

Supplementary Information for

Abrupt change in tropical Pacific climate mean state during the Little Ice Age

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Supplementary Notes

Supplementary Note 1 Age-Depth Model assessment

The analysis of the chronological uncertainty of the age-depth model for the nC_{29} alkane δD record shows that the model is well constrained, particularly around the marked increase in the δD_{wax} values (Supplementary Fig. 9). This is due to a relatively high density of radiocarbon dates generated for the Bulusan record (Supplementary Table 1). The two seemingly reversed radiocarbon dates have little bearing on the age-depth model's reliability. The first of these - SUERC-64003 - is most likely due to its $\delta^{13}C$ value being an estimated value because there was insufficient amount of material for an independent $\delta^{13}C$ measurement. The age-depth model corrected for this by excluding this particular date as an outlier. The other potentially reversed date - SUERC-64006 - comes from the lower portion of the core, and, consequently, its influence on the timing of the discussed change in δD_{wax} values ~AD 1630 is negligible.

The photographic and radiographic profile of the Bulusan sedimentary sequence, presented in Fig. 2d, as well as the magnetic susceptibility record (Supplementary Fig. 2), show undisturbed laminations throughout the core sequence, excluding the possibility of sediment slumping, the presence of depositional events (e.g., floods) or significant changes in the sedimentation rate, and with it, the presence of hiatuses in the record. This is to be expected considering the taphonomic conditions of the Bulusan lake basin, namely a stable 12-metre lake depth, gentle slopes and continuous forest vegetation surrounding it (as inferred from the fossil pollen record).

Given the lake's depth and absence of prior coring activities, it is highly unlikely that the top sediment layer was disturbed or removed, and thus the top of the sediment core has been assigned the year when the core was collected, i.e., 2013, which allows us to constrain the timing of the marked decrease in the δD_{wax} values to ~AD1900.

Nevertheless, while our results suggest rapid change in δD_{wax} values at ~AD 1630 and ~AD 1900, due to the inherent uncertainty in radiocarbon dating, it is difficult to pinpoint exactly how rapid these changes were based on our age-depth model alone.

Supplementary Note 2 Correlation between n-alkane records

The Pearson product-moment correlation coefficient was used to measure dependence between pairs of nC_{29-31} alkanes, and the significance of this dependence was evaluated with Welch's t-test (2-sided, p-value set to <0.05, equal variance not required¹). Prior to this calculation, we

accounted for temporal autocorrelation in the alkane records by first calculating the time between independent values (or the time to obtain a new degree of freedom, τ) and then used τ values to calculate the effective sample size (i.e., the effective number of independence values, n_{eff}), as outlined in ref.², with autocorrelation value set at the lag of 1 data point for both records.

Results show that the δD values of the three abundant terrestrial lipid biomarkers in the Bulusan core, nC_{27-31} , are highly correlated (Supplementary Fig. 3). The relationship between nC_{27} and nC_{29} had the highest correlation coefficient (~ 0.81), followed by the coefficients for the nC_{27} and nC_{31} and the nC_{29} and nC_{31} (~ 0.69). P-values were highly significant for all three relationships (i.e., $<10^{-6}$). The results confirm a common origin of these three n-alkanes.

Supplementary Note 3 Average chain length of n-alkanes

Average chain length of n-alkanes (ACL), calculated as $(25 \cdot A_{25} + 27 \cdot A_{27} + 29 \cdot A_{29} + 31 \cdot A_{31} + 33 \cdot A_{33}) / (A_{25} + A_{27} + A_{29} + A_{31} + A_{33})$, has remained around 30 throughout the record, except for a slight drop in the values down to 28 over the last 200 years (Supplementary Fig. 4b). Human activities such as logging and harvesting of certain tree species (e.g., rattan) have been recorded in the area during this time³, and the associated changes in the forest composition may have been the underlying cause to this drop in the ACL values.

Supplementary Note 4 Source variation of alkanes

While previous studies have suggested that grasses and trees both can be important contributors of nC_{29} and nC_{31} alkanes^{4,5}, the pollen record from the Bulusan site (Fig. 3) shows the dominance of arboreal, shrub and herbaceous taxa (C3 plants) over grasses and sedges (C4 plants) throughout the Bulusan record, and thus suggests that C3 plants were the main source of C_{27-31} alkanes in the Bulusan record. A recent study by Feakins et al.⁶, looking at the production of leaf wax n-alkanes across a tropical rain forest elevation transect and showing that tropical trees are dominated by both nC_{29} and nC_{31} alkanes (followed by nC_{27} alkane), provides further support to this interpretation. While the changes in nC_{27}/nC_{29} and nC_{27}/nC_{31} ratio and the ACL index values in the Bulusan record (Supplementary Fig. 4) indicate somewhat variable alkane sources, these are more likely to have been caused by the changes in the relative abundance of different tree and shrub taxa over time, rather than brought about by the changes in the trees and shrubs to grasses and sedges ratio. Since the pollen data from this site indicate a relatively stable ratio of grasses and sedges to other terrestrial plant taxa, it is unlikely that the recorded changes

in the C_{27-29} ratio have translated into changes in the $C3/C4$ ratio and exerted a major influence on δD of alkanes.

This understanding is further supported by the general lack of seasonality at the Bulusan site. Previous studies have shown that stronger seasonality favours $C4$ vegetation dominance because the warm and wet conditions (e.g., during winter) and drought conditions (e.g., during summer) would require increased water use efficiency⁶. However, eastern Philippines, as many other areas in Southeast Asia, has aseasonal climate with stable temperatures and high precipitation year round. Furthermore, according to Bulusan's fossil pollen record, there has been no increase in the abundance of $C4$ plants (grasses and sedges) over the last 1,400 years compared to present-day, and thus, no indication of changes in the (a)seasonality at the Bulusan site. Dubois et al.⁶ results provide further support to the lack of seasonality in this area as they show broadly similar vegetation cover in northeastern Borneo (also characterised by aseasonal climate) during the Last Glacial Maximum and the Holocene despite generally drier glacial conditions. These results indicate that in areas such as northeastern Borneo and eastern Philippines there was no pronounced dry season even under extreme glacial conditions.

Relatively small proportion of grasses and sedges pollen present throughout the Bulusan record (Fig. 3) suggests open lake conditions at the site over the last 1,400 years. Transition to swamp would have led to an increase in the abundance of sedge pollen (and to an extent of grass pollen) which there is no evidence of in the Bulusan pollen record. Furthermore, we also do not find major changes in the sediment type and sedimentation rates in the Bulusan record, which would be expected with a shift from forest to swamp, and vice versa. These results support a stable mechanism of transport and deposition of alkanes to the lake, most likely a combination of direct leaf input into the lake (there is high incidence of tropical storms at the site) and erosion (high precipitation levels throughout the year (Supplementary Fig. 1a)).

Given the closed nature of the Bulusan lake basin with no known inlets/ outlets, we anticipate that pollen transport to the lake has predominantly been through wind (eolian). Previous studies on pollen transport in tropical forest environments^{7,8} have shown that pollen tends to provide a more local signal (distances in 10s m). This local nature of pollen transport aligns well with the characteristic local nature of sources of alkanes in small catchment lakes such as Bulusan, thereby making the two records readily comparable.

Supplementary Note 5 Influx rates of n-alkanes

Influx rates of n-alkanes, calculated as weight of n-alkanes deposited in a g of dry sediment in a year ($\text{g g}_{\text{sed}}^{-1} \text{yr}^{-1}$), ranged widely between different alkanes, with $n\text{C}_{27-31}$ being the most dominant among them. While the $n\text{C}_{29}$ and $n\text{C}_{31}$ alkanes exhibit similar patterns in abundance variability along the sequence, the $n\text{C}_{27}$ alkane showed a dissimilar pattern, indicating a different origin of $n\text{C}_{27}$ in relation to $n\text{C}_{29}$ and $n\text{C}_{31}$ (Supplementary Fig. 4a).

The high bi-decadal variability of $\delta\text{D}_{\text{wax}}$ values in the Bulusan record (ranging up to $\pm 10 \text{‰}$) suggests a fast transfer of leaf waxes into the lake sediments as opposed to the scenario of extended residence time (for instance in soils) which would lead to signal dampening.

Supplementary Note 6 Detection of regime shifts

The Sequential T-test Analysis of Regime-Shifts algorithm (STARS)^{9,10} was used to detect significant changes (2-sided, p-value set to <0.05) in the mean of δD values of the $n\text{C}_{27-29}$ alkanes. To address uneven spacing of the samples, the time series was sorted into the smallest bin size that still generated a continuous record (i.e., 22 years), and then standardised by the mean and standard deviation. Since the STARS algorithm assumes normality and does not explicitly account for autocorrelation, the time series was transformed to normal distribution using Box Cox transformation and passed through a white-noise filter using the ordinary least-squares method outlined in Rodionov¹⁰ using a version of the STARS algorithm coded in R^{11,12}.

The STARS algorithm detected two significant changes in the mean of δD values of the $n\text{C}_{27-29}$ alkane records (Supplementary Table 2 and Supplementary Fig. 5). The first shift was towards lower δD values at $\sim\text{AD } 1630$ and was followed by a shift to higher δD values at $\sim\text{AD } 1900$.

Supplementary Note 7 Annual rainfall amount and δD values in the Bulusan area from instrumental measurements

To complement the analysis of CRU TSv4 rainfall and $\delta\text{D}_{\text{pw}}$ in isoGSM2, we examine the variability in modern monthly precipitation amount and modern precipitation δD ($\delta\text{D}_{\text{precip}}$) values for the broader Bulusan area using instrumental measurements from seven Global Network of Isotopes in Precipitation (GNIP) sites near Bulusan spanning the period from 1990 to 1998: Balasbas (N $13^{\circ}6'0''$, E $123^{\circ}54'0''$), Bonga station (N $13^{\circ}1'48''$, E $123^{\circ}55'12''$), Botong (N $13^{\circ}3'0.00''$, E $123^{\circ}58'12''$), Cawayan (N $13^{\circ}1'48.00''$, E $123^{\circ}56'24''$), Guinlajon (N $13^{\circ}0'36''$, E $123^{\circ}57'36''$), Inang (N $13^{\circ}4'12''$, E $123^{\circ}54'36''$) and Palayang (N $13^{\circ}3'36''$, E $123^{\circ}55'48''$)¹³

(Supplementary Fig. 8). Note that while GNIP station data more directly addresses precipitation and δD_{precip} characteristics for the Bulusan area, the data is also temporally limited and suffers from missing data, making it unsuitable for analysing interannual variability.

Supplementary Note 8 Physical and chemical characterisation of Bulusan cores

Laminations in the Bulusan sediments were mapped using a combination of optical and radiograph images taken with the Itrax Core Scanner¹⁴ at 0.2 mm resolution at the University of Aarhus in September 2013. These data were used to link the 1 m segments of the two sedimentary sequences into a single composite core with undisturbed sediments (Fig. 2d). While the Bulusan sediments exhibit fine lamination throughout the sequence, the low frequency, uneven thickness, and widely varying colour of these formations make it unlikely for them to represent varves (i.e., annual laminations). While the origin of the Bulusan laminations remains uncertain, likely candidates include droughts, storms, seasonal changes in algal communities and any combination of these. There is also a possibility that some laminations reflect past El Niño events (e.g., extreme drought conditions). However, further investigation is required to identify the origin(s) of laminations, and this particular inquiry is beyond the scope of our study. Instead, the principal purpose of the lamination analysis is to confirm the absence of any local depositional events and sediment slumping that may have influenced the Bulusan record.

Magnetic susceptibility measurements were taken on intact Bulusan cores using the Barrington MS2 Magnetic Susceptibility System made of a magnetic susceptibility metre coupled with a core logging sensor at 2 cm spatial resolution and 11 s SI (9 s CGS) measurement period. Arithmetic mean of magnetic susceptibility values was calculated over 4 cm long slices to align the data with the sample resolution of nC_{27-31} alkanes. The magnetic susceptibility values are relatively low throughout the Bulusan sequence with the exception of four sharp peaks which correspond to <1 cm thick tephra layers (Supplementary Fig. 2). These results indicate consistently low soil erosion rates into the Bulusan Lake which is to be expected given the forest cover that has surrounded it during the last 1,400 years. The four tephra layers have likely been created during past volcanic eruptions of the nearby Mount Bulusan volcano, though other volcanoes in the region such as the very active Mount Mayon represent another potential source of the tephra material deposited in the Bulusan sediments.

Supplementary Note 9 Relationship between δD of precipitable water and δD of precipitation

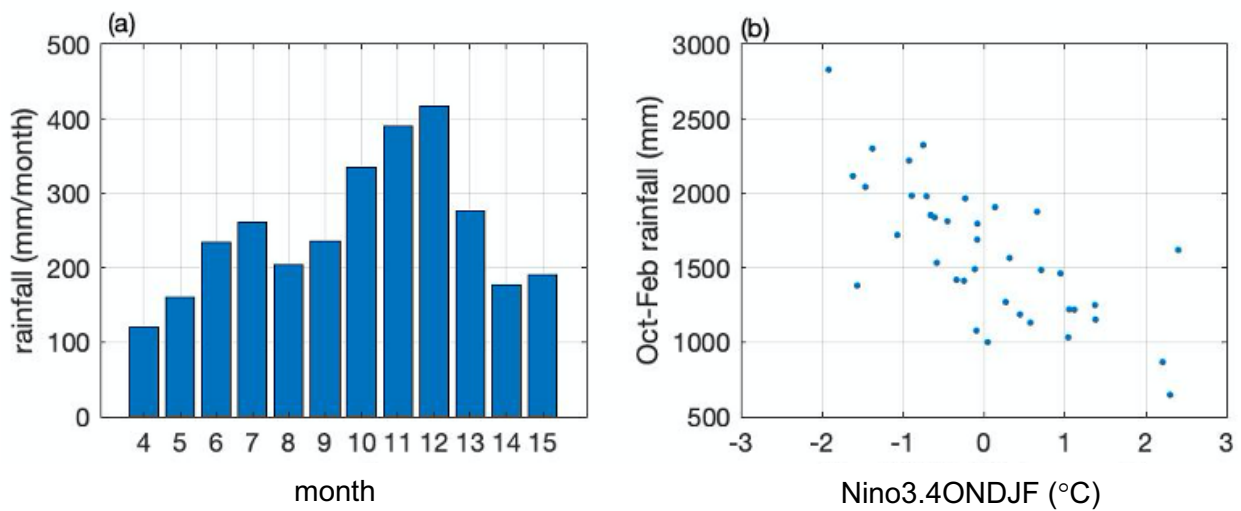
We evaluated the relationship between δD of precipitable water obtained from isoGSM2 output and δD of precipitation from the GNIP sites close to Bulusan, in conjunction with typhoons and heavy storms, using Generalised Linear Least Squares (GLS), with GNIP δD as the response variable, and isoGSM2 δD and the presence/ absence of typhoons and storms as the explanatory variables (Supplementary Fig. 6). GLS is an extended linear fixed-effects model in which errors are permitted to be correlated and/ or have unequal variance¹⁵. Several GLS models were applied in R version 3.5.2.¹¹ using the nlme 3.1-128 package¹⁶ with different combinations of temporal correlation and variance structures imposed on the error components to allow unequal variance of the errors¹⁷. Errors were specified to follow an autoregressive-moving-average (ARMA) process and variance structure was defined with the explanatory variable as a variance covariate. The validity of individual models was then evaluated using standard diagnostic tests¹⁷. The best fitting model with satisfying diagnostics was selected based on the lowest Akaike Information Criterion (AIC) coefficients with a simpler model selected whenever the difference in AIC coefficients between two models was smaller than 2¹⁸. Models were considered significant at the 95% level of confidence. Positive and negative slopes are indicated as (+) or (−), respectively. Data were sourced from GNIP¹⁴ and isoGSM2¹⁹, plotted with *ggplot2* package²⁰ in R version 3.5.2.¹¹.

The results confirm that δD of precipitable water, given by isoGSM2, closely corresponds to δD of precipitation, provided by GNIP data, in the Bulusan area, especially when the effect of typhoons and heavy storms is included (Supplementary Fig. 6, Supplementary Table 3). Specifically, GLS models show a positive effect of precipitable water δD (isoGSM2) (and negative effect of typhoons/ storms) on rainfall δD (GNIP data).

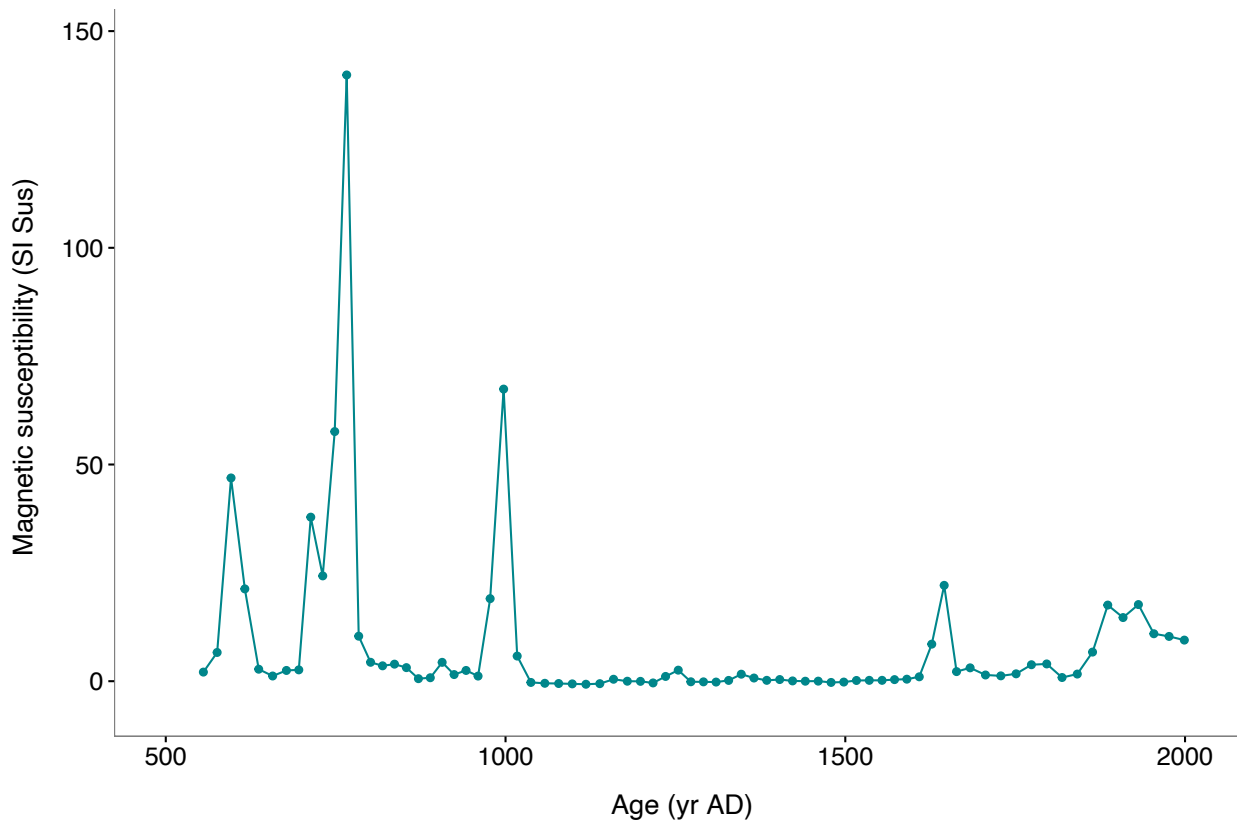
These results allow us to directly relate the observed pattern of δD precipitable water in isoGSM2 to changes in δD of precipitation for the Bulusan area, and estimate the effect of El Niño (and La Niña) on precipitation-weighted δD . For example, in August, the precipitation δD from the GNIP sites is around -50 per mil, so if we take an offset of +127 per mil to the δD of precipitable water to estimate the δD of rainfall, we get a precipitation weighted δD of -18.2 per mil for El Niño rainfall, -23.6 per mil for La Niña rainfall, and -22.7 per mil for neutral rainfall. According to these calculations, El Niño rainfall is approximately +5 per mil isotopically heavier compared to La Niña rainfall. Therefore, while there is less winter rainfall

for El Niño years, the fact that El Niño precipitable water δD is heavier overrides the effect of less winter rainfall.

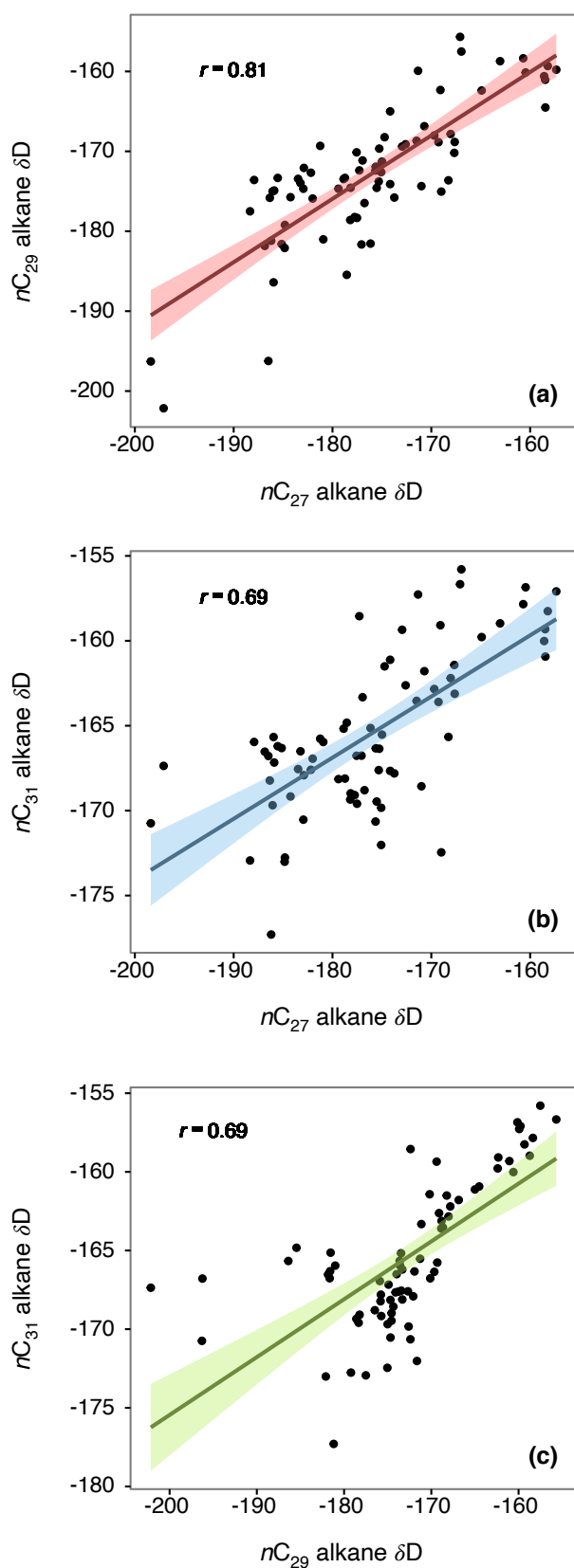
Supplementary Figures and Tables



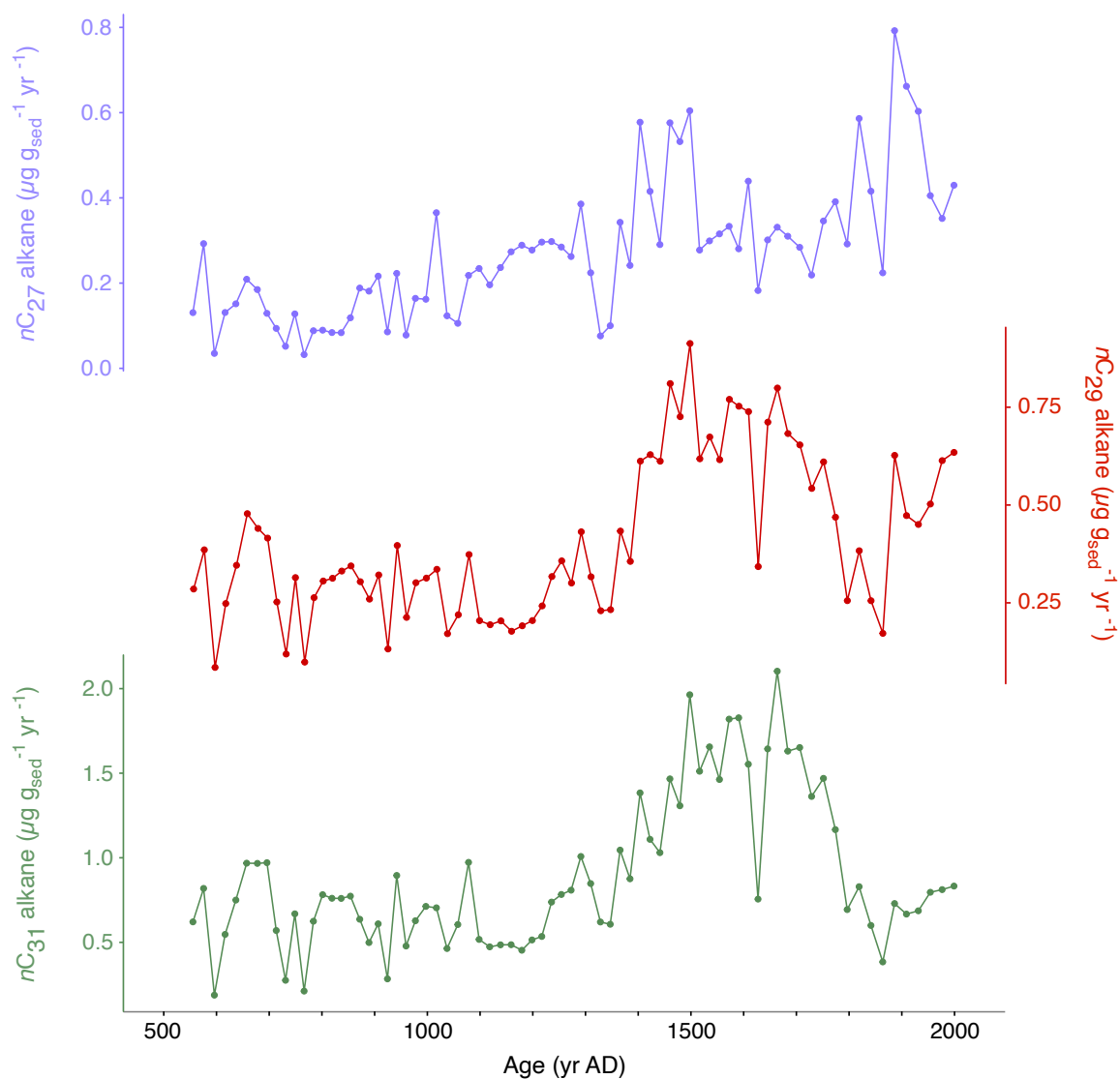
Supplementary Fig. 1. (a) Monthly mean precipitation at Bulusan, using the CRU TSv4 gridpoint closest to Bulusan lake (N 12°45', E 124°15'). The climatology is calculated for the period from 1979 to 2017, and the month covers April through the following March. The onset of the Western North Pacific monsoon is apparent in the rainfall peak around June-July, but the main rainfall season is in winter. The summer months of June-September contribute ~31% of the total annual rainfall, whereas the winter months of October-January contribute ~47%. **(b) Relationship between wintertime rainfall over Bulusan with ENSO.** Nino3.4 averaged over Oct-Feb (x-axis) plotted against Bulusan rainfall summed over the Oct-Feb period. The correlation coefficient between the two is -0.72 ($p < 0.001$).



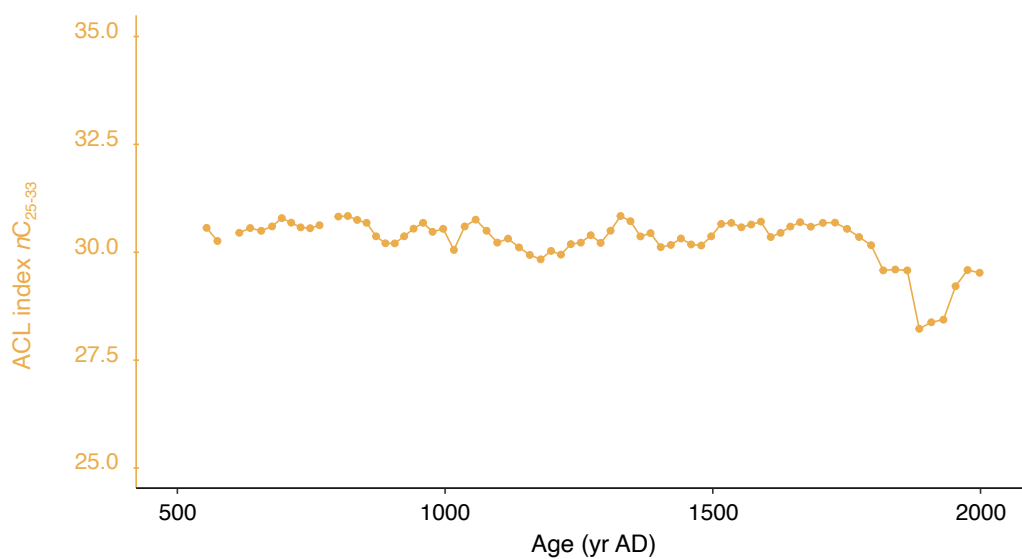
Supplementary Fig. 2. Magnetic susceptibility measurements from the Bulusan sedimentary core. The four sharp peaks in measurement values correspond to <1 cm thick tephra layers. Data plotted with *ggplot2* package²⁰ in R version 3.2.4¹¹.



Supplementary Fig. 3. Correlation between the δD values of n-alkanes from the Bulusan sedimentary core. (a) nC_{27} and nC_{29} alkanes (p-value = 4.9×10^{-12}), (b) nC_{27} and nC_{31} alkanes (p-value = 1.8×10^{-7}), and (c) nC_{29} and nC_{31} alkanes (p-value = 2.1×10^{-7}). The shaded area around the line represents the 95% confidence interval of the fitted linear model. Data plotted with *ggplot2* package²⁰ in R version 3.2.4¹¹.

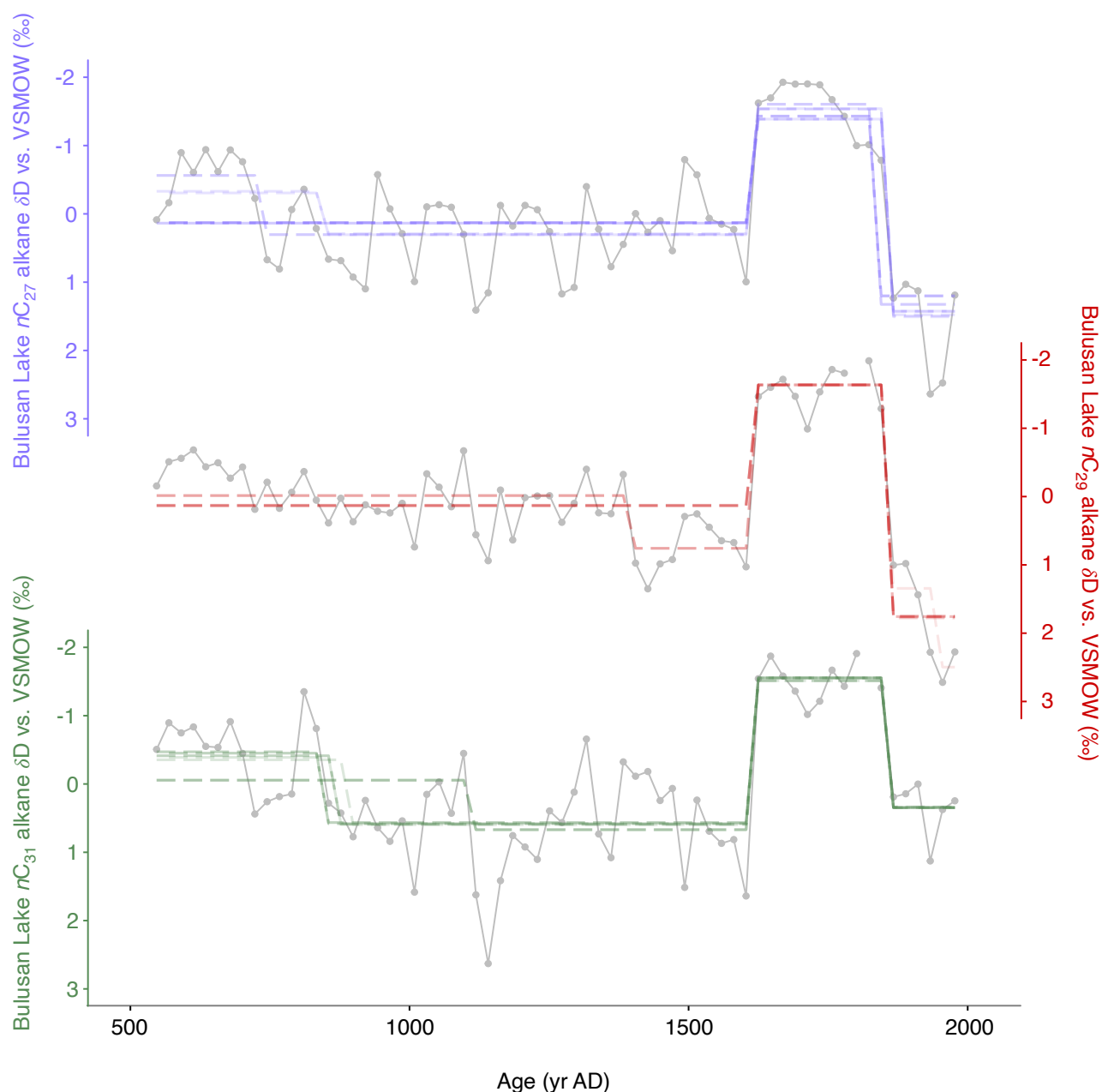


(a)

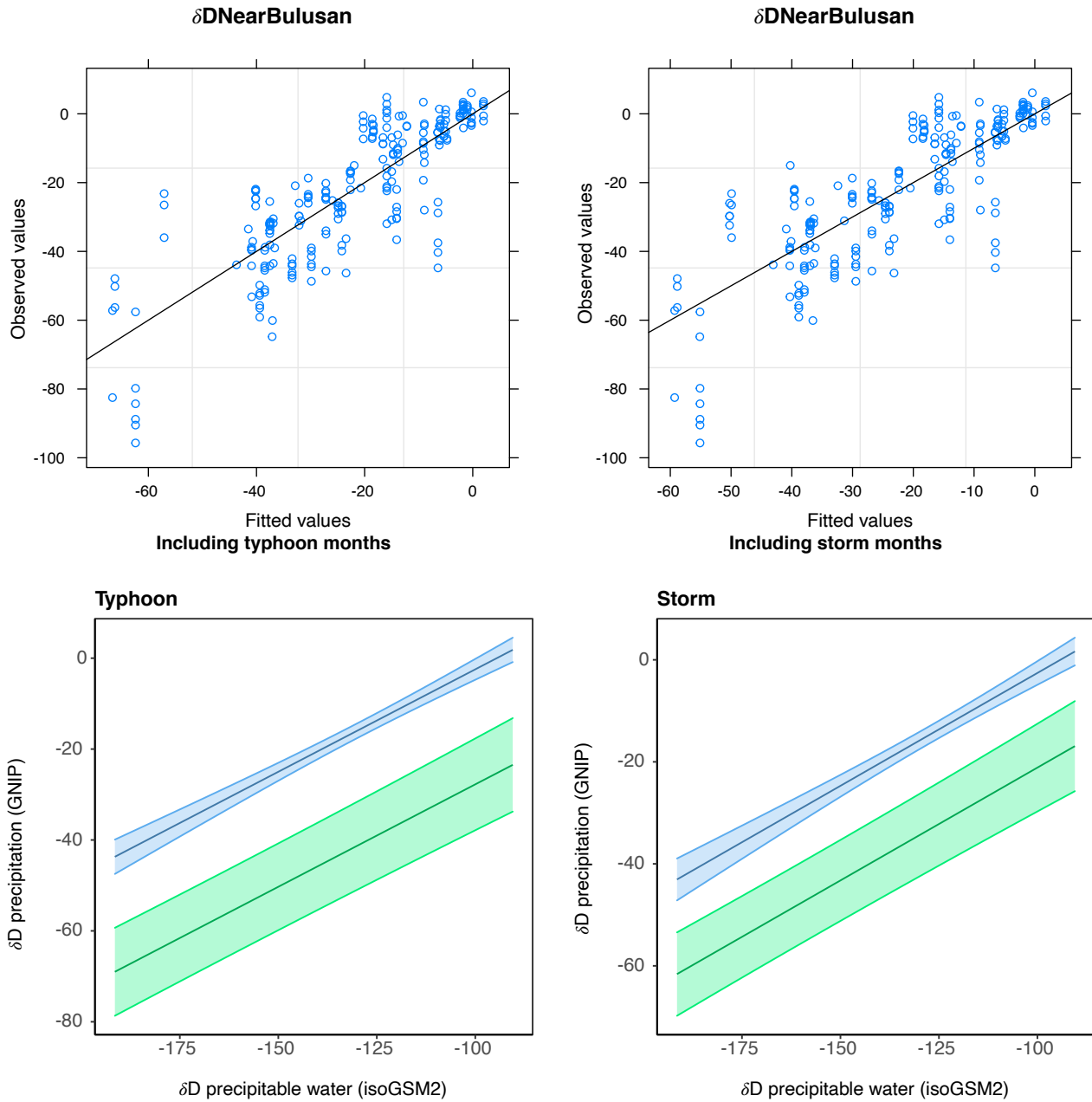


(b)

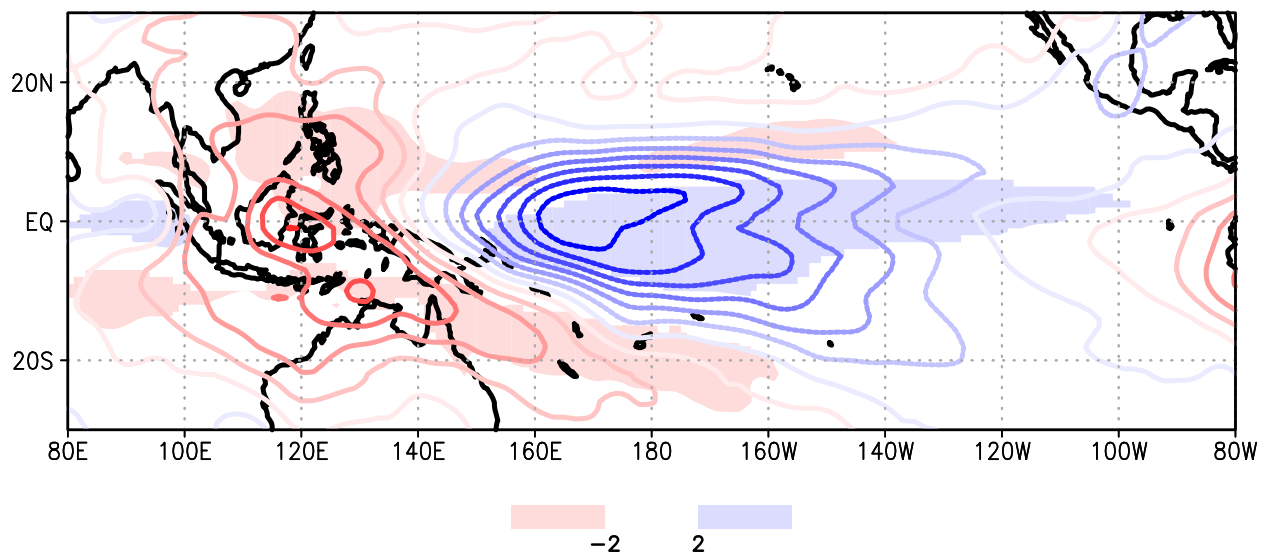
Supplementary Fig. 4. (a) Influx rates of nC_{27-31} alkanes in the Bulusan sedimentary sequence in μg per g of sediment (dry weight) per year. (b) Average chain length (ACL) of nC_{25-33} alkanes in the Bulusan record. Data plotted with *ggplot2* package²⁰ in R version 3.2.4¹¹.



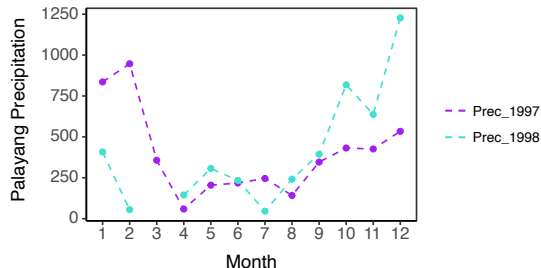
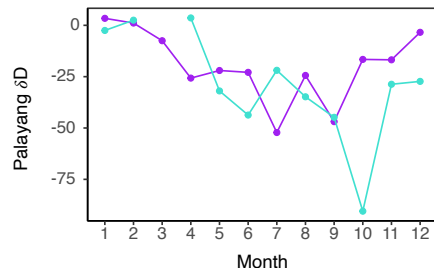
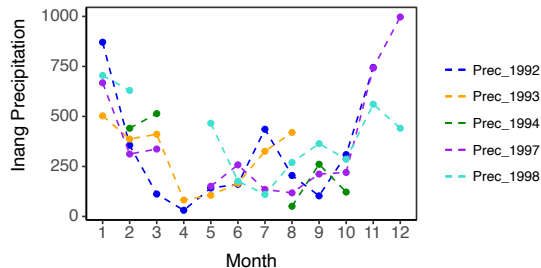
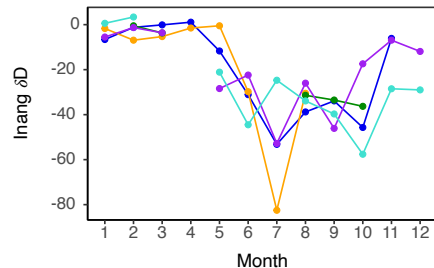
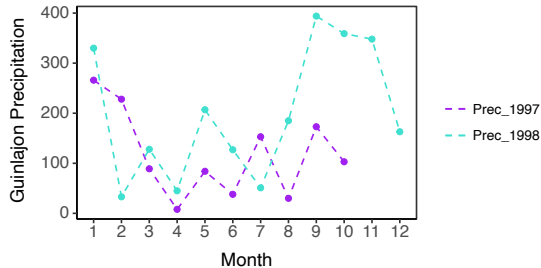
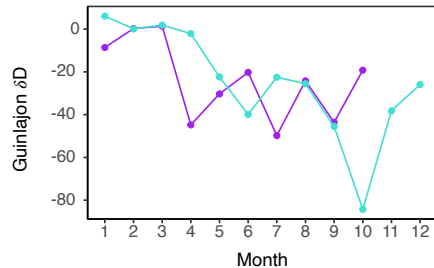
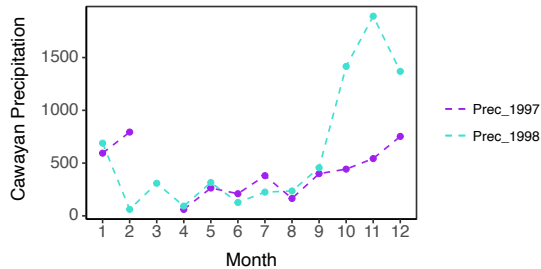
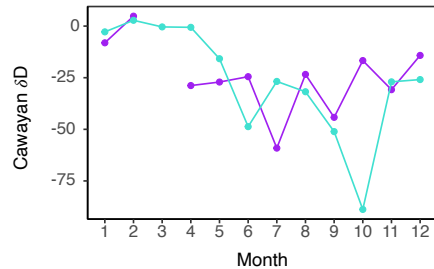
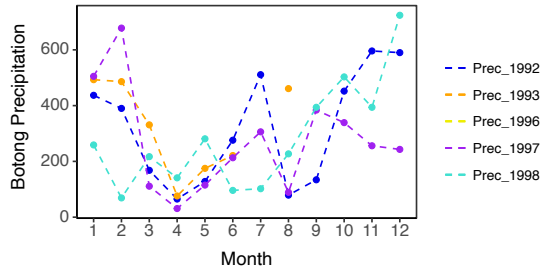
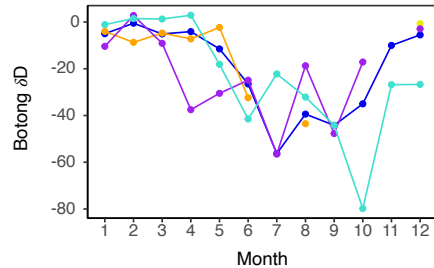
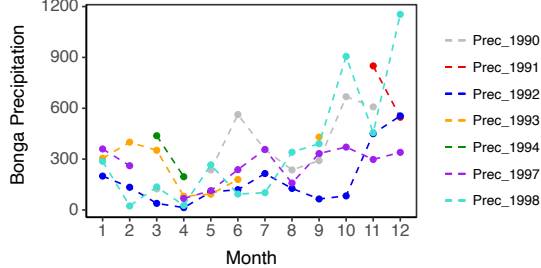
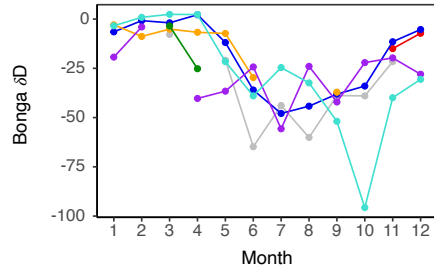
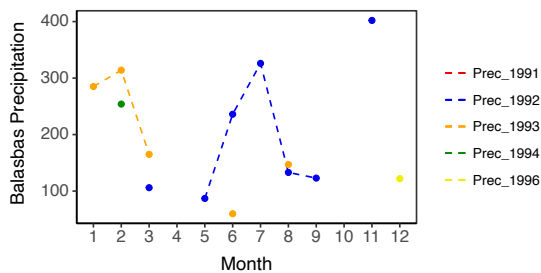
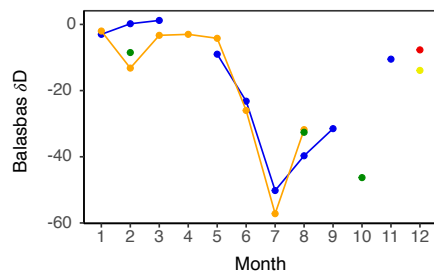
Supplementary Fig. 5. Significant changes in the mean of δD values of nC_{27-31} alkane records from the Bulusan sequence, as detected with the STARS algorithm. The grey line depicts δD values of n-alkanes after Box Cox transformation and pre-whitening. Overlaying coloured lines depict the sequential sample mean of δD records for incremental time windows size from 5 to 15 data points (~100-300 years). Significance of the change in the sample mean is set to p-value <0.05. Data plotted with *ggplot2* package²⁰ in R version 3.2.4¹¹.



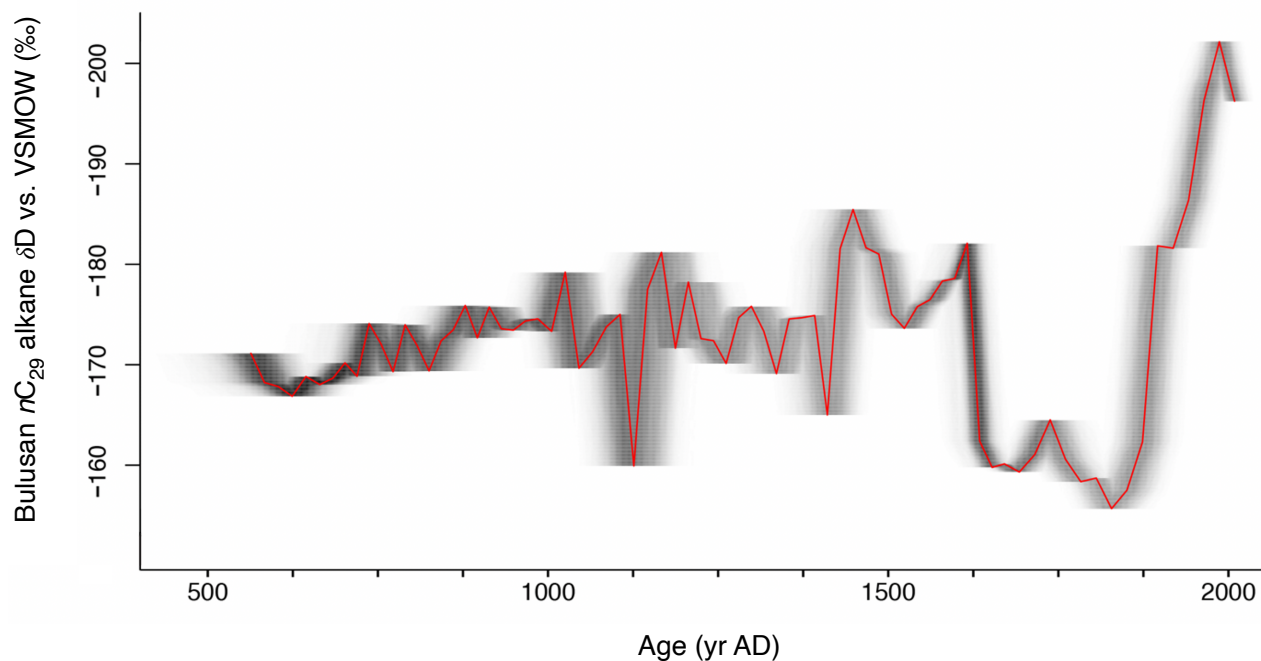
Supplementary Fig. 6. Best fitted GLS models of the relationship between δD of precipitable water from isoGSM2 model output and δD of precipitation from the Global Network of Isotopes in Precipitation (GNIP) sites close to Bulusan. Effect of typhoons and heavy storms on δD of precipitation is also considered. Upper panel shows model fit, and the lower panel shows model predicted relationship between the variables (blue line indicates relationship under regular conditions, and green line relationship under typhoon or storm conditions). The shaded area around the line represents the 95% confidence interval for the fitted GLS model. Data from GNIP¹³ and isoGSM2¹⁹, plotted with *ggplot2* package²⁰ in R version 3.5.2.¹¹.



Supplementary Fig. 7. Change to δD_{pw} and rainfall associated with El Niño. Shown are the El Niño minus La Niña composites of October-February averaged δD of precipitable water (δD_{pw}) (contour interval 5 per mil, blue dashed lines are negative) and precipitation (shaded; red shading is < -2 mm/d, and blue shading is > 2 mm/d). The precipitation field is shaded only if the difference is significant at the 5% level, using a 2-sided t-test. Note in particular the enriched δD_{pw} over the western tropical Pacific tied to a decrease in rainfall over the region.



Supplementary Fig. 8. Seasonality of rainfall in the Bulusan area. Average monthly values spanning the period from 1990 to 1998 (years not continuous for all sites). Precipitation δD and precipitation amount values measured at the Global Network of Isotopes in Precipitation (GNIP) sites near the Bulusan site¹³. Data plotted with *ggplot2* package²⁰ in R version 3.5.2.¹¹.



Supplementary Fig. 9. The chronological uncertainty of the age-depth model²¹ for the Bulusan nC_{29} alkane δD record. Mean 95% confidence range is depicted by grey shading, with darker grey indicating calendar ages that are more likely for specific proxy values. Data plotted with *Bacon* 2.2^{22,23} and *ggplot2* package²⁰ in R version 3.2.4¹¹.

Supplementary Table 1. AMS¹⁴C dates of the Bulusan sedimentary sequence measured at the NERC Radiocarbon Facility, East Kilbride. *An estimated value due to insufficient material for an independent ¹³C measurement.

Lab ID	Sample Material	Core Depth (cm)	Radiocarbon Age (yr BP $\pm$ 1 σ)	Carbon content (% by wt.)	$\delta^{13}\text{C}_{\text{VPD}}$ B‰ ($\pm$ 0.1)
SUERC-64001	Terrestrial plant	59	240 $\pm$ 35	55.2	-30.0
SUERC-64002	Terrestrial plant	69	293 $\pm$ 37	57.7	-29.7
SUERC-64003	Terrestrial plant	74	450 $\pm$ 37	38.9	-30.2*
SUERC-64005	Terrestrial plant	82	323 $\pm$ 37	52.6	-28.7
SUERC-64004	Terrestrial plant	84	401 $\pm$ 37	48.9	-31.6
SUERC-51111	Terrestrial plant	126	617 $\pm$ 38	55.8	-29.9
SUERC-64006	Terrestrial plant	163	609 $\pm$ 37	55.0	-31.2
SUERC-51112	Terrestrial plant	204.5	1146 $\pm$ 35	46.3	-28.0
SUERC-64010	Terrestrial plant	272	1235 $\pm$ 37	50.1	-29.2
SUERC-64011	Terrestrial plant	342.5	1629 $\pm$ 37	58.0	-30.8

Supplementary Table 2a. The timing and p-values of the significant changes in the mean of δD values of the nC₂₇ alkane in the Bulusan sequence identified by the STARS algorithm with incremental time window sizes. Increases and decreases in the sample mean are denoted by asterisk (*) and obelisk (†), respectively.

Time window (no. data points)	Change Point 1 (AD 745 yr)	Change Point 2 (AD 855 yr)	Change Point 3 (AD 1625 yr)	Change Point 4 (AD 1845 yr)	Change Point 5 (AD 1867 yr)
5	/	* 3.42E-03	† 5.15E-11	/	*3.16E-05
6	/	/	† 3.73E-10	/	*3.16E-05
7	/	/	†3.73E-10	/	/*3.16E-05
8	*2.87E-05	/	†7.21E-12	*3.59E-04	/
9	*2.87E-05	/	†7.21E-12	*3.59E-04	/
10	/	/	†1.17E-10	*3.67E-04	/
11	/	/	†1.17E-10	*3.67E-04	/
12	/	/	†1.17E-10	*3.67E-04	/
13	/	*5.72E-03	†1.40E-10	/	*4.33E-05
14	/	/	†9.55E-10	/	*4.33E-05
15	/	/	†9.55E-10	/	*4.33E-05

Supplementary Table 2b. The timing and p-values of the significant changes in the mean of δD values of the nC_{29} alkane in the Bulusan sequence identified by the STARS algorithm with incremental time window sizes. Increases and decreases in the sample mean are denoted by asterisk (*) and obelisk (†), respectively.

Time window (no. data points)	Change Point 1 (AD 1405 yr)	Change Point 2 (AD 1625 yr)	Change Point 3 (AD 1867 yr)	Change Point 4 (AD 1945 yr)
5	*2.64E-05	†3.77E-12	*9.20E-04	*4.94E-02
6	/	†7.96E-12	*3.04E-05	/
7	/	†7.96E-12	*3.04E-05	/
8	/	†7.96E-12	*3.04E-05	/
9	*2.64E-05	†3.77E-12	*3.04E-05	/
10	*2.64E-05	†3.77E-12	*3.04E-05	/
11	*2.64E-05	†3.77E-12	*3.04E-05	/
12	/	†7.96E-12	*3.04E-05	/
13	/	†7.96E-12	*3.04E-05	/
14	/	†7.96E-12	*3.04E-05	/
15	/	†7.96E-12	*3.04E-05	/

Supplementary Table 2c. The timing and p-values of the significant changes in the mean of δD values of the nC_{31} alkane in the Bulusan sequence identified by the STARS algorithm with incremental time window sizes. Increases and decreases in the sample mean are denoted by asterisk (*) and obelisk (†), respectively.

Time window (no. data points)	Change Point 1 (AD 855 yr)	Change Point 2 (AD 877 yr)	Change Point 3 (AD 899 yr)	Change Point 4 (AD 1119 yr)	Change Point 5 (AD 1625 yr)	Change Point 6 (AD 1867 yr)
5	/	/	/	*8.39E-04	†1.61E-13	*5.38E-06
6	/	/	/	*8.39E-04	†1.61E-13	*5.38E-06
7	/	/	/	*8.39E-04	†1.61E-13	*5.38E-06
8	/	/	*5.52E-06	/	†1.30E-16	*5.38E-06
9	/	* 2.43E-06	/	/	†9.28E-17	*5.38E-06
10	/	*2.43E-06	/	/	†9.28E-17	*5.38E-06
11	*1.54E-06	/	/	/	†7.74E-17	*5.38E-06
12	*1.54E-06	/	/	/	†7.74E-17	*5.38E-06
13	*7.52E-06	/	/	/	†1.55E-16	*6.39E-06
14	*7.52E-06	/	/	/	†1.55E-16	*6.39E-06
15	/	*1.15E-05	/	/	†1.88E-16	*6.39E-06

Supplementary Table 3. Summary statistics of best fitted GLS models of the relationship between δD of precipitable water from isoGSM2 model¹⁹ output and δD of precipitation from the Global Network of Isotopes in Precipitation (GNIP) sites¹³ close to Bulusan. Effect of typhoons and heavy storms on δD of precipitation is also considered. $\delta D_{NearBulusan}$ = δD of precipitation, $\delta D_{DisoGSM2}$ = δD of precipitable water, typhoons = presence/ absence of typhoons per month, storms = presence/ absence of storms per month.

<i>Storms/ Typhoons</i>	Typhoons only included	All heavy storms included
<i>Model Structure</i>	$\delta D_{NearBulusan} \sim \delta D_{DisoGSM2} +$ typhoons	$\delta D_{NearBulusan} \sim \delta D_{DisoGSM2} +$ storms
<i>Fixed effects</i>		
<i>Analysis of variance(F-test)</i>		
Intercept	390.51/ 0.0001***	315.61/ 0.0001***
$\delta D_{DisoGSM2}$	296.80/ 0.0001***	264.28/ 0.0001***
typhoons	26.28/ 0.0001***	/
storms	/	20.12/ 0.0001***
<i>Coefficients table (coefficient/ SE/p-value)</i>		
Intercept	42.62/ 3.73/ p=0	41.67/ 3.87/ p=0
$\delta D_{DisoGSM2}$	0.45/ 0.03/ p=0	0.44/ 0.03/ p=0
typhoons	-25.31/ 4.94/ p=0	/
storms	/	-18.55/ 4.14/ p=0
<i>Variance</i>	expon	expon
<i>Function (95% CI)</i>	-0.013 (-0.018, -0.007)	-0.015 (-0.021, -0.0096)
<i>Correlation</i>	corCAR1(form = ~ time site)	corCAR1(form = ~ time site)
<i>Structure (95% CI)</i>	0.21 (0.11, 0.37)	0.25 (0.14, 0.40)
<i>Scale (σ)</i>	8.14 (6.97, 9.50)	7.90 (6.76, 9.24)

Supplementary References

1. Ruxton, G. D. The unequal variance t-test is an underused alternative to Student's t-test and the Mann–Whitney U test. *Behavioral Ecology* **17**, 688–690 (2006).
2. Yan, H. *et al.* Dynamics of the intertropical convergence zone over the western Pacific during the Little Ice Age. *Nature Geoscience* **8**, 315–320 (2015).
3. Feakins, S. J. *et al.* Production of leaf wax n-alkanes across a tropical forest elevation transect. *Organic Geochemistry* **100**, 89–100 (2016).
4. Maffei, M. Chemotaxonomic significance of leaf wax alkanes in the gramineae. *Biochemical Systematics and Ecology* **24**, 53–64 (1996).
5. E. Abada Gatumbato, W. Carandang, N. Pampolina, N. A. Mallar, S. Narvadez. *Final Report: Physical and Geopolitical Characteristics, Biological Resources, Socio-Cultural and Economics Conditions and Institutional Arrangements/Governance of the Bulusan Volcano Natural Park.* (2011).
6. Dubois, N. *et al.* Indonesian vegetation response to changes in rainfall seasonality over the past 25,000 years. *Nat. Geosci.* **7**, 513–517 (2014).
7. Kershaw, A. P. & Strickland, K. M. A 10 year pollen trapping record from rainforest in northeastern Queensland, Australia. *Review of Palaeobotany and Palynology* **64**, 281–288 (1990).
8. Bush, M. & Rivera, R. Pollen dispersal and representation in a neotropical rain forest. *Global Ecology and Biogeography* **7**, 379–392 (1998).
9. Rodionov, S. N. A sequential algorithm for testing climate regime shifts. *Geophysical Research Letters* **31**, L09204 (2004).
10. Rodionov, S. N. Use of prewhitening in climate regime shift detection. *Geophysical Research Letters* **33**, L12707 (2006).
11. R Core Team, R: A language and environment for statistical computing. <<http://www.R-project.org/>> (Foundation for Statistical Computing, Vienna, Austria, 2013).

12. Seddon, A. W. R., Froyd, C. A., Witkowski, A. & Willis, K. J. A quantitative framework for analysis of regime shifts in a Galápagos coastal lagoon. *Ecology* **95**, 3046–3055 (2014).
13. IAEA/WMO, Global Network of Isotopes in Precipitation: The GNIP Database. <<http://www.iaea.org/water>> (2017).
14. Croudace, I. W., Rindby, A. & Guy Rothwell, R. ITRAX: description and evaluation of a new multi-function X-ray core scanner. *Geological Society, London, Special Publications* **267**, 51–63 (2006).
15. Pinheiro, J. C. & Bates, D. M. Mixed-Effects Models in Sand S-PLUS. *Statistics and Computing* (2000) doi:10.1007/978-1-4419-0318-1.
16. J. C. Pinheiro, D. M. Bates, S. DebRoy, D. Sarkar, R Core Team. *nlme: Linear and Nonlinear Mixed Effects Models, R package*. (2016).
17. Gałęcki, A. & Burzykowski, T. *Linear Mixed-Effects Models Using R: A Step-by-Step Approach*. Springer Science & Business Media (2013).
18. Akaike, H. Information theory and an extension of the maximum likelihood principle. In *Second International Symposium on Information Theory* (ed. B. Petrov, F. C.) Akadémiai Kiado (1973).
19. Yoshimura, K. Stable Water Isotopes in Climatology, Meteorology, and Hydrology: A Review. *Journal of the Meteorological Society of Japan. Ser. II* **93**, 513–533 (2015).
20. Wickham, H. *ggplot2: Elegant Graphics for Data Analysis*. Springer Science & Business Media (2009).
21. Blaauw, M., Christen, J. A., Mauquoy, D., van der Plicht, J. & Bennett, K. D. Testing the timing of radiocarbon-dated events between proxy archives. *The Holocene* **17**, 283–288 (2007).
22. Blaauw, M. & Andrés Christen, J. Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Analysis* **6**, 457–474 (2011).

23. M. Blaauw, J. A. Christen, Bacon. <<http://www.chrono.qub.ac.uk/blaauw/bacon.html>.
(2015).