Persistent drying in the tropics linked to natural forcing

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

1. University of Puerto Rico, Mayaguez, Puerto Rico 00681-9000, USA.
2. Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York 10964, USA
3. Stony Brook University, Stony Brook, New York 11790, USA.
4. Max Planck Institute for Meteorology, Bundesstr. 53, 20157 Hamburg, Germany
5. University of Venice, Dorsoduro 2137, 30123 Venice, Italy
6. Alfred Wegener Institute for Polar and Marine Research, 27570 Bremerhaven, Germany
7. University of Minnesota, Minneapolis, Minnesota 55455, USA
8. Sediment and Isotope Geology, Ruhr-University Bochum, Universitätsstr. 150, 44801, Bochum, Germany.
9. CEREGE (CNRS-Université Aix Marseille), 13545 Aix en Provence, France.
10. 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.

Introduction

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. The data for this study derive from stalagmite GU-XI-1 collected 250 m inside the large cavern of Xibalba in the Campur Formation[1] 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, 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 33 cm tall, but only the upper 18 centimeters are used for this study (Supplementary Fig. 2). Our age model (Supplementary Fig. 3) is highly constrained by nine U/Th multicollector inductively coupled plasma mass spectrometry dates (Supplementary Information Table S1) and the collection date in 2007.

The climate of Mesomerica is characterized by a boreal summer/fall (June-October) rainy season and a relatively dry winter[2]. Low-level atmospheric circulation in the region is dominated by the North Atlantic northeast trade winds. The largest amounts of annual precipitation in the region fall on the high mountain ranges of Guatemala to the 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[3] has previously been observed for the region[4.] A plot of speleothem $\delta^{18}O$ lagging precipitation from nearby Belize City over the interval of instrumental overlap data by six years shows a significant correlation (Fig. 2).

The complete three-century precipitation-proxy record is characterized by interannual to sub-decadal variability superimposed on several distinct multi-decadal drying episodes (Fig. 3c). Mesoamerica's rainfall is influenced by moisture, originating usually from the vicinity of the 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[5]. 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[6]. Today, year-to-year rainfall variability in the Guatemala mountain regions is correlated with the thermal gradient between SSTs in the western tropical Atlantic and eastern tropical Pacific[2]. 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 Niña) events, force an equatorward (northward) displacement of the east Pacific ITCZ and contribute to drying (wetting) in most of Central America[9,10] (Supplementary Fig. 4).

Results

Mesoamerican hydrological reconstruction and large volcanic eruptions

The most prominent aspects of our reconstruction are the occurrences of three distinct multi-decadal drying trends during the 19th and 20th centuries (Fig. 3c). Based on the modern relationship between $\delta^{18}O$ and regional precipitation anomalies[11], 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 correlate with each other with variable strength during the reconstruction period (Fig. 4, Supplementary Fig. 5), 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. The three pronounced decreases in regional precipitation coincided with clusters of strong tropical volcanic eruptions (Fig. 3a). 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 cumulative volcanic radiative forcing best describes the precipitation evolution during these periods (Fig. 3b, Supplementary Figs. 6, 7). 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[4,12]. 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)[13,14,15]. Thus we surmise that the decadal drying trends in the early and late decades of the 19th century and during the second half of the 20th century are largely a consequence of the clustered volcanic forcing, with the most recent period superposed on long-term anthropogenic drying[16]. Periods of strong volcanic activity during the last millennium often coincide with periods of anomalous solar activity. This is the case, for instance, for the first volcanic cluster that coincides with the prolonged period of weak solar activity known as Dalton Minimum[17]. Therefore, we cannot attribute the reconstructed changes to volcanic forcing alone.

Dynamical interpretation of reconstructed changes

Based on the close agreement between the drying phases and the eruption clusters, we hypothesize that volcanic clusters played a primary role in these climatic changes. This, we propose, was driven by changes the eruption induced in patterns of SST variability that crucially influence the Pacific-Atlantic tropical SST gradient, which in turn dominate the Mesoamerican hydroclimate. These are the El Niño Southern Oscillation (ENSO) in the equatorial Pacific and the long-term variations of tropical Atlantic SSTs, which is governed by the Atlantic Multidecadal Oscillation (AMO)[18]. An increasing number of studies based on climate reconstructions and simulations describe statistical and dynamical connections between volcanic forcing and both ENSO[19] and AMO[20-22]. Indeed, drying (recovery) phases during the volcanic clusters correspond to cold (warm) phases in a recent marine-proxy-based AMO reconstruction[23] (Supplementary Fig. 8), while reconstructed data[24] suggest an increased role for ENSO in interdecadal Mesoamerican precipitation variability during the 20th century (Supplementary Fig. 8). Such changes in the relative roles of climatic modes indicates that internal dynamics play a substantial role in communicating to the surface the evolution during the different volcanic eruption clusters. It also exemplifies the complexity of a dynamical interpretation, hence attribution, of the reconstructed changes in Mesoamerican precipitation. Moreover, reconstructions of climate modes often lack robustness due to the inherent uncertainties implicated in reconstructing large-scale features from a limited number of local climate proxies. This has been shown, for instance, for the North Atlantic Oscillation[25] that captures a dominant part of the large-scale atmospheric circulation short- and long-term variability over the North Atlantic, which is a known factor influencing Mesoamerican precipitation (Supplementary Fig. 4) and is sensitive to volcanic forcing.

A warranted dynamical interpretation based on modeling results is also complicated by the fact that last-millennium simulations from state-of-the-art global climate models do not show a consistent response of Mesoamerican precipitation to strong volcanic activity (Supplementary Fig. 9), failing to robustly reproduce the evolution reconstructed from our speleothem. The discrepancy between our reconstruction and the simulations can be ascribed to general deficiencies still affecting the simulated representation of key chemical and physical processes related to aerosol forcing, and the consequent large uncertainties in the simulated climate response to volcanic forcing[15,26]. Further possible explanations are the common model deficiencies concerning regional precipitation variability at the decadal and multidecadal time scales[27], which is linked to poor and hence not robust simulated representation of dominant modes of large-scale climate variability and associated teleconnections including ENSO[28] and the AMO[29]. Large uncertainties also affect the reconstructed forcing[30] and we have very limited knowledge about the background climate conditions at the time of volcanic eruptions that occurred prior to the last half of the 20th century[22].

Conclusions

The prolonged post-eruption drying conditions in Mesoamerica described by our new stalagmite-based data provide independent evidence that volcanic effects on tropical climate persist well beyond the duration of the direct radiative imbalance. We suggest that volcanically-induced changes induced in dominant modes of large-scale, ocean-atmosphere climate variability is a likely physical mechanism contributing to such persistence. Further studies are needed to clarify the dynamics governing the response. Still, our observation relating clusters of large volcanic eruptions to prolonged decreased Guatemalan precipitation should expand the emerging discussion fostered by indications from global climate models regarding the strong sensitivity of the world's other monsoons to external forcing[31,32]. Our results in combination with studies of global streamflows after large volcanic eruptions[33] imply that certain tropical hydroclimates may be highly sensitive to volcanic forcing or more generally to large stratospheric aerosols loading. Global climate models have become increasingly important to our physical understanding of such "global forcing to regional response" connections. As discussed here, however, related uncertainties affecting the simulated representation (or lack thereof) of key processes as well as the reconstructed external forcing that is imposed to paleo-simulations remain considerable. Thus, we need to better understand such critical aspects of reconstructed as well as simulated pre-industrial tropical 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 Summary

We collected the GU-XI-1 stalagmite in 2007 from the Xibalba cave located in the Guatemala/ Belize border, and mapped its underground location relative to the surface. 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 0.3 mm intervals along the stalagmite growth axis resulting in annual to sub-annual resolution for our stable isotope data. Volcanic forcing estimates from ECHAM5/MPIOM and Bergen Climate Model (BCM) are derived from volcanic forcing-only last-millennium simulations. Volcanic forcing estimates for CCSM4 are derived from the full-forcing last-millennium simulation (past1000_r1) available in the repository of the Coupled Model Intercomparison Project 5 (CMIP5). Long-term influences from greenhouse gases in CCSM4 are accounted for by removing the fourth-order polynomial trend over the period 1750-2005. Volcanic forcing is then estimated based on clear-sky top-of-atmosphere radiative fluxes to discard cloud related feedbacks.

Acknowledgements

AW thanks the Swiss Federal Institute of Technology both for hosting his sabbatical and for the analysis of the stable isotopes. Collection of GU-XI-1 by TM was supported through a sabbatical granted by the University of Puerto Rico (Mayagüez) and the National Geographic Society Grant #3089-85 to TM partially supported survey of the cave and location of the stalagmite. The research was supported in part by the National Science Foundation ATM-1003502. Y. Kushnir was also supported by grant NA10OAR4310137 from the National Oceanic and Atmospheric Administration – Climate Program Office. S.F. M.B. acknowledges financial support from the Schweizer National Fond Project CRS122 132646/1. D. Black was supported by National Science Foundation Grant ATM-1003219. GL acknowledges support from Helmholtz through PACES and REKLIM. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups for producing and making available their model output.

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, YK, DB, GL, DZ wrote most of the paper. AB, GH, JEM, SB, LB, DZ and HC performed the experiments and analytical work.

References

1. Miller, T. E. Geologic and Hydrologic Controls on Karst and Cave Development in Belize. *J. Cave Karst Stud.* **58,** 100–120 (1996).

2. Giannini, A., Kushnir, Y. & Cane, M. A. Interannual Variability of Caribbean Rainfall, ENSO, and the Atlantic Ocean. *J. Climate* **13,** 297–311 (2000).

3. Dansgaard, W. Stable isotopes in precipitation. *Tellus* **16,** 436–468 (1964).

4. Kennett, D. J. *et al.* Development and disintegration of Maya political systems in response to climate change. *Science* **338,** 788–791 (2012).

5. Waliser, D. E. & Gautier, C. H. A satellite-derived climatology of the ITCZ. J. Climate 6, 2162–2174 (1993).

6. Richey, J. N., Poore, R. Z., Flower, B. P., Quinn, T. M. & Hollander, D. J. Regionally coherent Little Ice Age cooling in the Atlantic Warm Pool. *Geophys. Res. Lett.* **36,** L21703 (2009).

7. Lachniet, M. S., Patterson, W. P., Burns, S., Asmerom, Y. & Polyak, V. Caribbean and Pacific moisture sources on the Isthmus of Panama revealed from stalagmite and surface water $\delta^{18}O$ gradients. *Geophys. Res. Lett.* **34,** L01708 (2007).

8. Seager, R. *et al.* Mexican drought: an observational modeling and tree ring study of variability and climate change. *Atmósfera* **22,** 1–31 (2009).

9. Kushnir, Y., Seager, R., Ting, M., Naik, N. & Nakamura, J. Mechanisms of Tropical Atlantic SST Influence on North American Precipitation Variability. *J. Climate* **23,** 5610–5628 (2010).

10. Dai, A. & Wigley, T. M. L. Global patterns of ENSO-induced precipitation. *Geophys. Res. Lett.* **27,** 1283–1286 (2000).

11. Lachniet, M. S. & Patterson, W. P. Oxygen isotope values of precipitation and surface waters in northern Central America (Belize and Guatemala) are dominated by temperature and amount effects. *Earth Planet. Sci. Lett.* **284,** 435–446 (2009).

12. Webster, J. W. *et al.* Stalagmite evidence from Belize indicating significant droughts at the time of Preclassic Abandonment, the Maya Hiatus, and the Classic Maya collapse. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **250,** 1–17 (2007).

13 Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G. Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari and X. Zhang, 2013: Detection and Attribution of Climate Change: from Global to Regional. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

14 Ding, Y., J. A. Carton, G. A. Chepurin, G. Stenchikov, A. Robock, L. T. Sentman, and J. P. Krasting. Ocean response to volcanic eruptions in Coupled Model Intercomparison Project 5 (CMIP5) simulations. J. Geophys. Res. **119**, 5622-5637 (2014).

15 Santer B. D. *et. al*. Volcanic contribution to decadal changes in tropospheric temperature. *Nature Geoscience* **7**, 185–189 (2014).

16 Rauscher, S. A., Giorgi, F., Diffenbaugh, N. S. & Seth, A. Extension and Intensification of the Meso-American mid-summer drought in the twenty-first century. *Clim. Dynam.* **31,** 551–571 (2008).

17 Anet, J. G., S. Muthers, E. V. Rozanov, C. C. Raible, A. Stenke, A. I. Shapiro, S. Brönnimann, F. Arfeuille, Y. Brugnara, J. Beer, F. Steinhilber, W. Schmutz, and T. Peter (2014) Impact of solar versus volcanic activity variations on tropospheric temperatures and precipitation during the Dalton Minimum. Clim. Past, **10**, 921–938, (2014).

18 Schlesinger, M. E.. "An oscillation in the global climate system of period 65-70 years". *Nature* **367**: 723–726 (1994).

19 Li, J., *et al.* El Niño modulations over the past seven centuries. Nature Clim. Ch. **3**, 822–826 (2013).

20 Otterå, O. H., Bentsen, M., Drange, H. & Suo, L. External forcing as a metronome for Atlantic multidecadal variability. Nature Geosci. **3**, 688–694 (2010).

21 Mignot, J., Khodri, M., Frankignoul, C. & Servonnat, J. Volcanic impact on the Atlantic Ocean over the last millennium. *Clim. Past* **7,** 1439–1455 (2011).

22 Zanchettin, D., Bothe, O., Graf, H. F., Lorenz S. J., Luterbacher J., Timmreck, C. & Jungclaus, J. H. Background conditions influence the decadal climate response to strong volcanic eruptions. *J. Geophys. Res*. **118**, 1-17 (2013).

23 Svendsen, L., Hetzinger, S., Keenlyside, N. & Gao, Y. Marine-based multiproxy reconstruction of Atlantic multidecadal variability. *Geophys. Res. Lett.*, **41**:1295-1300, (2014).

24 McGregor, S., Timmermann, A. & Timm, O. A unified proxy for ENSO and PDO variability since 1650, *Clim. Past* **6**, 1-17 (2010).

25 Lehner, F., Raible, C. C. & Stocker, T. F. Testing the robustness of a precipitation proxy-based North Atlantic Oscillation reconstruction. *Quat. Sc. Rev*. **45**, 85-94 (2012).

26 Timmreck C. Modeling the climatic effects of large explosive volcanic eruptions. *WIREs Clim Change*, **3**:545–564 (2012).

27 Ault, T. R., Cole, J. E. & St. George, S. The amplitude of decadal to multidecadal variability in precipitation simulated by state-of-the-art climate models. *Geophys. Res. Lett*., **39**, L21705, (2012).

28 Zou,Y., Yu J.-Y., Lee T., Lu M.-M. & Kim S. T., CMIP5 model simulations of the impacts of the two types of El Niño on the U.S. winter temperature, *J. Geophys. Res. Atmos*., **119** (2014)

29 Kavvada, A., Ruiz-Barradas, A., & Nigam, S. AMO's structure and climate footprint in

observations and IPCC AR5 climate simulations. *Clim. Dyn*., doi:10.1007/s00382-0 (2013)

30 Schmidt, G. A., *et al.* Using paleo-climate comparisons to constrain future projections in CMIP5, *Clim. Past Discuss*. **9**, 775–835, (2013).

31. Zorita, E. *et al.* Climate evolution in the last five centuries simulated by an atmosphere-ocean model: global temperatures, the North Atlantic Oscillation and the Late Maunder Minimum. *Meteorol. Z.* **13**, 271–289 (2004).

32. Ammann, C. M., Joos, F., Schimel, D. S., Otto-Bliesner, B. L. & Tomas, R. A. Solar influence on climate during the past millennium: results from transient simulations with the NCAR Climate System Model. *Proc. Natl. Acad. Sci. USA* **104,** 3713–3718 (2007).

33. Oman, L., Robock, A., Stenchikov, G. L. & Thordarson, T. High-latitude eruptions cast shadow over the African monsoon and the flow of the Nile. *Geophys. Res. Lett.* **33,** L18711 (2006).

34 Jungclaus, J. H., et al. Climate and carbon-cycle variability over the last millennium. *Climate of the Past*, **6**, 723-737 (2010).

35 Crowley et al. Volcanism and the Little Ice Age. PAGES Newsletter, No. 16, PAGES International Project Office, Bern, Switzerland, 22–23 (2008).

36 Landrum et al. Last Millennium Climate and Its Variability in CCSM4. *J. of Clim.* **26**: 1085- 1111 (2012).

37 Gao, C., Robock A. & Ammann C. Volcanic forcing of climate over the last 1500 years: An improved ice core–based index for climate models. *J. Geophys. Res.* **113**, D23111, (2008).

38. Lachniet, M. S., Bernal, J. P., Asmerom, Y., Polyak, V. & Piperno, D. A 2400 yr Mesoamerican rainfall reconstruction links climate and cultural change. *Geology* 40 259-262 (2012).

39. Medina-Elizalde M, *et al.* High resolution climate record from the Yucatán Peninsula spanning the Maya terminal classic period. *Earth Planet. Sci. Lett.* **298:255-262** (2010).

Figure Captions

Figure 1 Location map of Mesoamerica and our speleothem site.

Figure. 2: Comparison between the time series of Guatemala-Belize border annual speleothem $\delta^{18}O$ (this study, black line units in permil) **and Belize City, Belize, June to November precipitation anomalies** (deviation from climatology in mm, blue line) smoothed with a 2-nd order binomial filter. The $\delta^{18}O$ time series is shown here lagging the rainfall time series by six years (i.e., speleothem $\delta^{18}O$ for 1945 is plotted in the year 1940 and so on). This lag maximizes the correlation between the two time series and emphasizes the delay associated with the transition between rainfall and carbonate deposits in the speleothem in the particular cave. The lag was determined based on a cross correlation analysis between the two time series with lags varying between -10 and +10 years. With this lag cross correlation value is 0.43. Given that the binomial smoothed 71-year precipitation record shown here only has 15 degrees of freedom, this correlation value 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 δ18O variations and not vice versa). 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/).

Figure 3 (A) Volcanic radiative forcing from 1700-2000 C. E. after[20]. Dark-brown boxes embeds volcanic eruption clusters noted in the text. (B) Different estimates of cumulative radiative forcing (based on cumulative adding the forcing of each volcanic event through time) from last-millennium climate simulations using different reconstructions of aerosol optical properties for volcanic forcing: ECHAM5/MPIOM[34] (brown) and BCM[20] (red) use the reconstruction by[35]; CCSM4[36] (green) uses the reconstruction by[37]. (C) Speleothem GU-Xi-1 $\delta^{18}O$ for the same time period as (A). Interpolated annual $\delta^{18}O$ is shown and the black line represents an eleven-point moving average of the annually interpolated data emphasizing the long-term variability in this figure. Multi-decadal drying events are coincident with volcanic eruption clusters 1, 2, and 3. The different estimates of cumulative volcanic forcing are provided to exemplify the effects of uncertainties such as those in reconstructed aerosol optical properties (which are used as volcanic forcing input to climate models), due to presence of additional varying forcing factors, and in the model-specific implementation of volcanic forcing.

Figure 4 Comparison of the Gua-Xi-1 with two other stalagmite records from MesoAmerica[38,39].

The Guatemala stalagmite significantly correlates with both other series, but the Medina and Lachniet records do not correlate with one other (see Supplementary Fig. 5). The difference in alignments of these records depends on their age models (note poor age control of the[39] record) sampling resolution and extent of local and cave environmental overprinting.