Northumbria Research Link

Northumbria University NEWCASTLE

UniversityLibrary

Aerosol forcing of intertropical convergence zone position

Harriet E. Ridley[1], Yemane Asmerom[2], James U.L. Baldini[1], Sebastian F.M. Breitenbach[3], Valorie V. Aquino[4], Keith M. Prufer[4], Brendan J. Culleton[5], Victor Polyak[2], Franziska A. Lechleitner[5], Douglas J. Kennett[4], Minghua Zhang[6], Norbert Marwan[7], Colin G. Macpherson[1], Lisa M. Baldini[1], Tingyin Xiao[6], Jaime Awe[8], and Gerald H. Haug[3].

[1]Department of Earth Sciences, University of Durham, Durham, DH1 3LE, UK.

[2]Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87106, USA.

[3]Department of Earth Science, Eidgenössische Technische Hochschule (ETH), CH-8092 Zürich, Switzerland.

[4]Department of Anthropology, University of New Mexico, Albuquerque, NM 87106, USA.

[5]Department of Anthropology, The Pennsylvania State University, University Park, PA 16802, USA.

[6]Institute for Terrestrial and Planetary Atmospheres, School of Marine and Atmospheric Sciences, Stony Brook, NY 11794-5000, USA.

[7]Potsdam Institute for Climate Impact Research, P.O. Box 60 12 03, 14412 Potsdam, Germany.

[8]Institute of Archaeology, Belmopan, Belize.

Intertropical convergence zone (ITCZ) position is the dominant control on low-latitude precipitation distribution and is largely controlled by hemispheric temperature contrasts[1,2]. Recent modelling[1,3,4] and observational[5,6] studies suggest that anthropogenic aerosols may have contributed to southward ITCZ shifts by moderating Northern Hemisphere (NH) relative to Southern Hemisphere (SH) warming[1,7,8]. Despite this abundant evidence suggesting that NH-SH temperature contrasts affected low latitude rain belts over the last few decades, differentiating between anthropogenic forcing and century-scale natural variability is problematic and requires a record with nearly no chronological error and very high temporal resolution. Unfortunately, these types of records are extremely uncommon in tropical regions affected by the ITCZ. Here, we use an exceptionally well-dated and monthly-resolved 456 year-long stalagmite

record from Belize to demonstrate that unprecedented rainfall decreases coincided with increasing anthropogenic aerosol emission rates. The record also suggests that short-lived drying occurred after large NH volcanic eruptions since 1550. These results strongly suggest that aerosol injections into the NH atmosphere result in southward ITCZ repositioning, and firmly implicate anthropogenic aerosol emissions as having caused 20th Century rainfall reductions in the northern tropics. Future changes in the distribution of aerosol emissions should therefore be a critical consideration when predicting regional susceptibility to severe rainfall variations.

ITCZ position largely controls low latitude seasonal rainfall distribution. Relative ITCZ position is strongly influenced by hemispheric temperature contrasts and subsequent atmospheric restructuring, which draw the ITCZ toward the warmer hemisphere[1,2,5]. Indeed, considerable proxy evidence links Northern Hemisphere temperature to low-latitude rainfall throughout the Holocene[9,10]. Since 1900 however, limited instrumental evidence suggests a southward shift in ITCZ position[3,5], a trend possibly driven by asymmetrical hemispheric warming due to the cooling effect of anthropogenic aerosols (e.g., sulphates[3,4] and black carbon[11]) in the NH, but that could also arise from undetected natural variability. Climate models have attempted to assess the relative contributions of greenhouse gases (GHG) and aerosols to ITCZ displacement with contradictory results[1,7]. Limited long-term instrumental climate records from low latitudes complicates detecting climate shifts attributable to anthropogenic influences, and consequently future precipitation projections remain ambiguous[12]. Furthermore, chronological uncertainties associated with low latitude rainfall proxy records prevent establishing robust links between low-latitude rainfall amount and atmospheric aerosol distributions at a suitable resolution. Here, we discuss an exceptionally well-dated, monthly-scale stalagmite rainfall record covering 456 years from 1550 to 2006

52   C.E., thus covering the critical transition into the Current Warm Period (CWP) with

53   unprecedented detail and providing much needed evidence to support modelling work.

54   Stalagmite YOK-G was obtained from Yok Balum Cave in southern Belize (16° 12' 30.780"

55   N, 89° 4' 24.420" W; 336 m.a.s.l.) (Supplementary Fig. S7). This site is near the

56   northernmost extent of the ITCZ, a remarkably sensitive location for reconstructing even

57   minor variations in ITCZ position. The cave was undisturbed prior to 2005 and is

58   characterised by a stable low-pCO$_2$ atmosphere, consistent year round temperatures (22.3°C

59   ± 0.5), and high relative humidity (>95%) (Supplementary Fig. S17 and S18). The cave is

60   remote and located below steep, dense forest that is unsuitable for farming or mechanised

61   logging, minimising potential past human interferences at the site. Outside air temperature

62   only varies between 20°C (December through February) and 24°C (June through August).

63   However, rainfall is distinctly seasonal, ranging from 40-70mm per month in the peak dry

64   season (February through April) to 400-700mm per month during the peak wet season (June

65   through September) due to seasonal ITCZ and associated trade wind migrations that track the

66   thermal equator[13]. Evapotranspiration surpasses precipitation during the dry months[14],

67   reducing effective rainfall and water input to the karst system. Stalagmite YOK-G was

68   collected in 2006 and is 1090mm tall, but only the top 365mm are discussed here. 3648

69   carbonate samples were collected by milling continuously at 100μm increments along the

70   central growth axis, and carbon and oxygen stable isotope ratios were determined using a

71   Thermo MAT 253 gas source mass spectrometer.

72   Annual carbon isotope ratio (δ^{13}C) cycles apparent throughout most of the record provide

73   exceptional chronological control. The uppermost 8mm milled at a 100μm spatial resolution

74   did not reveal δ^{13}C cycles, which prevented counting cycles back from the date of collection.

75   The δ^{13}C cycle chronology is instead anchored to the first evidence of atmospheric 'bomb'

76 radiocarbon in 1955 (Supplementary Information and Fig. S14). Higher resolution (25 μm;

77 weekly-scale) re-milling over the top 8mm also failed to detect $\delta^{13}C$ cycles (Supplementary

78 Fig. S12), strongly suggesting that no $\delta^{13}C$ cycles exist in the most recent part of the

79 stalagmite. If 2006 is used as the cessation of sample growth (due to collection), the calculate

80 growth rate for this interval deviates significantly from the nearly uniform growth rate for the

81 preceding ~500 years. This suggests that either that: a) carbonate precipitation slows down at

82 some point since 1984, b) that the sample stopped growing earlier than the date of collection,

83 or c) a combination of both a and b. This short interval (from 1984 to 2006) is therefore not

84 included in the discussion due to increased chronological uncertainty. XRD results indicate

85 that YOK-G is entirely aragonitic, which, due to its high capacity for uranium inclusion,

86 permits the construction of a precise ^{230}Th chronology (Fig. 1; Supplementary Table S1).

87 Eighteen high precision MC-ICP-MS ^{230}Th dates confirm that the $\delta^{13}C$ cycle-derived model

88 is robust (Fig.1). Between 1550 and 1983 C.E. YOK-G grew continuously with a mean

89 growth rate of 0.82mm a^{-1}.

90 Here we utilise the YOK-G $\delta^{13}C$ record as a palaeorainfall proxy. Stalagmite $\delta^{13}C$ in low

91 latitude regions not experiencing temporal shifts in vegetation type (e.g., shifts from C3 to C4

92 vegetation) largely reflects effective rainfall amount and the hydrology of the drip feeding the

93 stalagmite. Dry intervals promote: a) prior carbonate precipitation (due to lower groundwater

94 flow rates), b) increased bedrock carbon contributions, and c) reduced soil bioproductivity,

95 all contributing to a more positive $\delta^{13}C$. Conversely, wetter conditions result in more negative

96 $\delta^{13}C$ (see Supplementary Information). This interpretation is supported by the remarkable,

97 demonstrably annual $\delta^{13}C$ cycle reflecting seasonal water recharge conditions, as well as by

98 interpretations of other Belizean stalagmite $\delta^{13}C$ records as reflecting rainfall, notably

99 Frappier et al.[15], linking pronounced $\delta^{13}C$ increases to El Niño related rainfall reductions, and

100   Webster et al.[16] linking $\delta^{13}C$ shifts over the last 3,300 years to rainfall. We note that these two

101   studies represent the two published speleothem records from cave sites closest to Yok Balum

102   cave (ATM Cave, ~100km to the north, and Macal Chasm, ~80km to the north), and that

103   both utilised $\delta^{13}C$ as a palaeorainfall proxy (Supplementary Fig. S4). The YOK-G $\delta^{13}C$

104   record is also corroborated as a proxy of ITCZ related rainfall variability by the Cariaco

105   Basin record[10]. We stress that $\delta^{18}O$ is also an extremely useful complementary rainfall proxy

106   (see Supplementary Information), but we believe that under the conditions at our site, $\delta^{13}C$ is

107   more sensitive to subtle shifts in recharge.

108   Both wet and dry season $\delta^{13}C$ values ($\delta^{13}C_{wet}$ and $\delta^{13}C_{dry}$) are clearly distinguishable in the

109   YOK-G record (Fig. 1c), providing a rare opportunity to isolate rainfall amount during

110   specific seasons at a low latitude site. YOK-G $\delta^{13}C_{wet}$ and the NINO3.4 Center of Action

111   (COA) sea surface temperature (SST) reconstruction[17] are anticorrelated ($r = -0.3$, $p < 0.001$

112   with a nine-year moving average applied) during the preindustrial period (1550-1850),

113   suggesting that eastern equatorial Pacific SST exerted a significant control on Belizean

114   rainfall (Fig. 2a). Additionally, a weak but significant negative relationship ($r = -0.19$, $p <$

115   0.001) exists between the Esper Northern Hemisphere Temperature (NHT) reconstruction[18]

116   and $\delta^{13}C_{wet}$ during the preindustrial interval of the record (Fig. 2c). This suggests a warmer

117   NH tends to draw the ITCZ to a more northerly position, consistent with the results of

118   numerous previous studies[7,10,19]. No relationship exists between $\delta^{13}C_{dry}$ and NHT ($r = 0.05$, p

119     $= 0.43$), again consistent with the interpretation of YOK-G $\delta^{13}C_{wet}$ as an ITCZ rainfall proxy.

120   Elevated NHT tended to cause a more seasonal rainfall distribution (greater seasonality)

121   during the preindustrial portion of the YOK-G record ($r = 0.32$, $p < 0.001$ with nine-year

122   moving average applied) (Fig. 2b).

123   However, post-1850 all the $\delta^{13}C$ data (mean annual, wet season, and dry season) strongly

124   suggest a steady drying trend coinciding with increasing NHT, suggesting a dramatic reversal

125   in the relationship between NHT and ITCZ position (Fig. 3). Additionally, post-1850 YOK-G

126   annual mean $\delta^{13}C$ tracks trends in global GHG concentrations and anthropogenic aerosol

127   emissions (Fig. 4). This indicates a southward ITCZ migration despite increasing NHT.

128   The timing of this relationship reversal suggests an anthropogenic link. Recent research

129   highlights the competing effects of GHG and anthropogenic aerosols on low latitude rain

130   belts, with GHG increases believed to force the ITCZ to the north, and aerosols to the

131   south[5,7]. Modelling studies suggest that a heterogeneous regional cooling effect induced by

132   NH mid-latitude anthropogenic aerosol emissions drove the southward migration of the ITCZ

133   over recent decades[1,3,4,7], leading to drought in the Sahel[8,20] and parts of monsoonal Asia[21,22].

134   The rainfall decreases implied by the YOK-G record closely follow patterns of regional

135   industrialisation and aerosol emissions in North America and western Europe since ~1880

136   (Figs. 4 and Supplementary Fig. S24). Peak US aerosol production during the period 1970-

137   1990 is estimated to have had a direct radiative forcing of -6 Wm^{-2} over the central and

138   eastern US resulting in relative cooling of 0.5-1.0°C[23,24]. Cooling over the North Atlantic

139   region modifies atmospheric circulation to accommodate cross equatorial thermal contrasts

140   and subsequently drives the ITCZ southward [25].

141   The YOK-G record also illustrates that very similar ITCZ repositioning occurred following

142   large NH volcanic eruptions that injected sulphate aerosols into the atmosphere. These

143   affected the ITCZ through a similar mechanism as anthropogenic aerosols, causing

144   preferential NH cooling, southward ITCZ migration, and consequently drying in Belize.

145   Particularly noteworthy is the coincidence of the large and climatologically significant Laki

146   eruption (1783-1784) with the height of the largest preindustrial drought in Belize since 1550

147   C.E., evident in both the YOK-G and the historical records. The Laki eruption produced a

148   peak estimated direct radiative forcing in August 1783 of -5.5 Wm^{-2} in the NH[26], similar to

149   the magnitude of the anthropogenic aerosol peak during 1970-1990 (-6 Wm^{-2}), and resulted in

150   comparable drying in Belize. However, we note that the direct climate effects attributable to

151   the Laki eruption were unlikely to have lasted more than three years[26], so the 1783 eruption

152   may have exacerbated or prolonged the 1765-1800 drought but was not the principal driver.

153   SH volcanic eruptions, including those at low southerly latitudes, appear to force the ITCZ to

154   the north. Most notable of these is the Tambora eruption in 1815, associated with increased

155   Belizean rainfall the following year (Fig. 4). Of the nine largest NH eruptions identified in

156   the GISP2 ice core sulphate record and the historical record since 1550[27], all are associated

157   with drying in Belize; conversely, all three large SH eruptions are associated with increased

158   rainfall at our site. Specifically, the YOK-G record indicates that NH eruptions result in

159   substantially elevated $\delta^{13}C_{dry}$, and we suggest that this reflects a longer dry season caused by

160   delayed onset of the summer wet season. Our data suggest that NH eruptions shortened the

161   duration of the wet season, and SH eruptions extended wet season duration. The record

162   provides compelling evidence that stratospheric sulphate aerosol injections associated with

163   explosive volcanism resulted in short-lived ITCZ migration (Fig. 4). This result is consistent

164   with recent modelling results suggesting that large volcanic eruptions that inject aerosols into

165   the NH cause the ITCZ to migrate to the south, whereas SH eruptions push the ITCZ to the

166   north (HAYWOOD et al., 2013), and with historical records suggesting reduced Nile

167   discharge following the 1783 Laki eruption (Oman et al. 2006). Similarly, continuous NH

168   anthropogenic aerosol emissions during the 20th Century drove sustained southward ITCZ

169   repositioning.

170   The monthly-resolved YOK-G δ^{13}C rainfall record provides the strongest proxy evidence

171   currently available that recent droughts in the northern tropics are attributable to extra-

172   tropical anthropogenic forcing. Rather than being a cyclic natural phenomenon, sustained

173   rainfall reductions only occurred after atmospheric aerosols increased following regional

174   industrialization in the NH. The record also indicates that similar (albeit shorter lived) ITCZ

175   repositioning occurred in response to sulphate aerosol forcing associated with large NH

176   volcanic eruptions. Future modelling should focus on determining how shifts in regional

177   aerosol emission rates might affect ITCZ position. This is particularly relevant to currently

178   industrialising regions where large populations are dependent on seasonal rainfall.

179

180

181 **References**

182

183 1   Hwang, Y. T., Frierson, D. M. W. & Kang, S. M. Anthropogenic sulfate aerosol and
184   the southward shift of tropical precipitation in the late 20th century. *Geophys. Res.*
185   *Lett.* **40**, 2845-2850 (2013).

186 2   Broccoli, A. J., Dahl, K. A. & Stouffer, R. J. Response of the ITCZ to Northern
187   Hemisphere cooling. *Geophys. Res. Lett.* **33** (2006).

188 3   Rotstayn, L. D. & Lohmann, U. Tropical rainfall trends and the indirect aerosol effect.
189   *J. Climate* **15**, 2103-2116 (2002).

190 4   Chang, C. Y., Chiang, J. C. H., Wehner, M. F., Friedman, A. R. & Ruedy, R. Sulfate
191   aerosol control of tropical Atlantic climate over the twentieth century. *J. Climate* **24**,
192   2540-2555 (2011).

193 5   Zhang, X. *et al.* Detection of human influence on twentieth-century precipitation
194   trends. *Nature* **448**, 461-465 (2007).

195 6   Lu, H. Y. *et al.* Variation of East Asian monsoon precipitation during the past 21 k.y.
196   and potential CO_2 forcing. *Geology* **41**, 1023-1026 (2013).

197 7   Friedman, A. R., Hwang, Y. T., Chiang, J. C. H. & Frierson, D. M. W.
198   Interhemispheric temperature asymmetry over the twentieth century and in future
199   projections. *J. Climate* **26**, 5419-5433 (2013).

200 8   Booth, B. B. B., Dunstone, N. J., Halloran, P. R., Andrews, T. & Bellouin, N.
201   Aerosols implicated as a prime driver of twentieth-century North Atlantic climate
202   variability. *Nature* **484**, 228-232 (2012).

203 9   Dykoski, C. A. *et al.* A high-resolution, absolute-dated Holocene and deglacial Asian
204   monsoon record from Dongge Cave, China. *Earth Planet Sci. Lett.* **233**, 71-86 (2005).

205 10   Haug, G. H., Hughen, K. A., Sigman, D. M., Peterson, L. C. & Rohl, U. Southward
206   migration of the intertropical convergence zone through the Holocene. *Science* **293**,
207   1304-1308 (2001).

208 11   Zhang, P. Z. *et al.* A test of climate, sun, and culture relationships from an 1810-year
209   chinese cave record. *Science* **322**, 940-942 (2008).

210 12   Diffenbaugh, N. S. & Field, C. B. Changes in ecologically critical terrestrial climate
211   conditions. *Science* **341**, 486-492 (2013).

212 13   Poveda, G., P.R., W. & R., P. Modern climate variability in northern South America
213   and southern Mesoamerica. *Palaeogeogr. Palaeocl.* **234**, 24 (2006).

214 14 Heyman, W. D. & Kjerfve, B. Hydrological and oceanographic considerations for
215 integrated coastal zone management in southern Belize. *Environ. Manage.* **24**, 229-
216 245 (1999).

217 15 Frappier, A., Sahagian, D., Gonzalez, L. A. & Carpenter, S. J. El Niño events
218 recorded by stalagmite carbon isotopes. *Science* **298**, 565-565 (2002).

219 16 Webster, J. W. *et al.* Stalagmite evidence from Belize indicating significant droughts
220 at the time of Preclassic Abandonment, the Maya Hiatus, and the Classic Maya
221 collapse. *Palaeogeogr. Palaeocl.* **250**, 1-17 (2007).

222 17 Wilson, R. *et al.* Reconstructing ENSO: the influence of method, proxy data, climate
223 forcing and teleconnections. *J. Quaternary Sci.* **25**, 62-78 (2010).

224 18 Esper, J., Cook, E. R. & Schweingruber, F. H. Low-frequency signals in long tree-
225 ring chronologies for reconstructing past temperature variability. *Science* **295**, 2250-
226 2253 (2002).

227 19 Kang, S. M., Held, I. M., Frierson, D. M. W. & Zhao, M. The response of the ITCZ to
228 extratropical thermal forcing: idealized slab-ocean experiments with a GCM. *J.*
229 *Climate* **21**, 3521-3532 (2008).

230 20 Kawase, H. *et al.* Physical mechanism of long-term drying trend over tropical North
231 Africa. *Geophys. Res. Lett.* **37** (2010).

232 21 Bollasina, M. A., Ming, Y. & Ramaswamy, V. Anthropogenic aerosols and the
233 weakening of the South Asian summer monsoon. *Science* **334**, 502-505 (2011).

234 22 Lau, K. M., Kim, M. K. & Kim, K. M. Asian summer monsoon anomalies induced by
235 aerosol direct forcing: the role of the Tibetan Plateau. *Clim. Dynam.* **26**, 855-864
236 (2006).

237 23 Leibensperger, E. M. *et al.* Climatic effects of 1950:2050 changes in US
238 anthropogenic aerosols: Part 2: climate response. *Atmos. Chem. Phys.* **12**, 3349-3362
239 (2012).

240 24 Leibensperger, E. M. *et al.* Climatic effects of 1950:2050 changes in US
241 anthropogenic aerosols: Part 1: aerosol trends and radiative forcing. *Atmos. Chem.*
242 *Phys.* **12**, 3333-3348 (2012).

243 25 Tokinaga, H. & Xie, S. P. Weakening of the equatorial Atlantic cold tongue over the
244 past six decades. *Nat. Geosci.* **4**, 222-226 (2011).

245 26 Highwood, E. J., Stevenson, D. S., Highwood, E. J. & Stevenson, D. S. Atmospheric
246 impact of the 1783-1784 Laki eruption: Part II - climatic effect of sulphate aerosol.
247 *Atmos. Chem. Phys.* **3**, 1177-1189 (2003).

248 27 Zielinski, G. A. *et al.* Record of volcanism since 7000-BC from the GISP2 Greenland
249   ice core and implications for the volcano-climate system. *Science* **264**, 948-952
250   (1994).
251 28 Marland, G., Andres, R. J. & Boden, T. A. in *Trends '93: A Compendium of Data on*
252   *Global Change* (eds T.A. Boden, D.P. Kaiser, R.J. Sepanski, & F.W Stoss) 505-584
253   (Oak Ridge Nat. Lab., 1994).
254 29 Robertson, A. *et al.* Hypothesized climate forcing time series for the last 500 years. *J*
255   *Geophys Res-Atmos.* **106**, 14783-14803 (2001).
256 30 Kennett, D. J. *et al.* Development and disintegration of Maya political systems in
257   response to climate change. *Science* **338**, 788-791 (2012).

258

259

260

Figure captions

Figure 1. YOK-G δ¹³C record and chronology. a, [230]Th dates with errors (black line) and $\delta^{13}C$ cycle

chronology (red line). Shaded grey boxes indicate intervals where the $\delta^{13}C$ cycles are present but

somewhat less clear. The shaded pink box indicates the interval (1983-2006) where $\delta^{13}C$ cycles are

absent. Both chronological models are fitted with cubic splines. The [230]Th dates were used to verify

the accuracy of the $\delta^{13}C$ cycle count chronology, but were not used directly in developing the

chronological model. **b,** The YOK-G $\delta^{13}C$ record against depth spanning the last 456 years, with inset

expanded in **c,** illustrating $\delta^{13}C$ annual cycles with peak wet ('W' = low $\delta^{13}C$) and dry ('D' = higher

$\delta^{13}C$) season $\delta^{13}C$ values identified. These were used as a further chronological tool, permitting

identification of season of deposition. The grey shaded area to the right illustrates cycles during an

interval where the $\delta^{13}C$ cycles are less clear.

Figure 2. YOK-G δ¹³C record. a, YOK-G $\delta^{13}C_{wet}$ record and the Niño 3.4 COA reconstruction [17] for

the period 1550 to 1850. **b,** Seasonality defined by the amplitude of each annual $\delta^{13}C$ from peak wet

season to peak dry season and Esper NHT [18] for the period 1550-1850. **c,** YOK-G $\delta^{13}C_{wet}$ against NHT

for the period 1550-1850. **d,** as in **a** but for the industrial interval of the record, 1851-1983. **e,** as in **b**

but for the period 1851-1983. **f,** as in **c** but for the period 1851-1983.

Figure 3. Scatterplot of YOK G δ¹³C_wet versus Esper NHT[18]. During the preindustrial period

(1550-1849) (unfilled circles), showing weak significant negative correlation (r = -0.19, p < 0.005),

and during the CWP (1850-1983) (black filled circles), which exhibits a switch to a significant

positive correlation (r = 0.43, p < 0.001).

Figure 4. Annual mean YOK-G δ¹³C links to aerosols. a, Annual mean $\delta^{13}C$ (black) and GISP2

total sulphate record (blue) [27] for the period 1550-1983. Estimated aerosol production based on CO_2

emission rates relative to 1992 levels [28,29] for western Europe (green) and North America (yellow)

post 1850. Major NH eruptions (red labels) and SH eruptions (dark blue labels) with a Volcanic

Explosivity Index (VEI) of 5 or above, identified from the historical and GISP2 record. The dashed

lines designate the date of the eruption thought to have caused the GISP2 sulphate peak rather than the

sulphate peak itself; occasionally the eruption occurred the year preceding the sulphate peak in the ice

core. The location of the volcano responsible for producing the large 1809 sulphate peak evident in

the GISP2 record is unknown. (*) denotes eruptions with a VEI of 6 or 7. The brown vertical bar

indicates the timing of a large drought identified in the historical record [30]. **b,** Relative climate

response to NH and SH eruptions exemplified by YOK-G $\delta^{13}C$ values (normalized to monthly means

in the year prior to the eruption) in the year preceding the volcanic eruptions identified in panel **a**

('Year -1'), the year of the volcanic eruptions ('Year of eruption'), and three years following the

eruptions ('Years +1, +2, and +3'). The grey shaded area represents one standard deviation from the

monthly mean values over the entire preindustrial period. Thick lines represent the average $\delta^{13}C$

response for NH eruptions (red line) and SH eruptions (blue line).