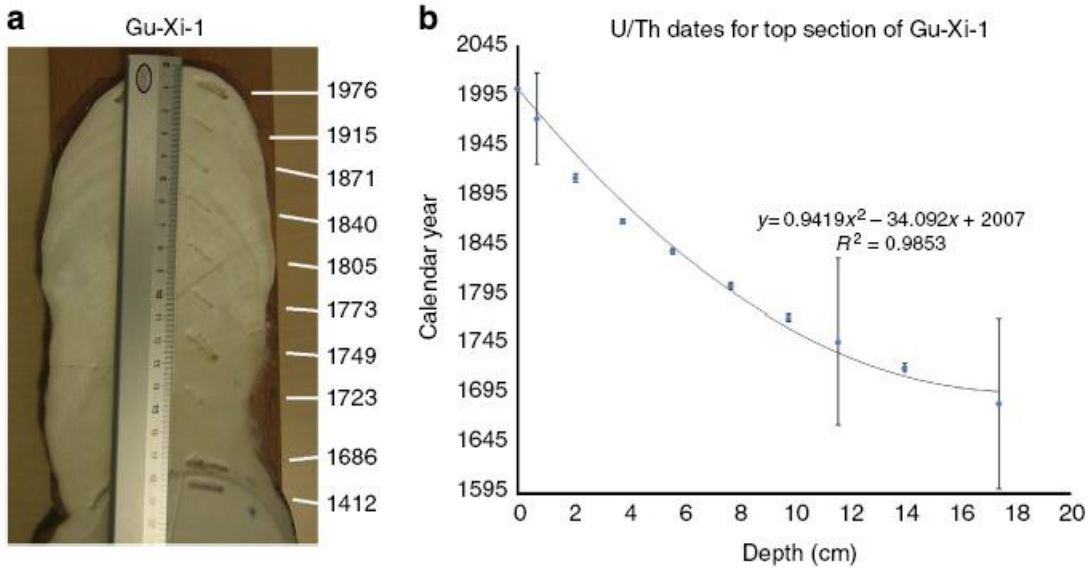


Figure 2: Image of the speleothem andage model. (**a**) The photograph of GU-Xi-1 stalagmite shows the height of the specimen used in this study (18 cm), with a rounded top and no "cup" that could imply drip erosion. Also shown is the milling channel for the stable isotopes adjacent to a cm ruler as well as the nine pits on stalagmite GU-Xi-1 used to determine 230Th. (**b**) Age model.

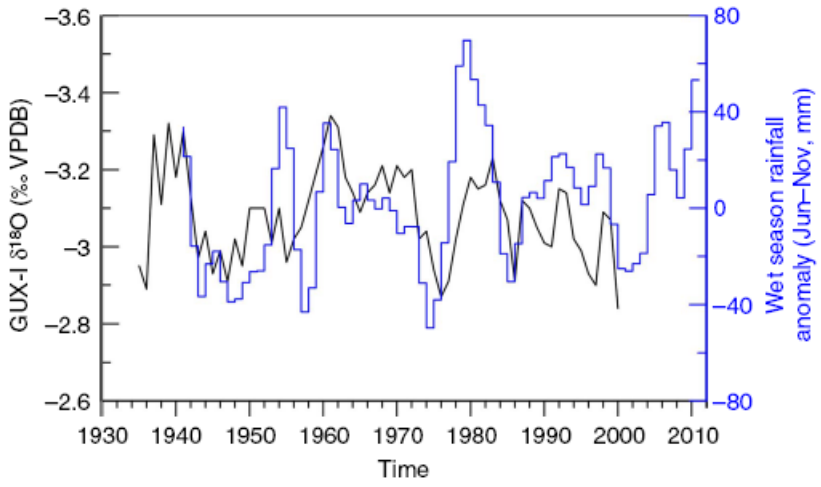


Figure 3: Comparison between reconstructed and observed Mesoamerican precipitation. Shown are the time series of speleothem GU-Xi-1 $\delta^{18}O$ (black line, units in permil) and June to November precipitation anomalies in Belize City, Belize (deviation from climatology in mm,

blue line) smoothed with a second order binomial filter. The $\delta^{18}O$ time series lags the rainfall time series by six years.

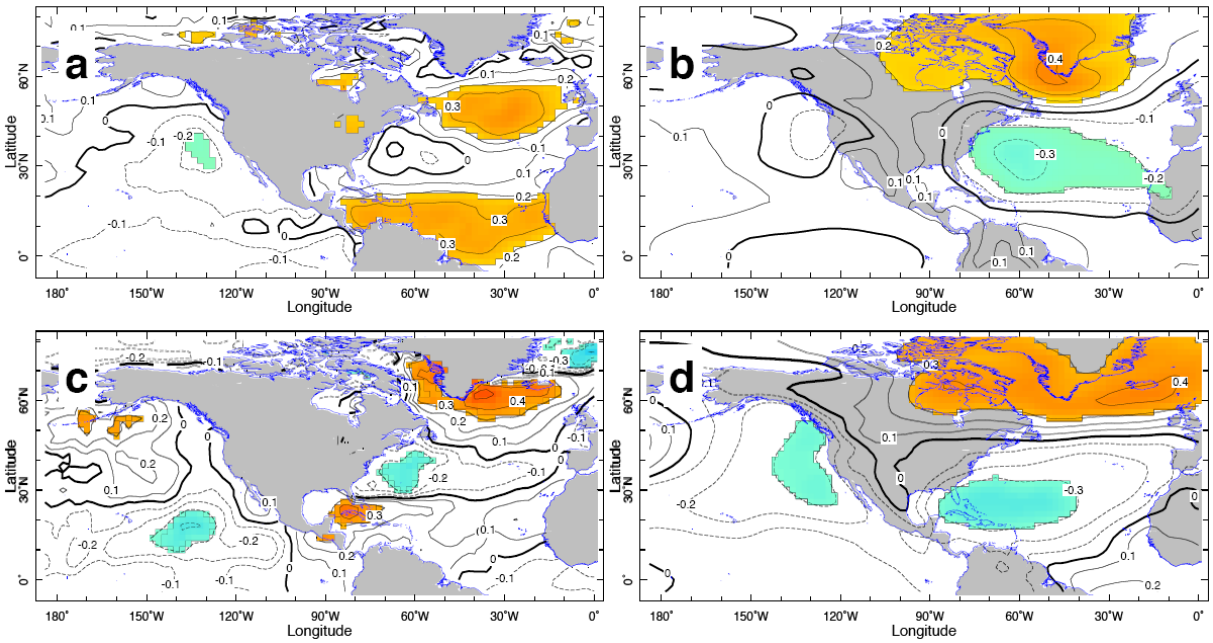
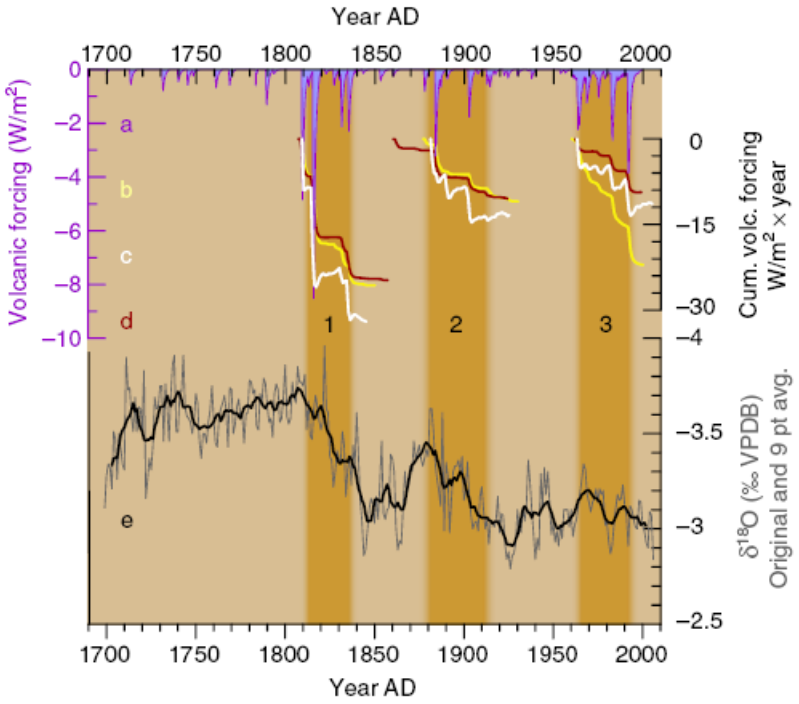


Figure 4: Atmosphere and ocean relationships to Mesoamerican rainfall. (**a**, **b**) Correlations between summertime (May-October) observed precipitation averaged over the Yucatán Peninsula and sea-surface temperature (SST, **a**) and sea level pressure (SLP,**b**). (**c**, **d**) Correlations of the SST and SLP fields with the GU-Xi-1 speleothem$\delta^{18}O$ (multiplied by -1). Contours in all figures are drawn at 0.1 intervals. Regions where the correlation exceeds the 95% confidence level for significance are shaded in color (orange for positive and light blue for negative).



405

406 **Figure 5: Persistent drying phases over Mesoamerica and volcanic forcing.**(**a**) Volcanic
407 radiative forcing from 1700-2000 C. E.after[24]. Dark-brown boxes indicatevolcanic eruption
408 clusters noted in the text. (**b**,**c**,**d**)Different estimates of cumulative top-of-atmosphere radiative
409 flux anomalies from different climate simulations: BCM (Fig. 5b, yellow), CCSM4 (Fig. 5c,
410 white) and ECHAM5/MPIOM (Fig. 5d, brown). (**e**) Interpolated annual time series of
411 speleothemGU-Xi-1 $\delta^{18}O$ (grey line) with corresponding 11-year moving average values (thick
412 black line).

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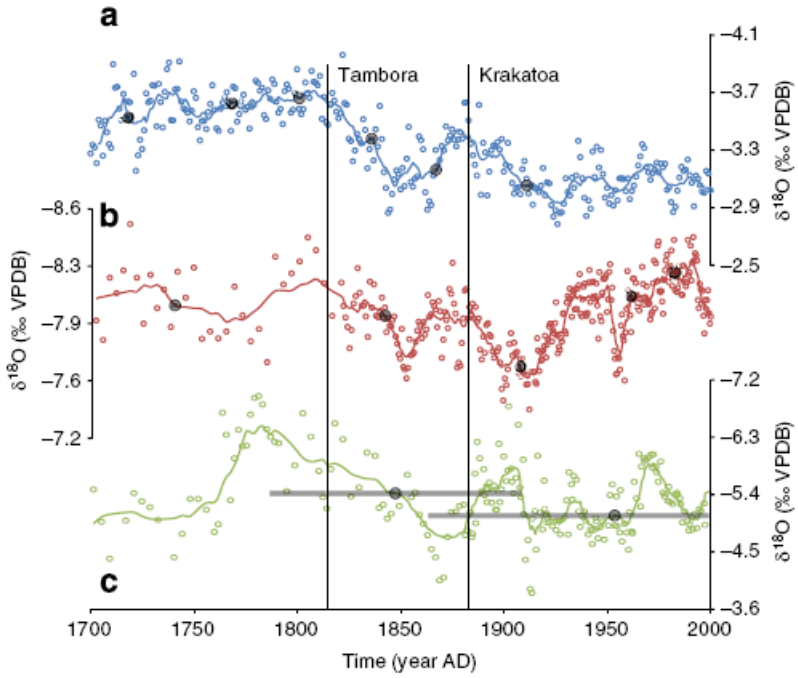

Figure 6: Comparison between stalagmite records from MesoAmerica. Top: GU-Xi-1 (this study); middle: southwestern Guerrero (Mexico)[13]; bottom: Yucatán peninsula (Mexico)[14].The difference in alignments of these records depends on their age models (note poor age control of theYucatánrecord[14]) sampling resolution and extent of local and cave environmental overprinting.

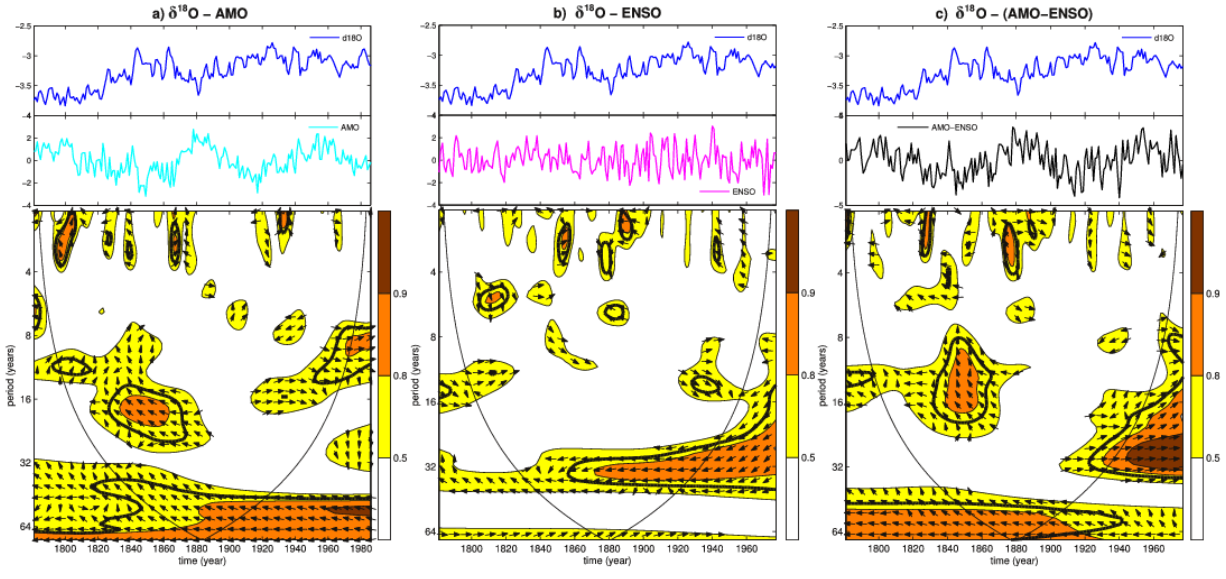

Figure 7: Linkage between reconstructed Mesoamerican precipitation and dominant modes of climate variability. The different panels show wavelet coherences (power in color shading) between the speleothem $\delta^{18}O$ and: **a**) the AMO reconstruction by[27], **b**) the integrated ENSO/PDO reconstruction by[28], and **c**) the difference between the two. The time series are shown in the top and middle panels (blue: $\delta^{18}O$; turquoise: AMO; magenta: ENSO; black: difference between AMO and ENSO). The arrows illustrate the phase relationship: rightward (leftward) arrows indicate co-phase (anti-phase); northward and southward oriented arrows indicate quadrature. Thick contour lines identify significant[58] coherence. The thin black lines are the cone of influence, where edge effects occur.

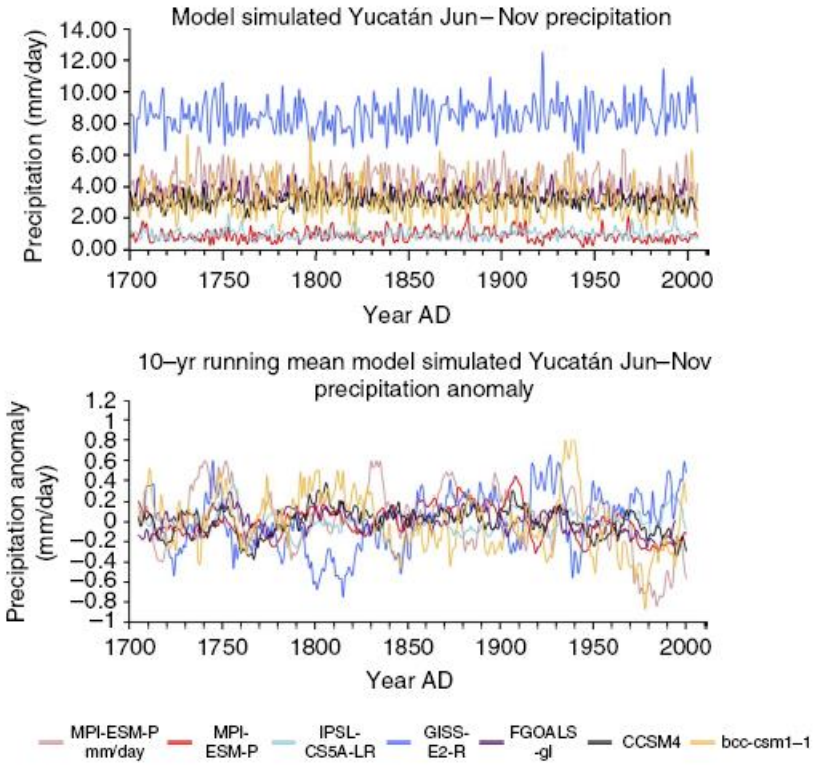

Figure 8: June-November precipitation in Yucatán fromCMIP5 simulations covering the period 1700 to 2005.a) raw time series, **b**) 10-year running mean, where the climatological mean has been subtracted.

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