Fire and ice: Anak Krakatau triggers volcanic freezer in the upper troposphere

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Abstract

Volcanic activity occurring in tropical moist atmospheres can promote deep convection and trigger volcanic thunderstorms. Intense heating at ground surface and entrainment of moist air generates positive buoyancy, rapidly transporting volcanic gases and ash particles up to the tropopause and beyond. Volcanically-induced deep convection, however, is rarely observed to last continuously for more than a day and so insights into the dynamics, microphysics and electrification processes are limited. Here we present a multidisciplinary study on an extreme case, where this phenomenon lasted for six days. We show that this unprecedented event was triggered and sustained by phreatomagmatic activity at Anak Krakatau volcano, Indonesia from 22-28 December 2018. During this period, a deep convective plume formed over the volcano and acted as a 'volcanic freezer' producing ˜3 × 109 kg of ice on average with maxima reaching ˜$10^1$0 kg. Our satellite analyses reveal that the convective anvil cloud, reaching 16-18 km above sea level, was ice-rich and ash-poor. Cloud-top temperatures hovered around -80 °C and ice particles produced in the anvil were notably small (effective radius from 20-30 µm). Our modelling suggests that ice particles began to form above 5 km and experienced vigorous updrafts (>30 m/s). These findings explain the impressive number of lightning strikes (˜100,000) recorded near the volcano during this time. Our results, together with the unique dataset we have compiled, provide new insights into volcanic and meteorological thunderstorms alike.

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Fire and *ice*: *Anak Krakatau triggers volcanic freezer in the upper troposphere*

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Background

Volcanic activity occurring in tropical moist atmospheres can promote deep convection and trigger volcanic thunderstorms. These phenomena, however, are rarely observed to last continuously for more than a day and so insights into the dynamics, microphysics and electrification processes are limited. Here we present a multidisciplinary study on an extreme case, where volcanically-triggered deep convection lasted for six days.

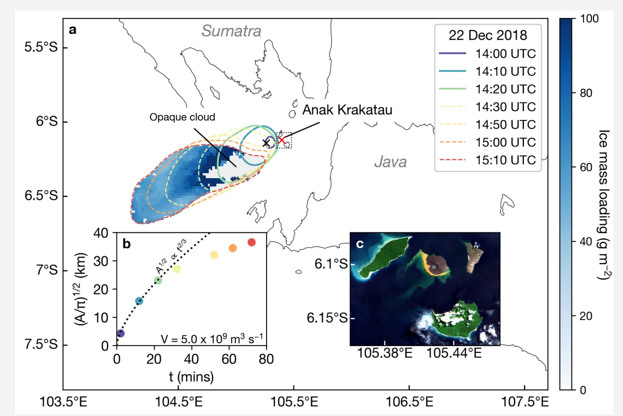

Fig. 1 | a, Umbrella spread of the initial plume with Himawari-8 ice mass loading retrievals plotted underneath. **b**, Change in average radius with time (t). Dashed line shows Woods and Kienle[1] model fit. **c**, Sentinel-2 image (02:56 UTC, 31 March 2019) showing remnant edifice of Anak Krakatau.

Key Results

- Our modelling suggests an ice mass flow rate of ~5 x 10^6 kg/s for the initial explosive eruption associated with a flank collapse.
- The 'volcanic freezer' produced ~3 x 10^9 kg of ice on average over six days (22-28 Dec 2019) with maxima reaching ~10^{10} kg (Fig. 4).
- The convective anvil cloud reached 16-18 km above sea level, was ice-rich and ash-poor (Fig. 1).
- Ice particles produced in the anvil were small (retrievals indicate effective radii ~20 μm; Fig. 2).
- Vigorous updrafts (>50 m/s) and prodigious ice production explain the impressive number of lightning flashes (~100,000) recorded near the volcano (Fig. 4).
- Strong correlation (R = 0.77, p-value < 0.001) found between lightning flash rate and plume height (Supplementary Fig. 2).

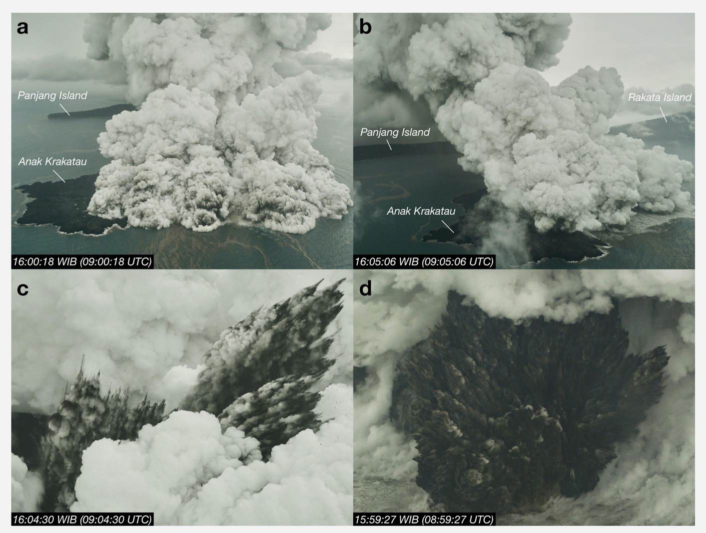

Fig. 3 | Aerial photographs of the Anak Krakatau eruption on 23 December 2018. **a, b** show two angles of the sprawling phreatomagmatic cloud. Plume extends toward the east over Panjang Island. **c, d** Cock's tail jets characteristic of Surtseyan volcanic activity. All photographs used with permission from the copyright owner Dicky Adam Sidiq/kumparan.

Discussion

The CAPE in the vicinity of Anak Krakatau was not large enough to support deep convection (~810 J/kg). However, if we consider that magma-seawater interactions at the surface had the effect of adding heat and moisture to surface air parcels, we find that CAPE increases significantly with only modest increases in parcel temperature and moisture (Fig. 5). By considering volcanically-induced CAPE ('volcanic-CAPE'), we find that a continual input of heat and moisture at the surface would lead to sustained, extreme convection (CAPE ~5000-6000 J/kg), but without this input, deep convection would not be expected.

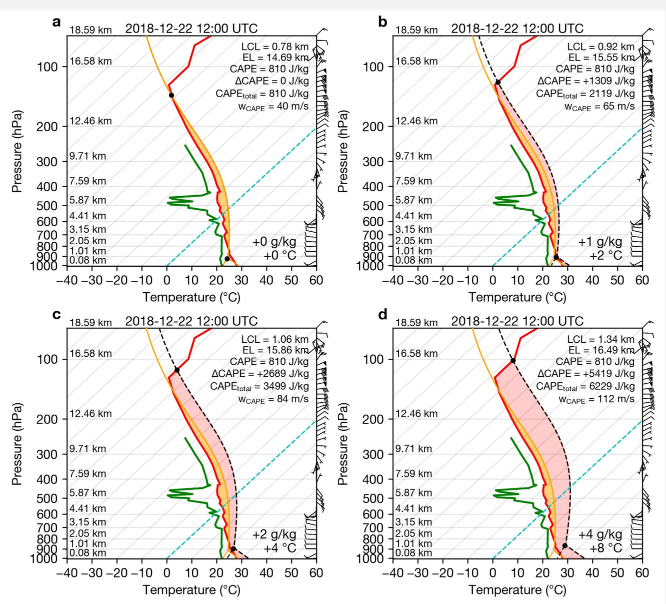

Fig. 5 | Thermodynamic skew-T diagrams for increases in surface parcel temperature and moisture. Red shaded area indicates increases in CAPE induced by volcanic activity (i.e. volcanic-CAPE). Maximum theoretical updraft velocities (w_{CAPE}) are also annotated on each panel. Sounding from Jakarta airport at 12:00 UTC on 22 December 2018.

Data accessed from: http://weather.uwyo.edu/upperair/

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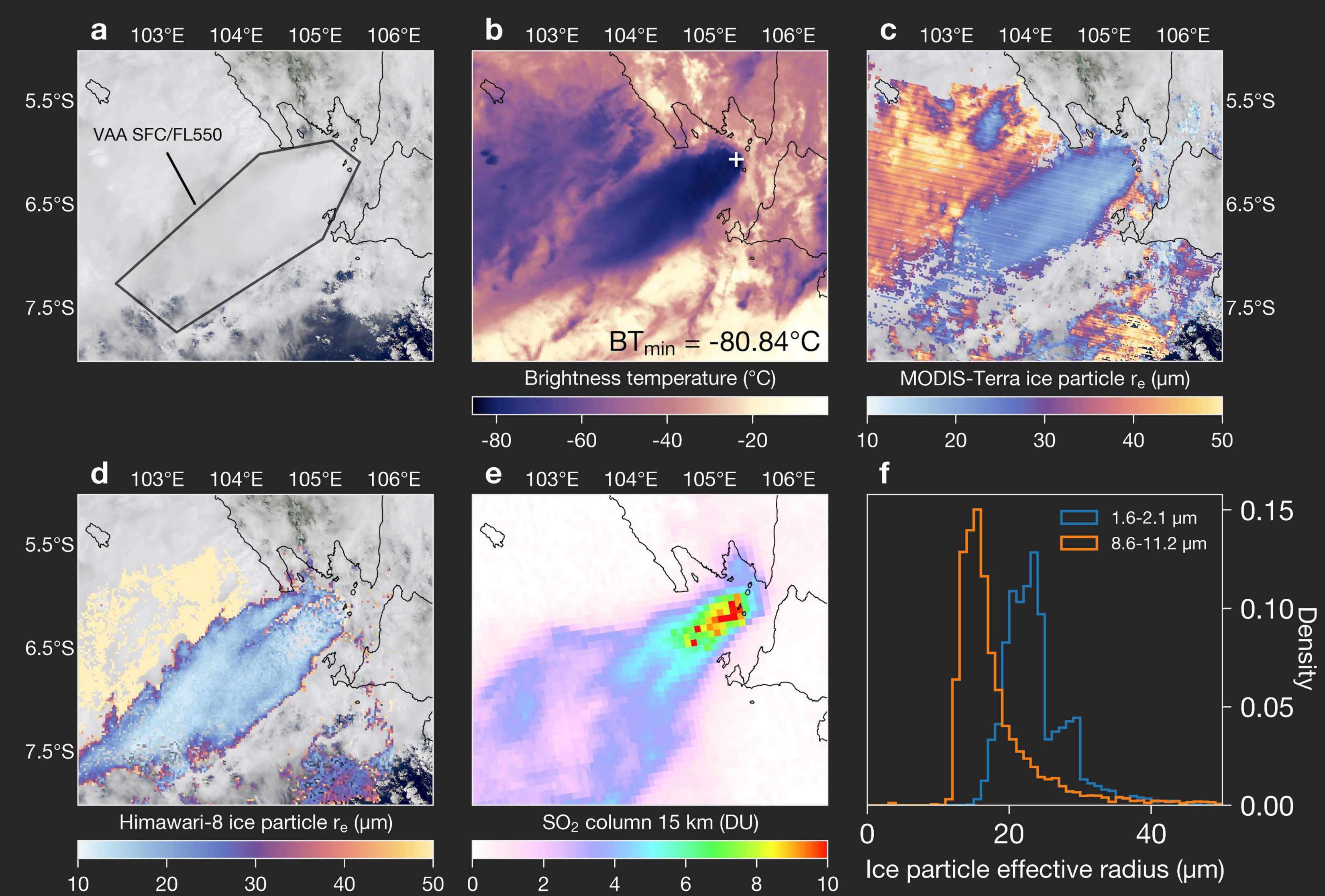
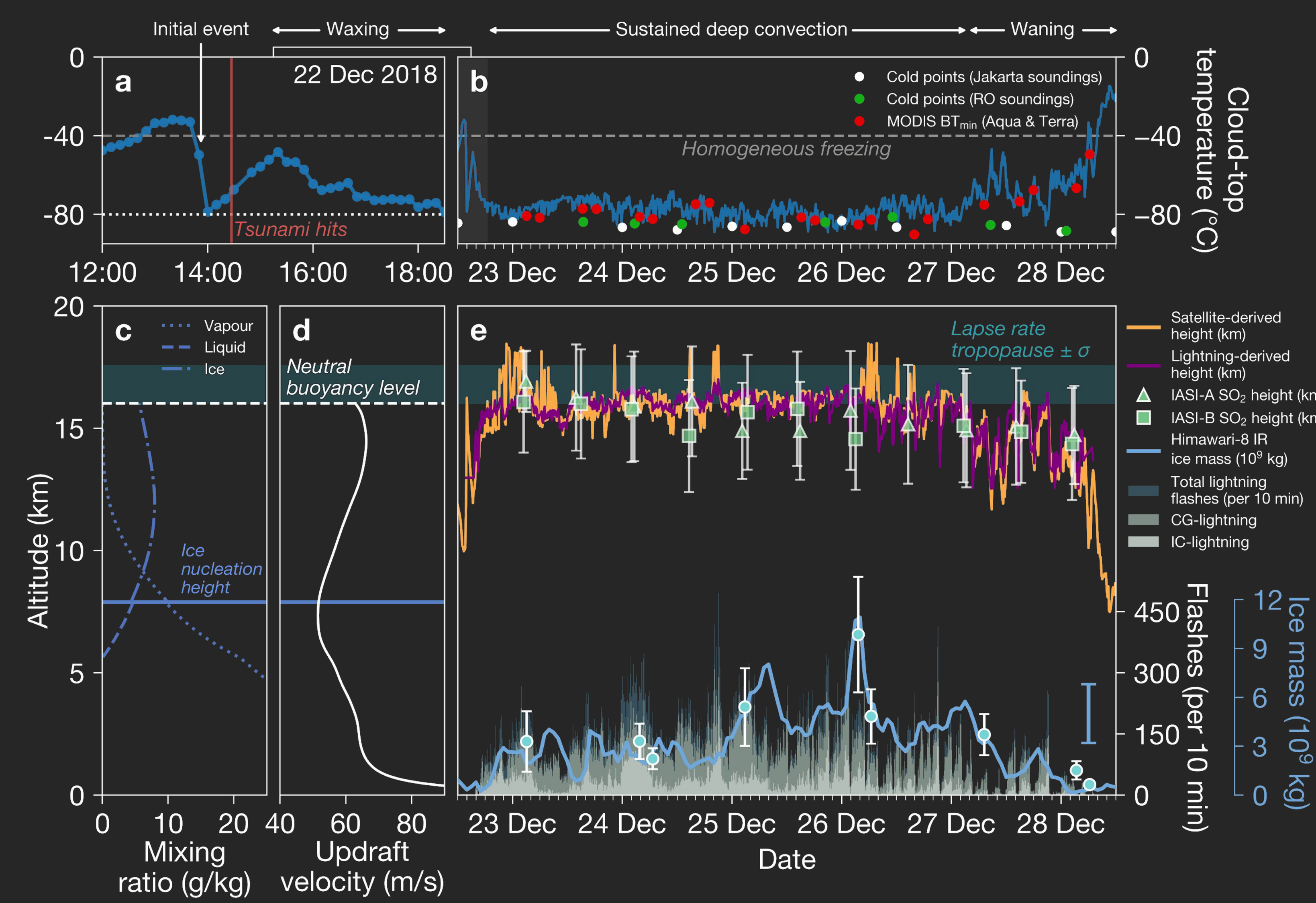
Anak Krakatau triggered a *volcanic freezer* that produced **ice** in the **upper troposphere** for almost a **week.**

Fig. 2 | Anatomy of the Anak Krakatau convective anvil



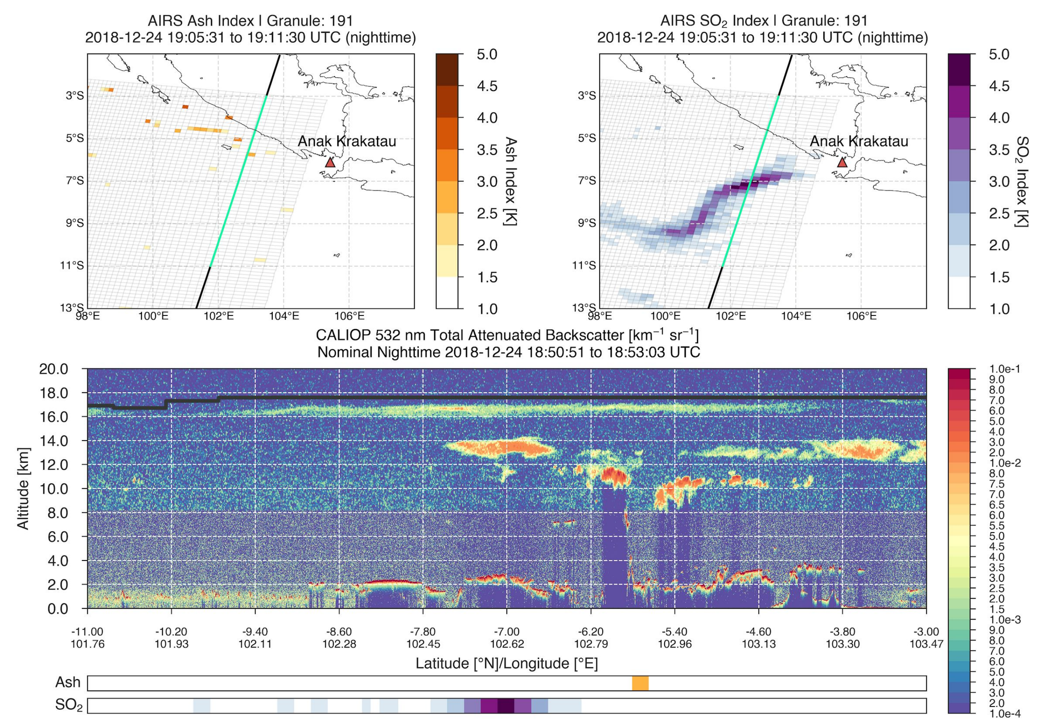
The paper is under review in ***Nature Scientific Reports***, but you can check out a cool animation of the sustained convective plume here

Fig. 4 | Time series of the Anak Krakatau convective plume

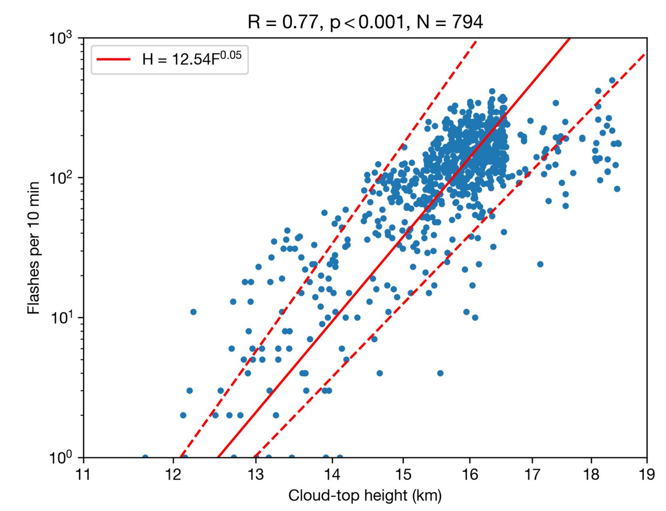


Supplementary Information

Processed by Andrew Prata. Data courtesy NASA/JPL and the AIRS and CALIPSO teams.

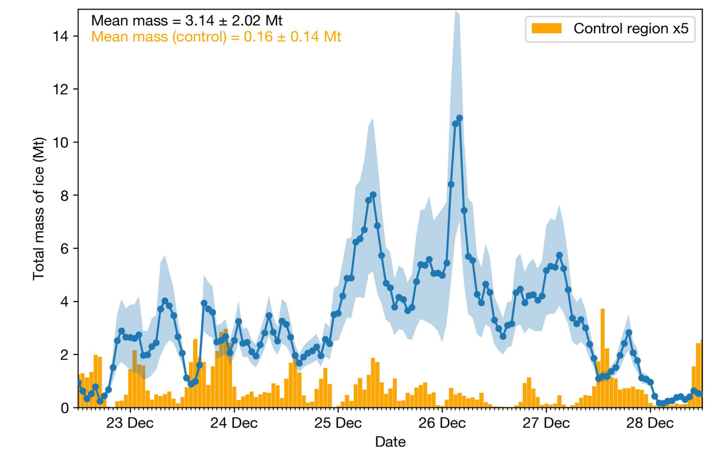


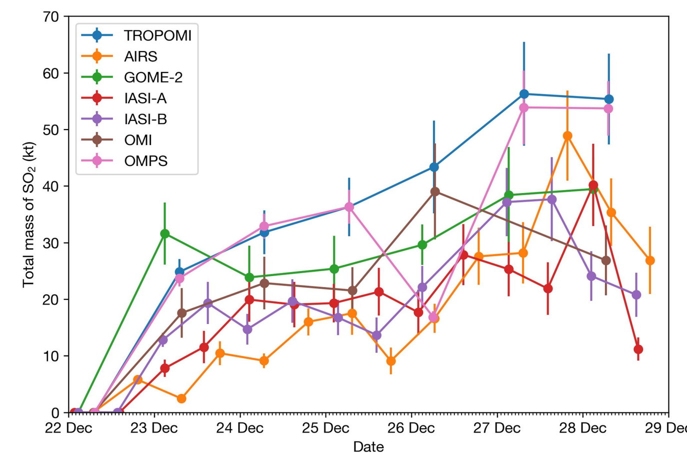
Supplementary Fig. 1 | CALIOP/AIRS analysis[2]. Black line with green highlight indicates CALIOP track over AIRS ash/SO_2 detection indices (top panels). UTLS volcanic feature present in CALIOP backscatter curtain (lower panel).



Supplementary Fig. 2 | Correlation between flash rate (*F*) and cloud-top height (*H*). Solid line indicates least squares fit using the equation, H=cF^d, where *c* and *d* are empirical constants (shown in legend). Dashed red lines indicate one standard deviation errors in *c* (±0.450) and *d* (±0.008). Correlation was calculated by taking the Pearson's correlation coefficient of the two data sets (*F* and *H*) in logspace (correlation only uses non-zero values of *F*).

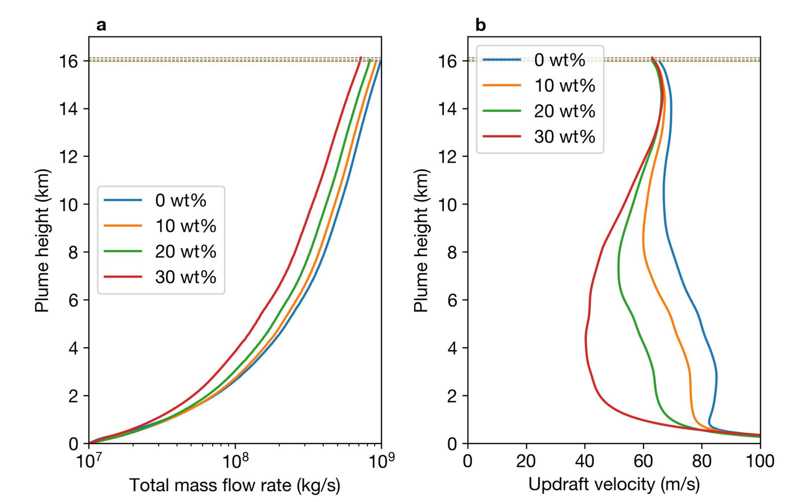
Supplementary Fig. 3 | Time series of Himawari-8 total ice mass. Solid line with dots indicates total ice mass (Mt) at hourly intervals calculated from Himawari-8 data (uncertainty indicated by shaded region). The total ice mass in the control region is shown by the orange-coloured bars and multiplied by 5 for clarity.





Supplementary Fig. 4 | Time series of SO_2 for the Anak Krakatau convective plume. Time-series indicates total mass of SO_2 retrievals from infrared and ultraviolet polar orbiting sensors taken from the SACS near-real time alert system[3]. Errors in the total mass loadings were obtained by considering two types of Air Mass Factors (AMFs).

Supplementary Fig. 5 | FPLUME[4] sensitivity study results. (a) Vertical profile of the total mass flow rate for different water fractions (0 wt%, 10 wt%, 20 wt% and 30 wt%). (b) Same as (a) but for updraft velocities. Horizontal dashed lines show neutral buoyancy level (NBL) for each simulation.



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