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Hemispherically asymmetric volcanic forcing of tropical hydroclimate during the last millennium

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Supplemental Figure Captions

Figure S1. Zonal-mean temperature anomalies as a function of atmospheric pressure and latitude in CESM volcanic eruption composites for each event and season classifications discussed in text.

Figure S2. GISS spatial composite of temperature anomaly (°C) for (top row) $ASYMM_{NH}$, (middle row) $ASYMM_{SH}$, and (bottom row) SYMM events, each in (left column) NDJFM and (right column) MJJAS. Note that scaling of colorbar is different from CESM composite (Figure 2).

Figure S3. As in Figure S2, except for precipitation (mm/day). Note colorbar range difference compared to CESM composite (Figure 4).

Figure S4. Precipitation anomaly (mm/day) for the 1763 C.E. Laki eruption for NDJFM. Results displayed for all 18 ensemble members in CESM relative to the 1757-1761 C.E. NDJFM mean. Surface air temperature anomalies (°C) averaged over the Niño 3.4 region displayed at topright of each panel. Note colorbar range difference compared to CESM all-event composite (Figure 4).

Figure S5. Precipitation asymmetry index (unitless) as defined in text vs. NH minus SH AOD gradient (hemispheric sulfate loadings divided by 75 Tg for the CESM results). Results displayed for both seasons in LM time series. Since most of the LM time series features zero or low volcanic activity, all seasons where $-0.1 <$ AOD gradient < 0.1 are shown by dashed box and whisker (GISS) and solid box only (CESM). The whisker lengths are very similar between the two models, and were omitted to avoid visual overlap. Results presented for the 18 and 3-member ensemble mean for each season, which suppresses the variability (represented by the box and whisker spread) for the non-eruption compilation but allows for comparison with the ensemble-mean volcanic responses.

Figure S6. Niño 3.4 SST anomalies for all $ASYMM_{NH}$ events, centered on Year 0 (the January before each eruption). The mean SST anomaly averaged over all eruption and ensemble members is shown as red line, and the eruption spread is shown as gray shading (after averaging 18 ensemble members). Composite-mean NH aerosol loading (Tg), aligned in the same way, is shown as purple line.

Figure S7. Composite Sea Surface Height (cm) and surface wind anomalies for $ASYMM_{NH}$ events. Composite formed from the boreal winter events in Table 1 in main text. Blue box shows the Niño 3.4 region.

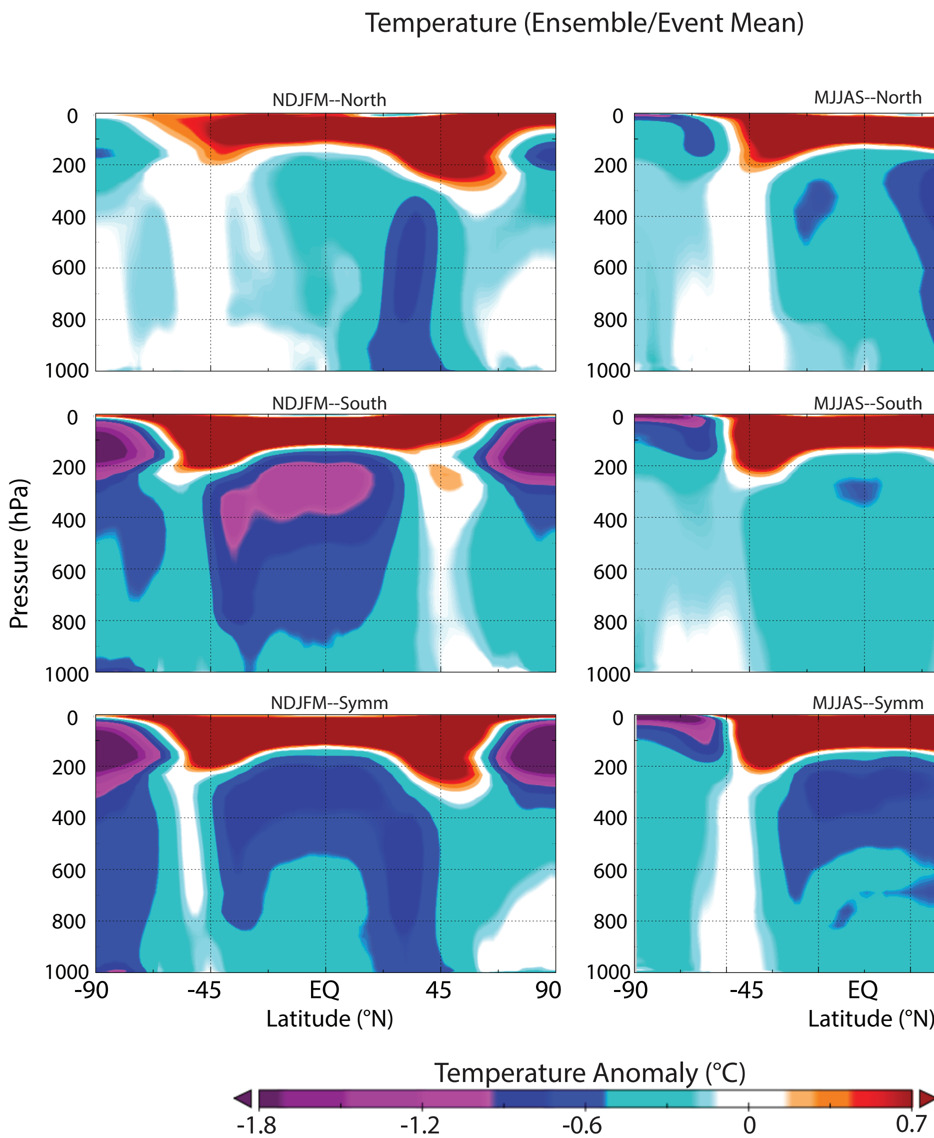
Figure S8. Distribution of precipitation anomalies (mm/day) in CESM (top) and GISS-E2 (bottom) during MJJAS averaged broadly over the Asian-Pacific monsoon sector (65°-150°E, 10°-40°N), including regions of the Indian summer monsoon, western North Pacific summer monsoon, and the East Asian summer monsoon. Each eruption is taken to be an independent event, and there are more events in CESM due to the greater ensemble size (note difference in y-axis scale and slightly different bin width). Solid lines correspond to a normal distribution for the (red, $ASYMM_{NH}$; blue, $ASYMM_{SH}$; black, SYMM) events.

Figure S9. Animation from May of Year -2 to December of Year +6 (as discussed in text) of monthly temperature anomalies (°C) associated with $ASYMM_{NH}$ volcanic forcing in CESM. For each time step, the global aerosol loading (in Tg) and hemispheric difference in loading (NH minus SH) are displayed. Months exceeding the 8 Tg global aerosol loading in the G08 dataset are displayed in red.

Figure S10. As in Figure S9, except for $ASYMM_{SH.}$

Figure S11. As in Figure S9, except for precipitation (mm/day).

Figure S12. As in Figure S11, except for $ASYMM_{SH.}$



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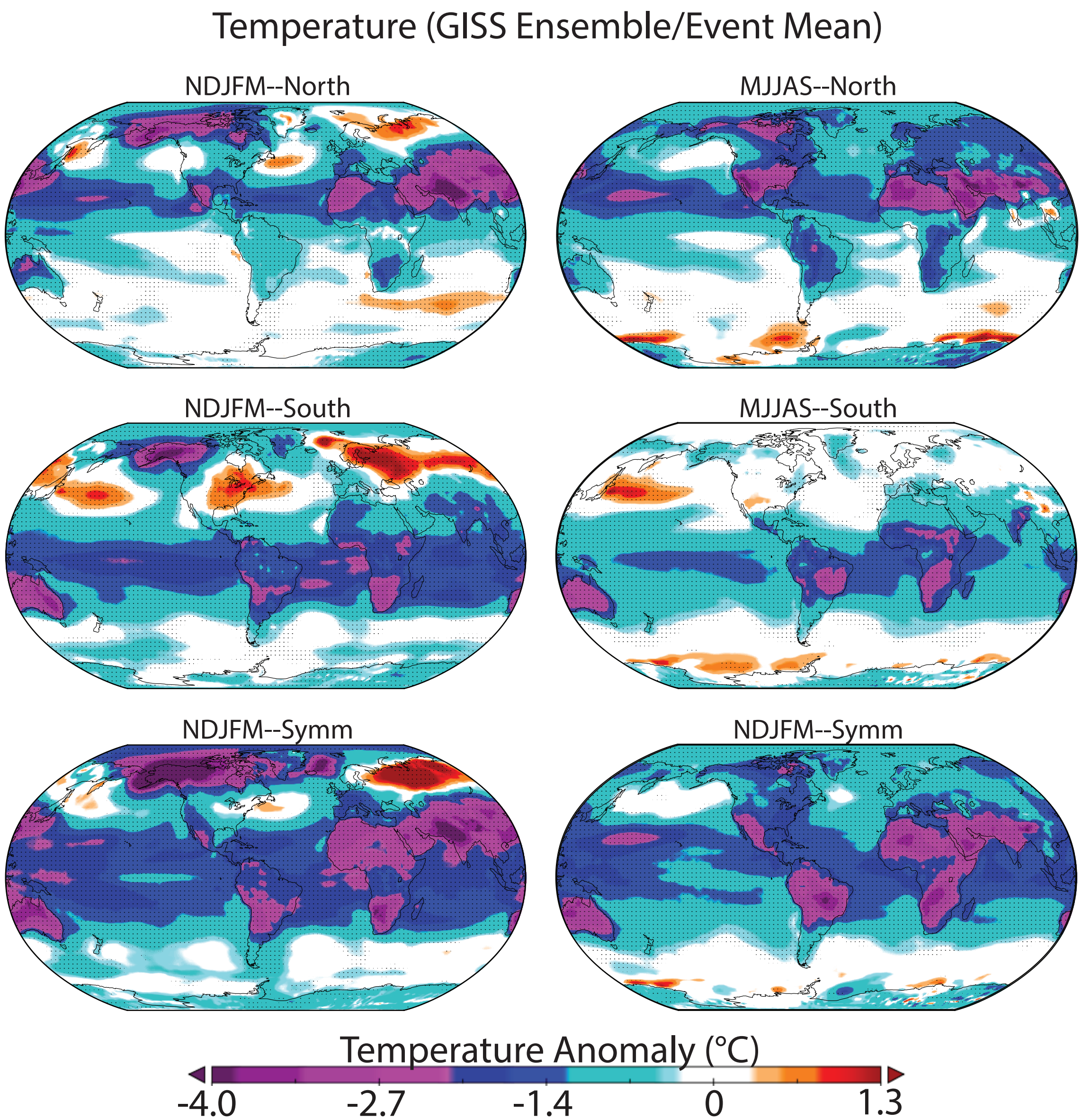

Figure S2. GISS spatial composite of temperature anomaly (°C) for (top row)

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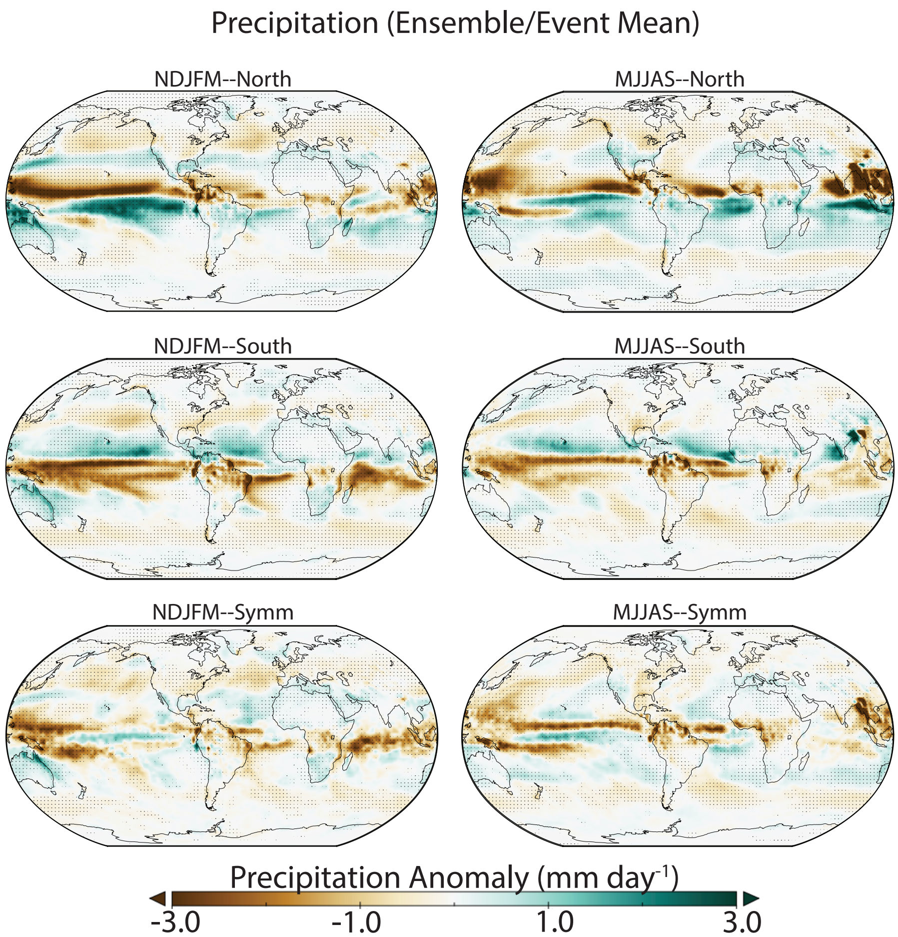

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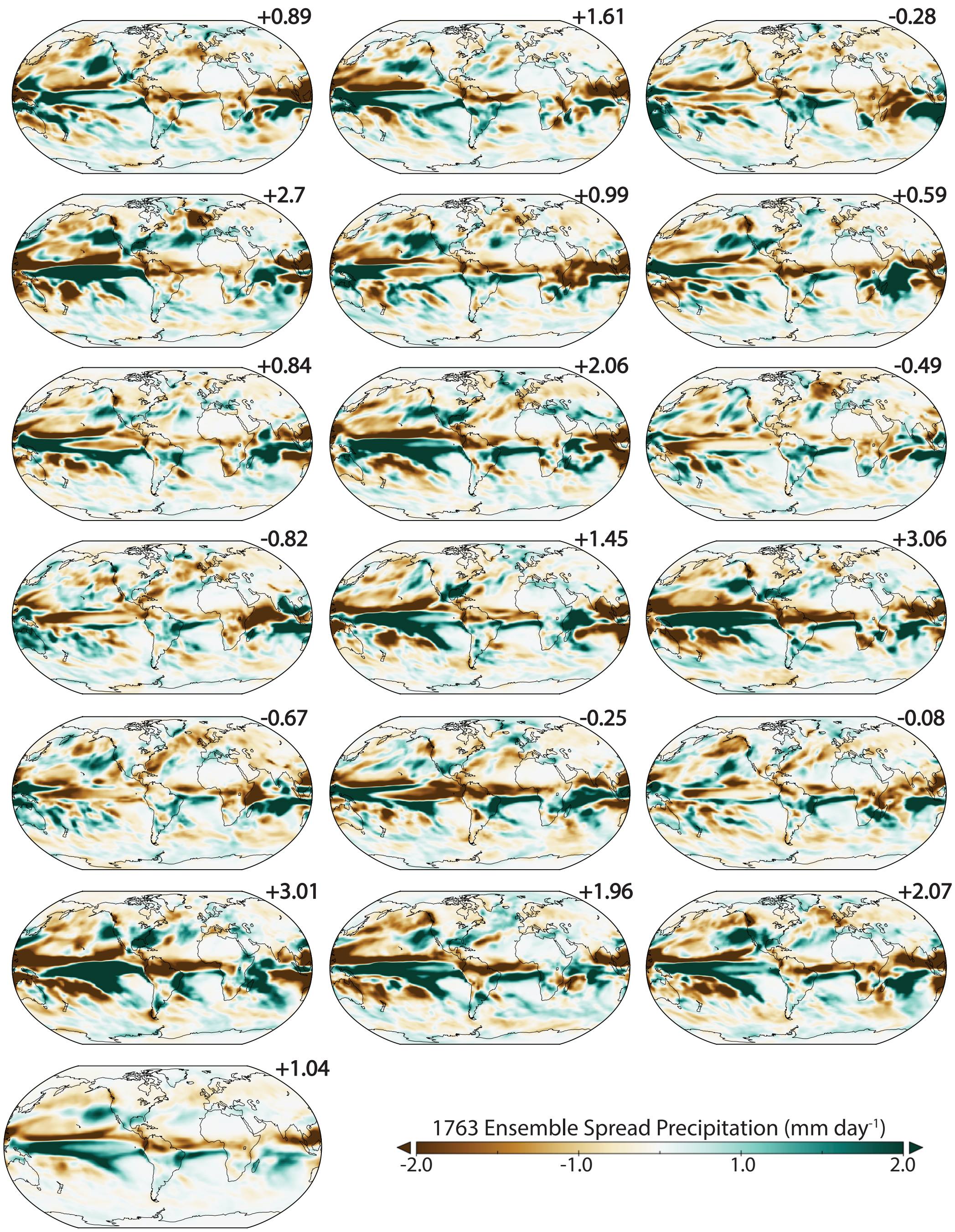

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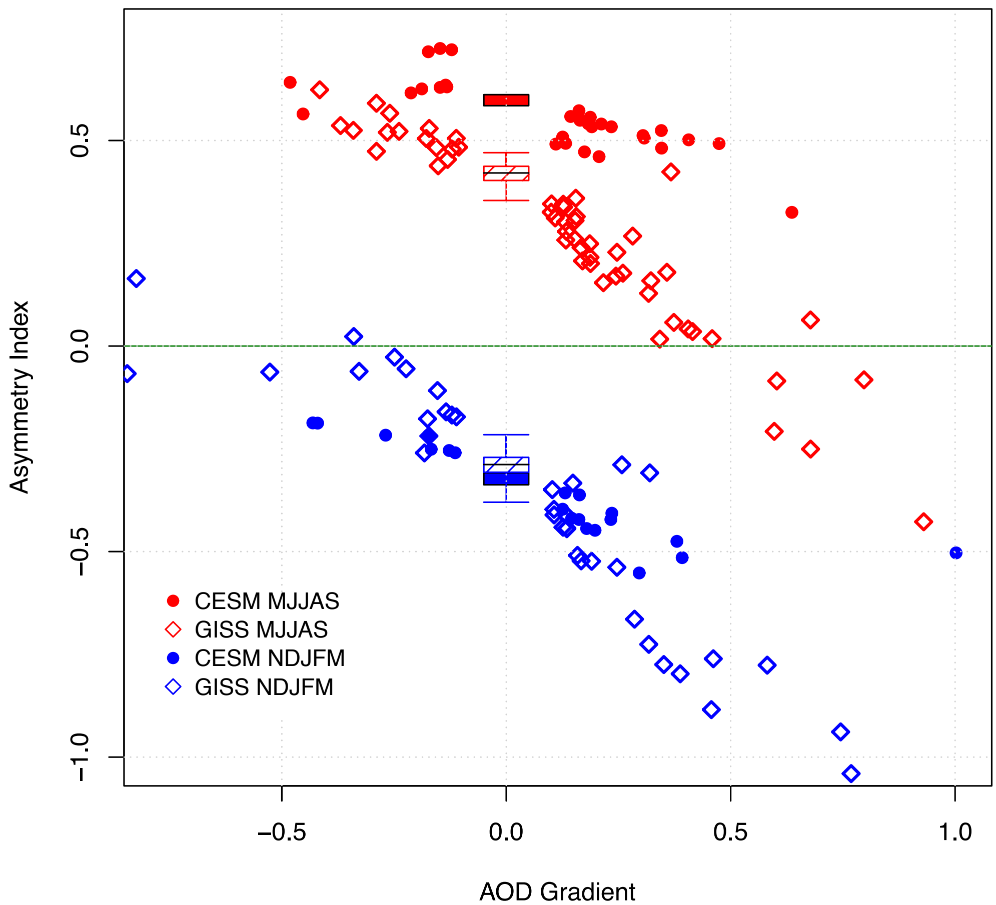

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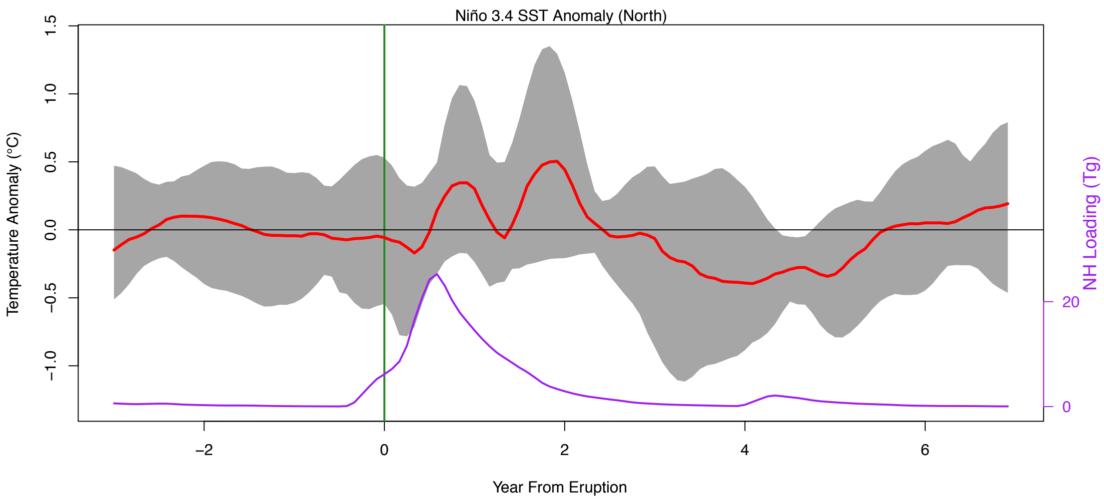
CESM LME uses the Parallel Ocean Program (POP2; Smith et al. 2010) as the ocean model component. This is where the sea surface temperature (SST) and sea surface height (SSH) diagnostics presented in Figure S6 and S7 are calculated. The model features 384 (latitude) x 320 (longitude) ocean grid points, with variable horizontal resolution that increases toward the tropics. There are 60 vertical levels, gradually increasing from 10 m resolution in the top 150 m to ~250 m below 3 km depth.

To perform a superposed epoch analysis for the state of the Pacific following all $ASYMM_{NH}$ events, the Niño 3.4 index is calculated for each ensemble member in CESM (averaging the SST from 120°W-170°W, 5°S-5°N) with the long-term annual cycle removed. "Year 0" corresponds to the January before each eruption. We only show results for $ASYMM_{NH}$, since no distinguishable behavior in the Niño 3.4 time series is exhibited for the other eruption classifications, as discussed in text. Months before Year 0 may feature a non-zero aerosol loading (as in Figure S6) due to the 8 Tg threshold for defining an eruption not being satisfied, or due to overlap with previous eruptions. Unlike the spatial composites discussed in the main text, pre-eruption months presented below are not replaced with the pre-eruption dates of previous overlapping eruptions. However, in the composite-mean, the aerosol loading is negligible for pre-eruption years, as well as after ~5 years after the composite eruption, and does not bias the results.

Figure S6 presents the Niño 3.4 time series averaged over all $ASYMM_{NH}$ eruptions and ensemble members. Grey shading corresponds to the eruption spread after averaging over the ensemble members. Since the CESM ENSO amplitude is large, even after averaging over 18 members, the pre-eruption envelope is still quite wide (individual events may be on the order of 5°C above normal). Averaging over fewer ensemble members would progressively increase the width of the envelope.



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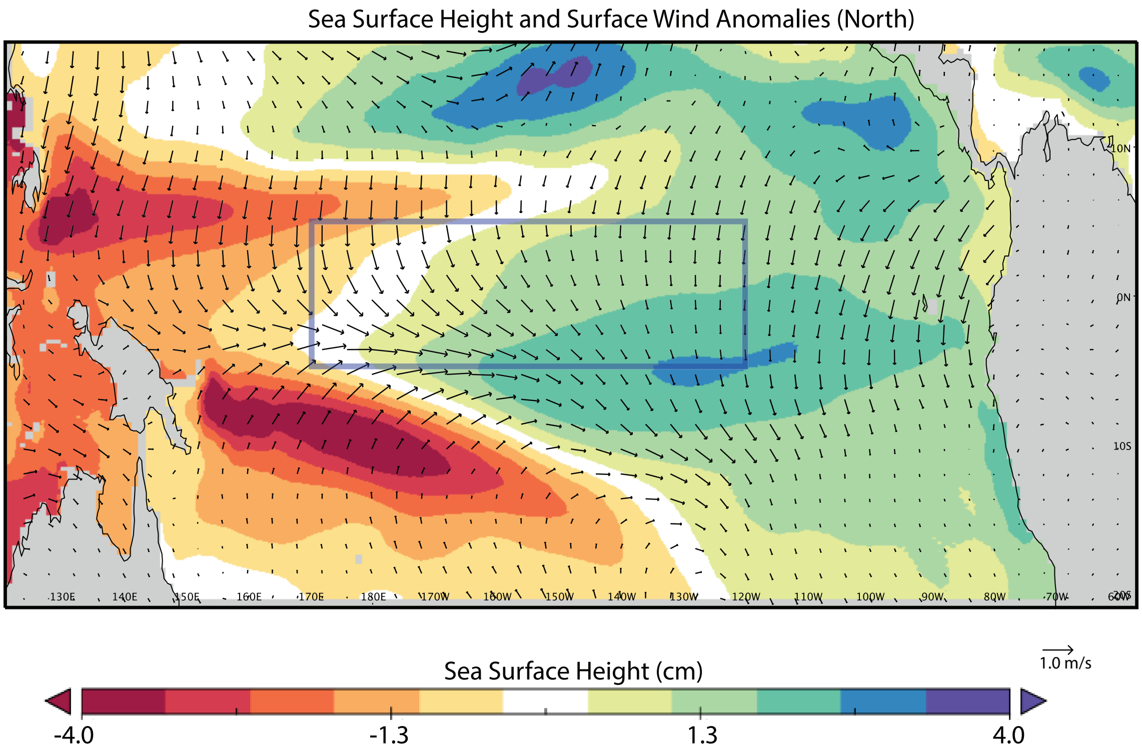

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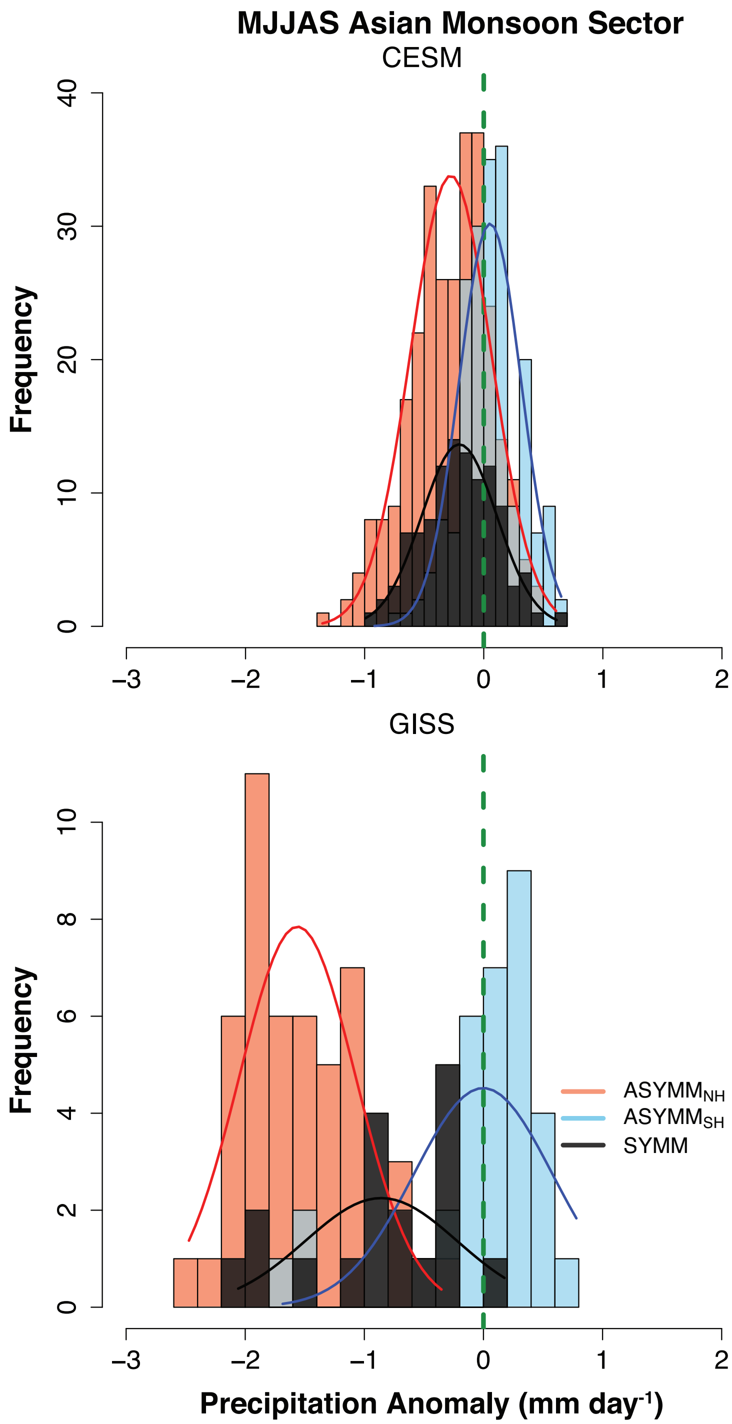

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In the animations below, monthly temperature and precipitation anomalies from CESM (for each event, using five years as a pre-eruption reference period) are shown in a loop from May of Year -2 to December of Year +6, where year 0 and month 1 corresponds to the January before each eruption, defined based on the same criteria as in main text. The animation shows the average anomaly field for all eruptions among 18 ensemble members, which suppresses the internal variability in pre-eruption months. There is still variability in the sequence of pre-eruption composites due to the finite number of realizations of natural variability, non-zero aerosol loading (only when the 8 Tg global aerosol loading is exceeded is an event aligned with Year 0), overlap with previous eruptions, in addition to non-volcanic radiative forcings that are still present in 13/18 of the ensemble members.

https://av.tib.eu/media/18569?48

Figure S9. Animation from May of Year -2 to December of Year +6 (as discussed in text) of monthly temperature anomalies (°C) associated with $ASYMM_{NH}$ volcanic forcing in CESM. For each time step, the global aerosol loading (in Tg) and hemispheric difference in loading (NH minus SH) are displayed. Months exceeding the 8 Tg global aerosol loading in the G08 dataset are displayed in red.

https://av.tib.eu/media/18571?16

Figure S10. As in Figure S9, except for $ASYMM_{SH.}$

https://av.tib.eu/media/18570?32

Figure S11. As in Figure S9, except for precipitation (mm/day).

https://av.tib.eu/media/18572?0

Figure S12. As in Figure S11, except for $ASYMM_{SH.}$

References

Smith, R. D., et al.: The Parallel Ocean Program (POP) reference manual, Ocean component of the Community Climate System Model (CCSM), Tech. Rep. LAUR-10-01853, 141 pp., Los Alamos Natl. Lab., Los Alamos, N. M., 2010.