# Aerosol forcing of intertropical convergence zone position

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**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

C.E., thus covering the critical transition into the Current Warm Period (CWP) with unprecedented detail and providing much needed evidence to support modelling work.

Stalagmite YOK-G was obtained from Yok Balum Cave in southern Belize (16° 12’ 30.780” N, 89° 4’ 24.420” W; 336 m.a.s.l.) (Supplementary Fig. S7). This site is near the northernmost extent of the ITCZ, a remarkably sensitive location for reconstructing even minor variations in ITCZ position. The cave was undisturbed prior to 2005 and is characterised by a stable low-$pCO_2$ atmosphere, consistent year round temperatures (22.3°C ± 0.5), and high relative humidity (>95%) (Supplementary Fig. S17 and S18). The cave is remote and located below steep, dense forest that is unsuitable for farming or mechanised logging, minimising potential past human interferences at the site. Outside air temperature only varies between 20°C (December through February) and 24°C (June through August). However, rainfall is distinctly seasonal, ranging from 40-70mm per month in the peak dry season (February through April) to 400-700mm per month during the peak wet season (June through September) due to seasonal ITCZ and associated trade wind migrations that track the thermal equator[13]. Evapotranspiration surpasses precipitation during the dry months[14], reducing effective rainfall and water input to the karst system. Stalagmite YOK-G was collected in 2006 and is 1090mm tall, but only the top 365mm are discussed here. 3648 carbonate samples were collected by milling continuously at 100μm increments along the central growth axis, and carbon and oxygen stable isotope ratios were determined using a Thermo MAT 253 gas source mass spectrometer.

Annual carbon isotope ratio ($\delta^{13}C$) cycles apparent throughout most of the record provide exceptional chronological control. The uppermost 8mm milled at a 100μm spatial resolution did not reveal $\delta^{13}C$ cycles, which prevented counting cycles back from the date of collection. The $\delta^{13}C$ cycle chronology is instead anchored to the first evidence of atmospheric ‘bomb’ radiocarbon in 1955 (Supplementary Information and Fig. S14). Higher resolution (25 μm; weekly-scale) re-milling over the top 8mm also failed to detect $\delta^{13}$C cycles (Supplementary Fig. S12), strongly suggesting that no $\delta^{13}$C cycles exist in the most recent part of the stalagmite. If 2006 is used as the cessation of sample growth (due to collection), the calculate growth rate for this interval deviates significantly from the nearly uniform growth rate for the preceding ~500 years. This suggests that either that: a) carbonate precipitation slows down at some point since 1984, b) that the sample stopped growing earlier than the date of collection, or c) a combination of both a and b. This short interval (from 1984 to 2006) is therefore not included in the discussion due to increased chronological uncertainty. XRD results indicate that YOK-G is entirely aragonitic, which, due to its high capacity for uranium inclusion, permits the construction of a precise $^{230}$Th chronology (Fig. 1; Supplementary Table S1). Eighteen high precision MC-ICP-MS $^{230}$Th dates confirm that the $\delta^{13}$C cycle-derived model is robust (Fig.1). Between 1550 and 1983 C.E. YOK-G grew continuously with a mean growth rate of 0.82mm $a^{-1}$.

Here we utilise the YOK-G $\delta^{13}$C record as a palaeorainfall proxy. Stalagmite $\delta^{13}$C in low latitude regions not experiencing temporal shifts in vegetation type (e.g., shifts from C3 to C4 vegetation) largely reflects effective rainfall amount and the hydrology of the drip feeding the stalagmite. Dry intervals promote: a) prior carbonate precipitation (due to lower groundwater flow rates), b) increased bedrock carbon contributions, and c) reduced soil bioproductivity, all contributing to a more positive $\delta^{13}$C. Conversely, wetter conditions result in more negative $\delta^{13}$C (see Supplementary Information). This interpretation is supported by the remarkable, demonstrably annual $\delta^{13}$C cycle reflecting seasonal water recharge conditions, as well as by interpretations of other Belizean stalagmite $\delta^{13}$C records as reflecting rainfall, notably Frappier et al.[15], linking pronounced $\delta^{13}$C increases to El Niño related rainfall reductions, and

Webster et al.[16] linking $\delta^{13}C$ shifts over the last 3,300 years to rainfall. We note that these two studies represent the two published speleothem records from cave sites closest to Yok Balum cave (ATM Cave, ~100km to the north, and Macal Chasm, ~80km to the north), and that both utilised $\delta^{13}C$ as a palaeorainfall proxy (Supplementary Fig. S4). The YOK-G $\delta^{13}C$ record is also corroborated as a proxy of ITCZ related rainfall variability by the Cariaco Basin record[10]. We stress that $\delta^{18}O$ is also an extremely useful complementary rainfall proxy (see Supplementary Information), but we believe that under the conditions at our site, $\delta^{13}C$ is more sensitive to subtle shifts in recharge.

Both wet and dry season $\delta^{13}C$ values ($\delta^{13}C_{wet}$ and $\delta^{13}C_{dry}$) are clearly distinguishable in the YOK-G record (Fig. 1c), providing a rare opportunity to isolate rainfall amount during specific seasons at a low latitude site. YOK-G $\delta^{13}C_{wet}$ and the NINO3.4 Center of Action (COA) sea surface temperature (SST) reconstruction[17] are anticorrelated ($r = -0.3$, $p < 0.001$ with a nine-year moving average applied) during the preindustrial period (1550-1850), suggesting that eastern equatorial Pacific SST exerted a significant control on Belizean rainfall (Fig. 2a). Additionally, a weak but significant negative relationship ($r = -0.19$, $p < 0.001$) exists between the Esper Northern Hemisphere Temperature (NHT) reconstruction[18] and $\delta^{13}C_{wet}$ during the preindustrial interval of the record (Fig. 2c). This suggests a warmer NH tends to draw the ITCZ to a more northerly position, consistent with the results of numerous previous studies[7,10,19]. No relationship exists between $\delta^{13}C_{dry}$ and NHT ($r = 0.05$, $p = 0.43$), again consistent with the interpretation of YOK-G $\delta^{13}C_{wet}$ as an ITCZ rainfall proxy. Elevated NHT tended to cause a more seasonal rainfall distribution (greater seasonality) during the preindustrial portion of the YOK-G record ($r = 0.32$, $p < 0.001$ with nine-year moving average applied) (Fig. 2b).

However, post-1850 all the $\delta^{13}C$ data (mean annual, wet season, and dry season) strongly suggest a steady drying trend coinciding with increasing NHT, suggesting a dramatic reversal in the relationship between NHT and ITCZ position (Fig. 3). Additionally, post-1850 YOK-G annual mean $\delta^{13}C$ tracks trends in global GHG concentrations and anthropogenic aerosol emissions (Fig. 4). This indicates a southward ITCZ migration despite increasing NHT.

The timing of this relationship reversal suggests an anthropogenic link. Recent research highlights the competing effects of GHG and anthropogenic aerosols on low latitude rain belts, with GHG increases believed to force the ITCZ to the north, and aerosols to the south[5,7]. Modelling studies suggest that a heterogeneous regional cooling effect induced by NH mid-latitude anthropogenic aerosol emissions drove the southward migration of the ITCZ over recent decades[1,3,4,7], leading to drought in the Sahel[8,20] and parts of monsoonal Asia[21,22]. The rainfall decreases implied by the YOK-G record closely follow patterns of regional industrialisation and aerosol emissions in North America and western Europe since ~1880 (Figs. 4 and Supplementary Fig. S24). Peak US aerosol production during the period 1970-1990 is estimated to have had a direct radiative forcing of $-6\ Wm^{-2}$ over the central and eastern US resulting in relative cooling of 0.5-1.0°C[23,24]. Cooling over the North Atlantic region modifies atmospheric circulation to accommodate cross equatorial thermal contrasts and subsequently drives the ITCZ southward [25].

The YOK-G record also illustrates that very similar ITCZ repositioning occurred following large NH volcanic eruptions that injected sulphate aerosols into the atmosphere. These affected the ITCZ through a similar mechanism as anthropogenic aerosols, causing preferential NH cooling, southward ITCZ migration, and consequently drying in Belize. Particularly noteworthy is the coincidence of the large and climatologically significant Laki eruption (1783-1784) with the height of the largest preindustrial drought in Belize since 1550

C.E., evident in both the YOK-G and the historical records. The Laki eruption produced a peak estimated direct radiative forcing in August 1783 of -5.5 $Wm^{-2}$ in the NH[26], similar to the magnitude of the anthropogenic aerosol peak during 1970-1990 (-6 $Wm^{-2}$), and resulted in comparable drying in Belize. However, we note that the direct climate effects attributable to the Laki eruption were unlikely to have lasted more than three years[26], so the 1783 eruption may have exacerbated or prolonged the 1765-1800 drought but was not the principal driver. SH volcanic eruptions, including those at low southerly latitudes, appear to force the ITCZ to the north. Most notable of these is the Tambora eruption in 1815, associated with increased Belizean rainfall the following year (Fig. 4). Of the nine largest NH eruptions identified in the GISP2 ice core sulphate record and the historical record since 1550[27], all are associated with drying in Belize; conversely, all three large SH eruptions are associated with increased rainfall at our site. Specifically, the YOK-G record indicates that NH eruptions result in substantially elevated $\delta^{13}C_{dry}$, and we suggest that this reflects a longer dry season caused by delayed onset of the summer wet season. Our data suggest that NH eruptions shortened the duration of the wet season, and SH eruptions extended wet season duration. The record provides compelling evidence that stratospheric sulphate aerosol injections associated with explosive volcanism resulted in short-lived ITCZ migration (Fig. 4). This result is consistent with recent modelling results suggesting that large volcanic eruptions that inject aerosols into the NH cause the ITCZ to migrate to the south, whereas SH eruptions push the ITCZ to the north (HAYWOOD et al., 2013), and with historical records suggesting reduced Nile discharge following the 1783 Laki eruption (Oman et al. 2006). Similarly, continuous NH anthropogenic aerosol emissions during the 20th Century drove sustained southward ITCZ repositioning.

The monthly-resolved YOK-G $\delta^{13}C$ rainfall record provides the strongest proxy evidence currently available that recent droughts in the northern tropics are attributable to extratropical anthropogenic forcing. Rather than being a cyclic natural phenomenon, sustained rainfall reductions only occurred after atmospheric aerosols increased following regional industrialization in the NH. The record also indicates that similar (albeit shorter lived) ITCZ repositioning occurred in response to sulphate aerosol forcing associated with large NH volcanic eruptions. Future modelling should focus on determining how shifts in regional aerosol emission rates might affect ITCZ position. This is particularly relevant to currently industrialising regions where large populations are dependent on seasonal rainfall.

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## Figure captions

**Figure 1. YOK-G $\delta^{13}$C 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 $\delta^{13}$C 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 $\delta^{13}C_{wet}$ 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 $\delta^{13}$C 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).