Supplementary Information for

Disentangling the causes of the European year without a summer 1816

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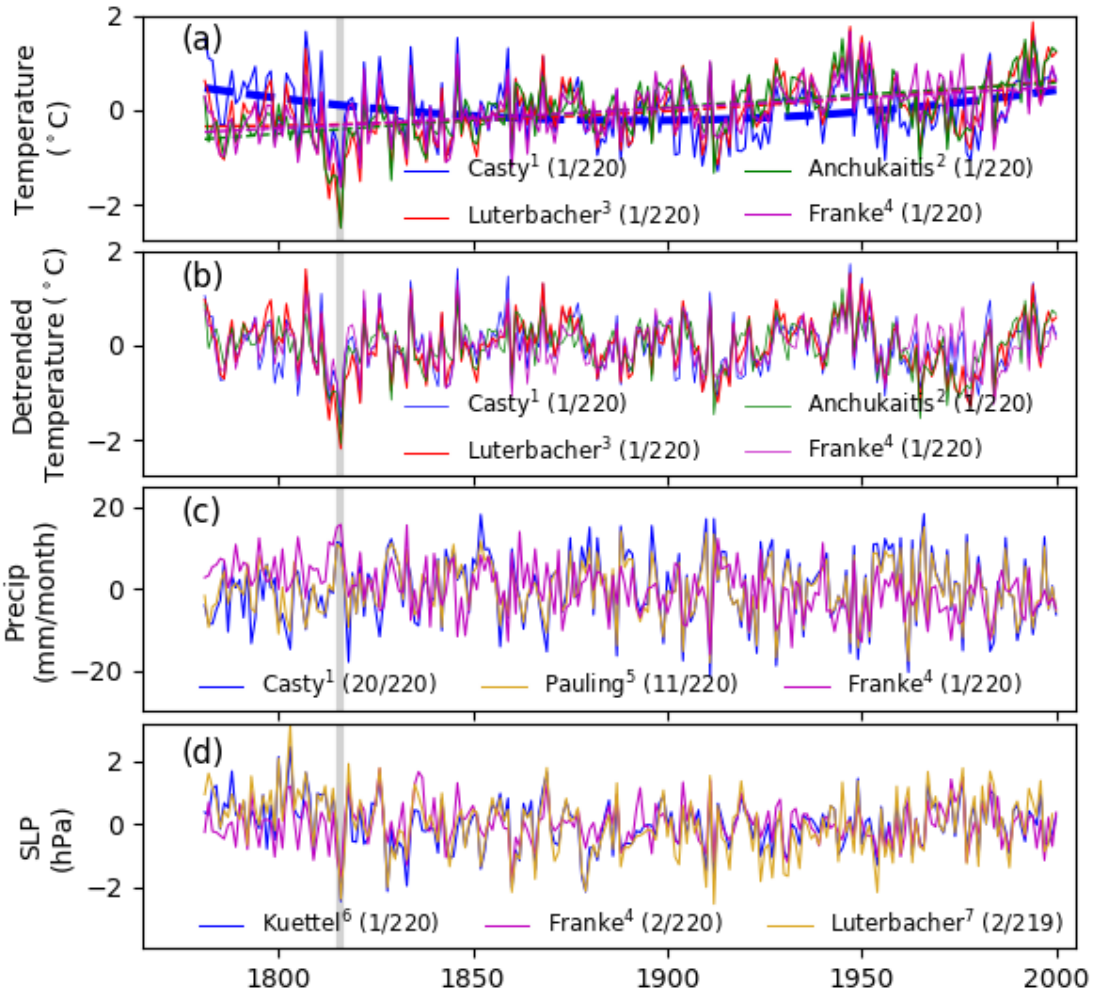
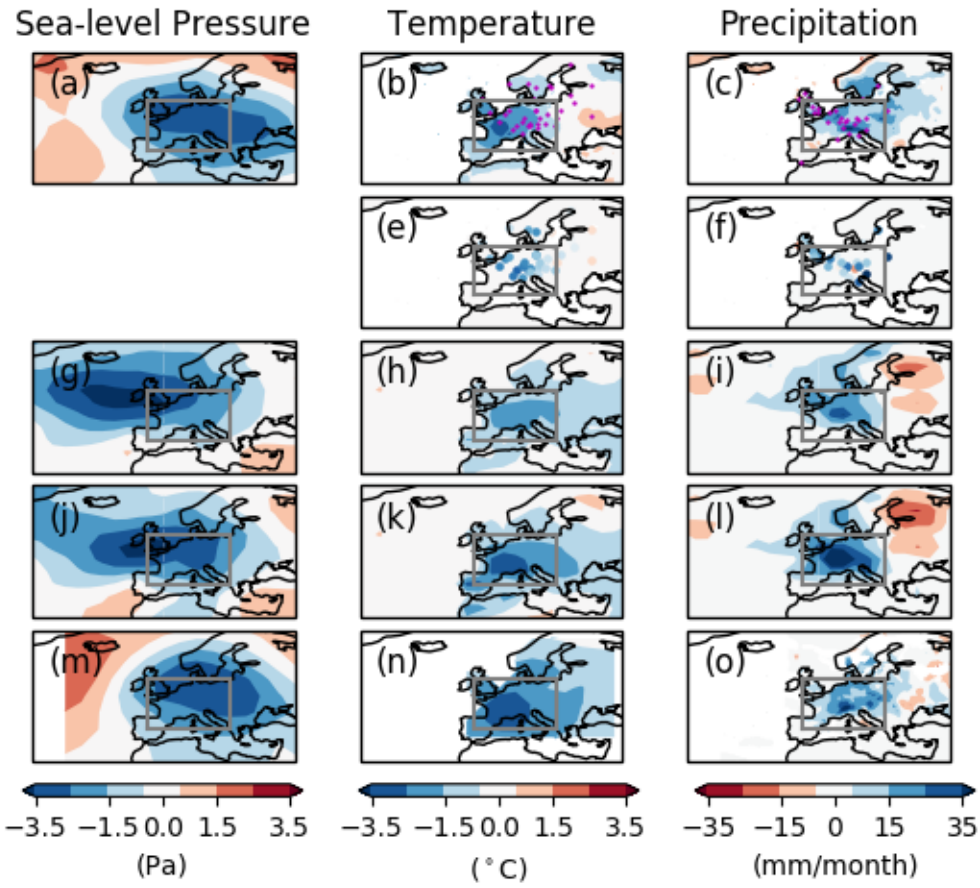
This supplementary information file contains:

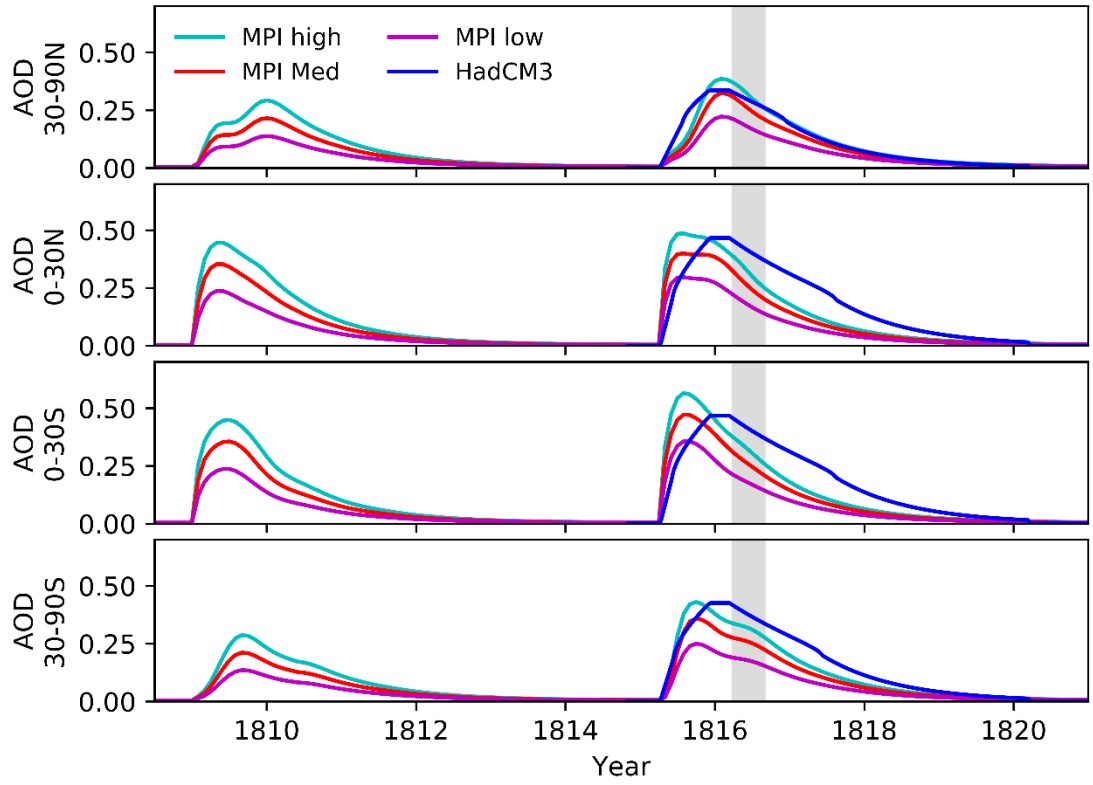
- **A comparison of the observational datasets used in the main article with alternative datasets.**
- **Details of the volcanic forcing used in each model experiment.**
- **Results for the individual models showing the sensitivity of the results shown in the main article to model and forcing.**
- **Further information about the HadCM3 simulation showing results from a wider geographical area than that shown in the main article.**
- **Root mean square values used to select the analogues shown in the main article.**
- **Spatial plots showing the patterns associated with the wettest summers.**
- **Spatial epoch analysis showing the response of temperature and precipitation in observations to other volcanic eruptions.**
- **Sensitivity studies showing the sensitivity to the choice of fitting the data with a Gaussian distribution.**



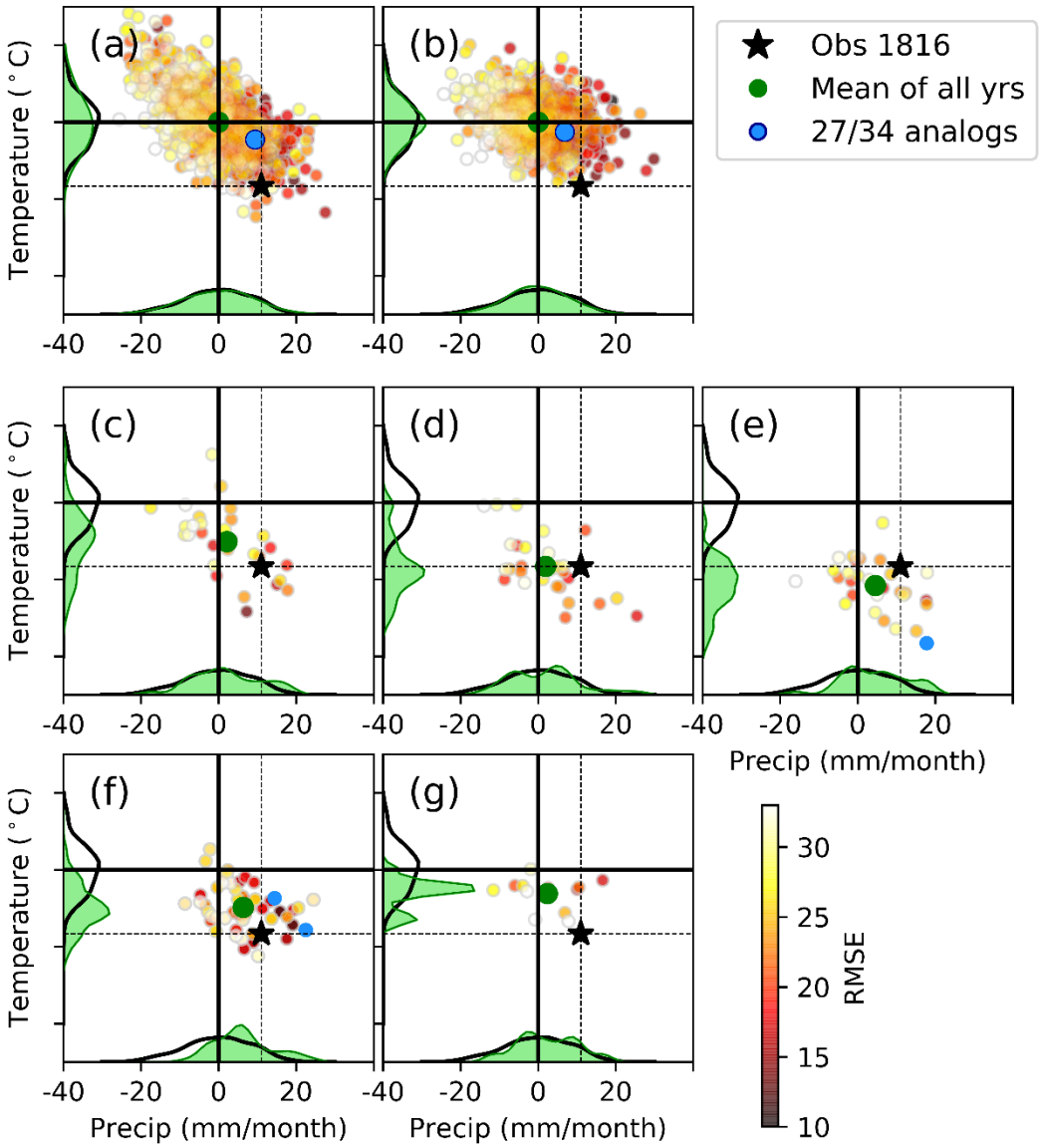
Supplementary figure 1 – Comparison of different datasets for surface air temperature, precipitation and sea level pressure for Central Europe Summer (JJA). *1816 is marked by the grey vertical line – and the ranking for the climate of this year is given in the legend. The dashed lines in (a) are second-order polynomials fits which are used to de-trend the raw observations in (b). Data are from Casty et al.[1], Anchukaitis et al.[2] , Luterbacher et al.[3] , Franke et al.[4] (reanalysis EKF400_v1), Pauling et al.[5], Kuettel et al.[6], Luterbacher et al.[7].*



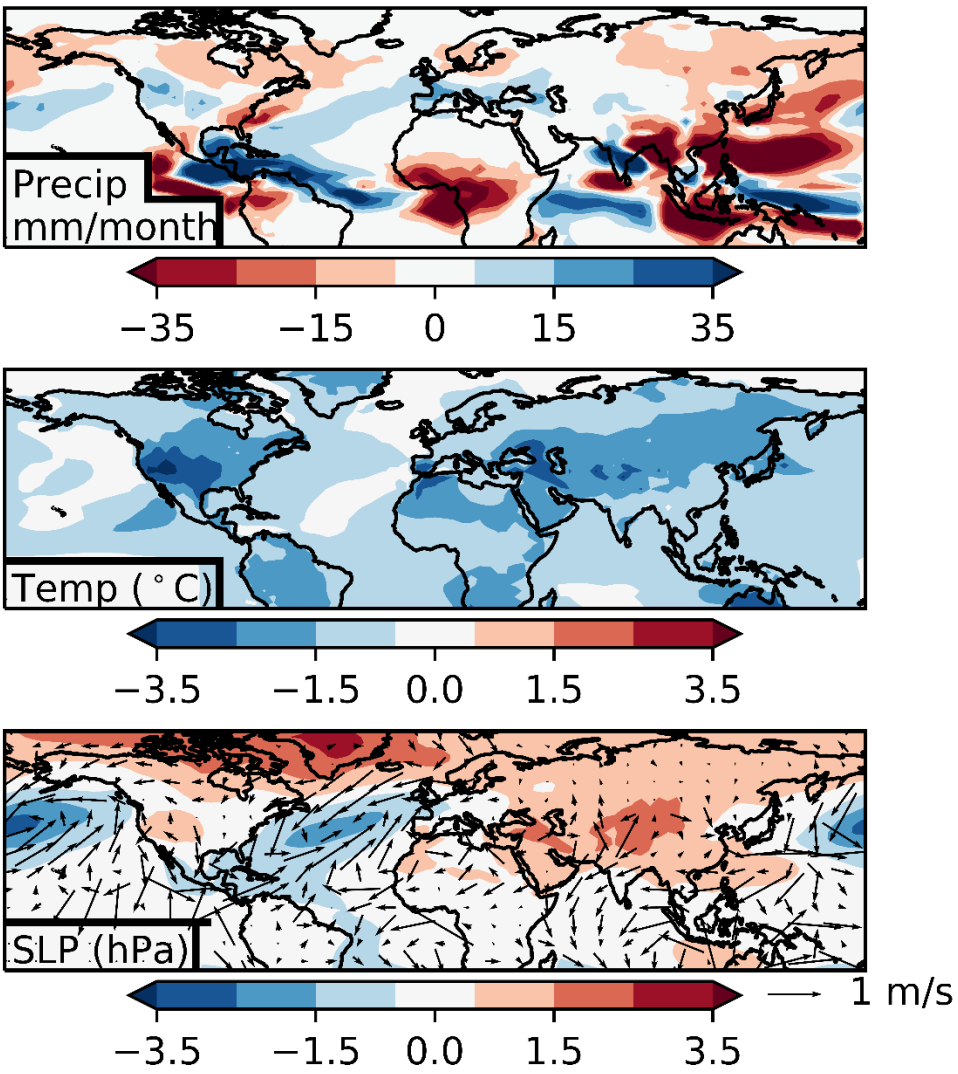
Supplementary figure 2 – Comparison of spatial anomaly patterns for summer 1816 from different datasets. *(a) Kuettel et al.*[6] *(b & c) Casty et al.*[1]*, purple dots show location of instrumental locations (e-f) Observed value at instrumental locations used in Casty et al.*[1] *(g-i) from Franke et al.*[4] *(reanalysis EKF400-v1), (j-l) from Franke et al.*[4] *(reanalysis EKF400-v1.1), (m) Luterbacher et al.*[7]*, (n) Luterbacher et al.*[3]*, (o) Pauling et al.*[5]*. For each variable all spatial reconstructions share common data so are not independent, except (n) which only uses proxy data so is independent of the other temperature datasets which rely on instrumental observations. Box shows the region for which means are calculated in Fig S1.*



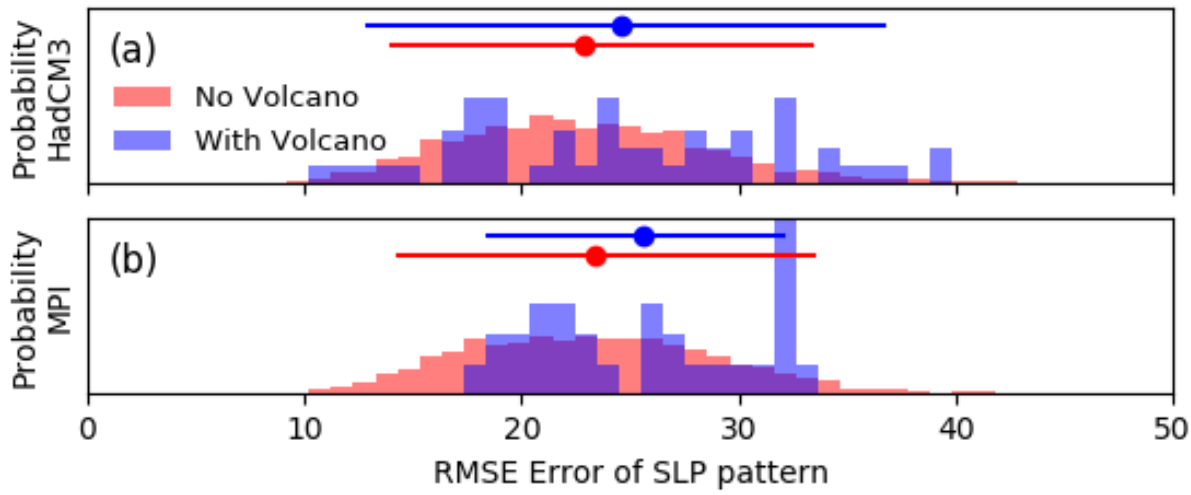
Supplementary figure 3 – Aerosol optical depth used in the model experiments *given as the zonal mean of four latitudinal bands. Note that the HadCM3 simulations start in December 1814 and start from a control simulation and therefore do not include the 1809 eruption.*



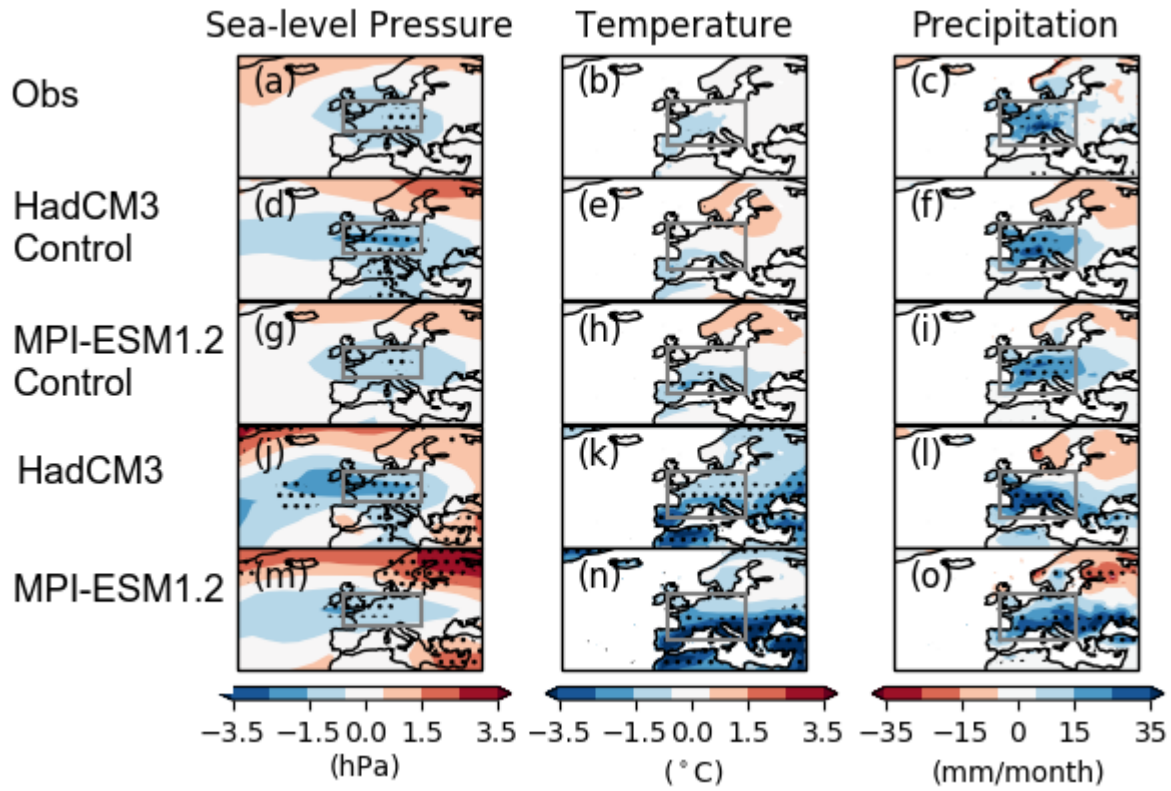
Supplementary figure 4 – Central summer climate in 1816 for different model experiments. *Similar figure to Fig. 3 but for (a) MPI-ESM1.2 piControl simulation, (b) HadCM3 piControl simulation, where the large blue circles are the mean of the first 27 and 34 analogues respectively. (c) MPI-ESM1.2 simulations using weak Tambora forcing, (d) MPI-ESM1.2 simulations using medium Tambora forcing, (e) MPI-ESM1.2 simulations using strong Tambora forcing, (f) HadCM3 (g) CESM (from the Last Millennium Ensemble[8]). The large green circle are the mean of all years. Blue circles are analogues which pass the criteria used to select the 2 analogues in figure 3c. Colour of smaller circles dependent on closeness of observations and simulations to observed SLP pattern determined by RMSE. Black star and black dashed lines – actual observed values in the summer of 1816. Distributions on x and y-axis show observation/model spread where the black distribution in all panels shows observation spread, green shading shows the spread of results in each panel.*



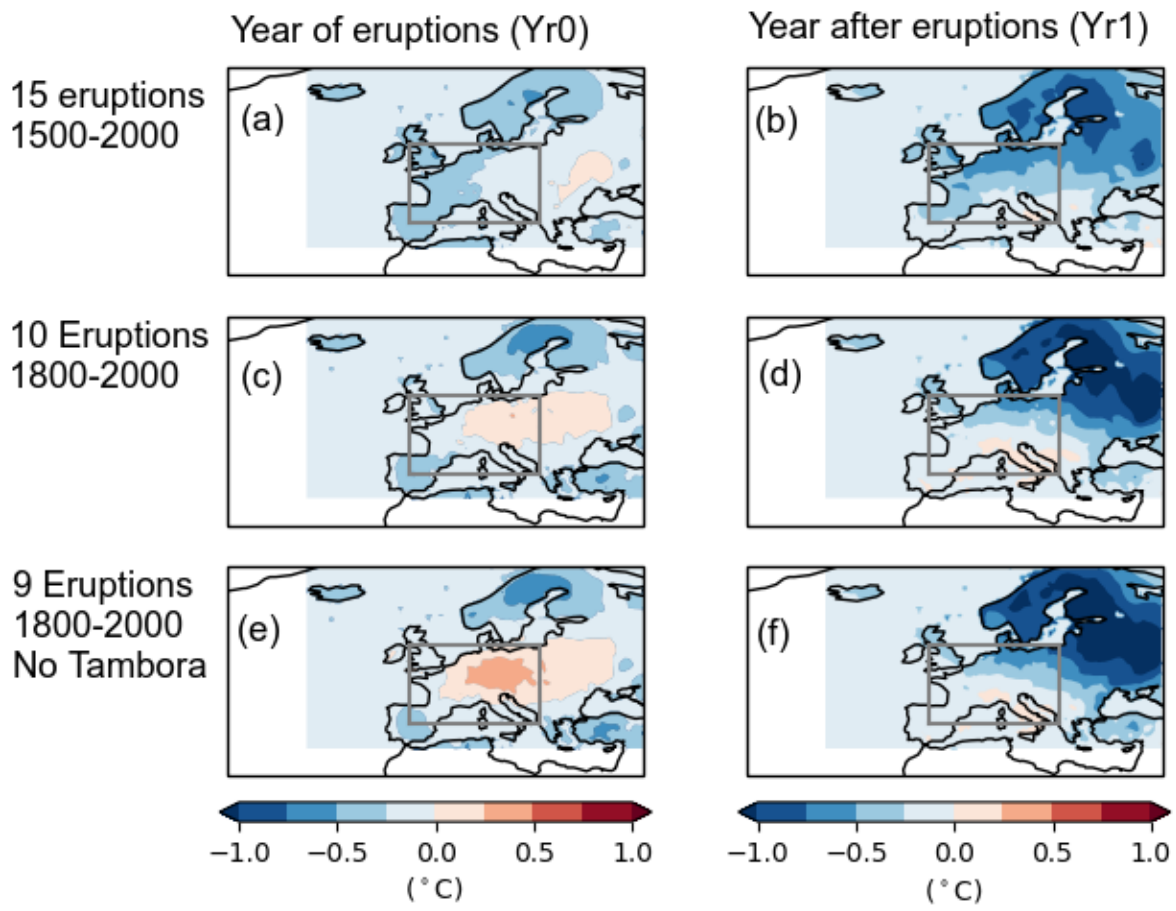
Supplementary figure 5 – HadCM3 ensemble mean for summer of 1816 for models which include the Tambora eruption. *Results show the mean of 50 ensemble members. The arrows in the lower panel indicate surface wind direction and strength. Anomalies are calculated relative to the mean of the piControl simulation.*



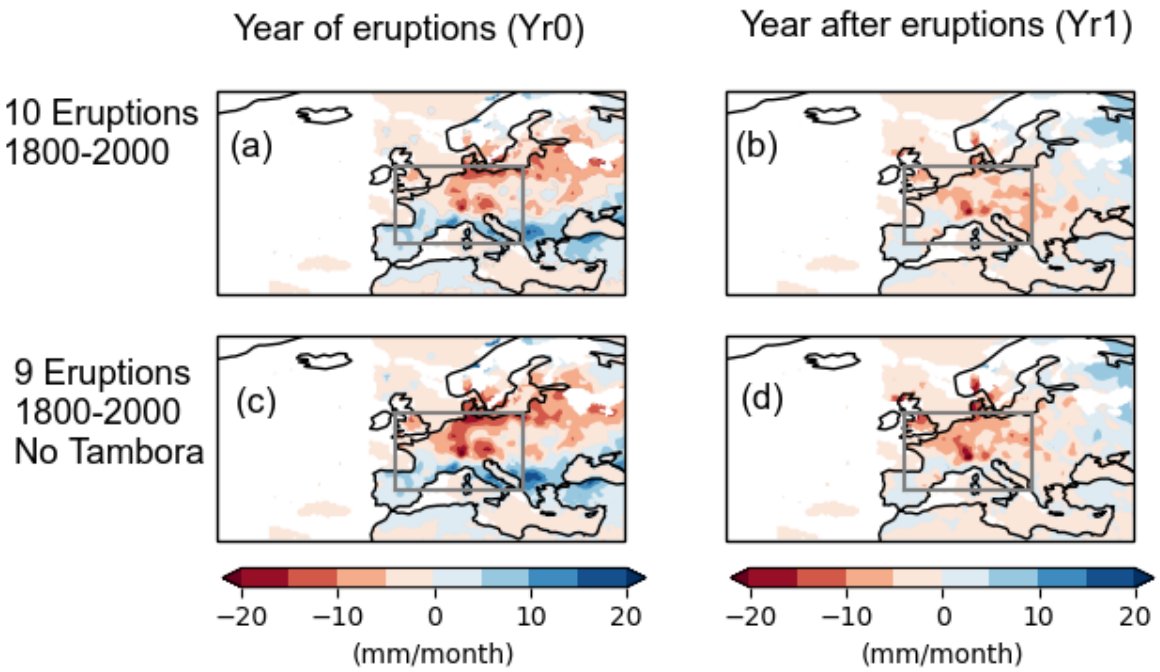
Supplementary Figure 6 – RMSE error *for control simulations (red) and forced simulations with Tambora (blue) from (a) HadCM3, (b) MPI-ESM1.2. Horizontal bar shows the mean and 5-95% range of the distribution.*



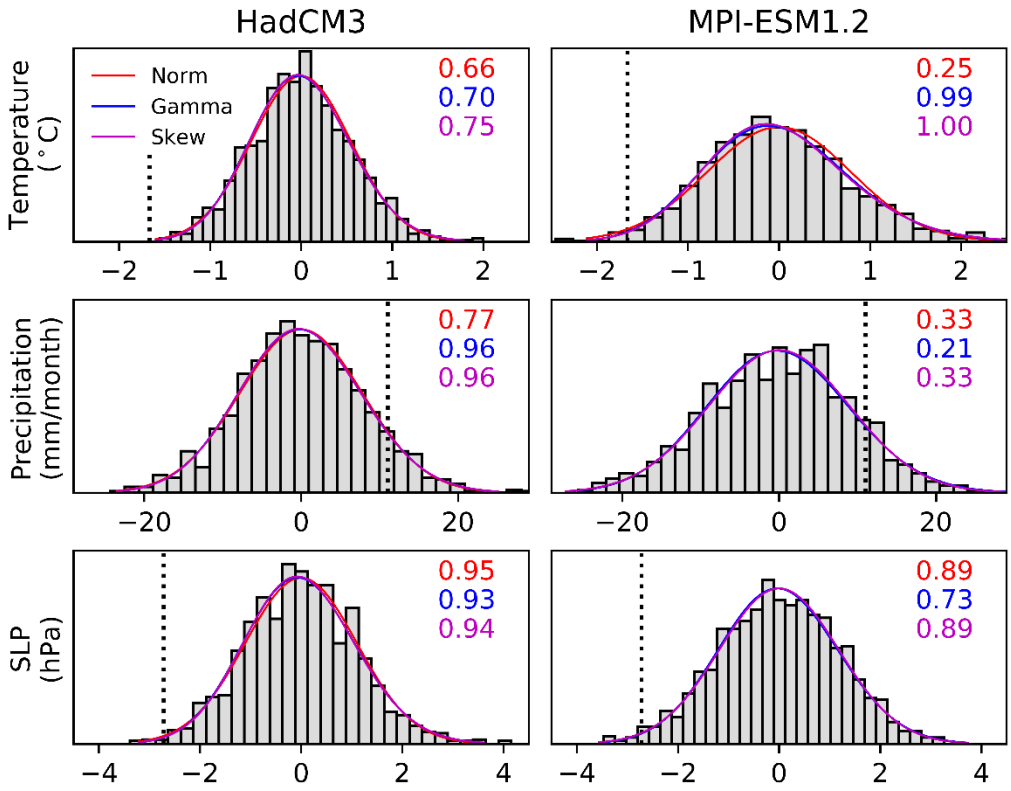
Supplementary figure 7 – Spatial anomaly patterns of wet years with Central European precipitation defined as those exceeding that observed in summer 1816. *(a-c) Mean patterns for all wet years in observations. (d-f) All wet years in HadCM3 control simulations. (g-i) All wet years in MPI-ESM1.2 control simulations. (j-l) All wet years in HadCM3 simulations with Tambora. (g-i) All wet years in MPI-ESM1.2 simulations with Tambora. The key region is identified as the box in the left panels (latitude 45° to 55°N; longitude 5°W to 20°E), and this is the region which the SLP return times is calculated over.*



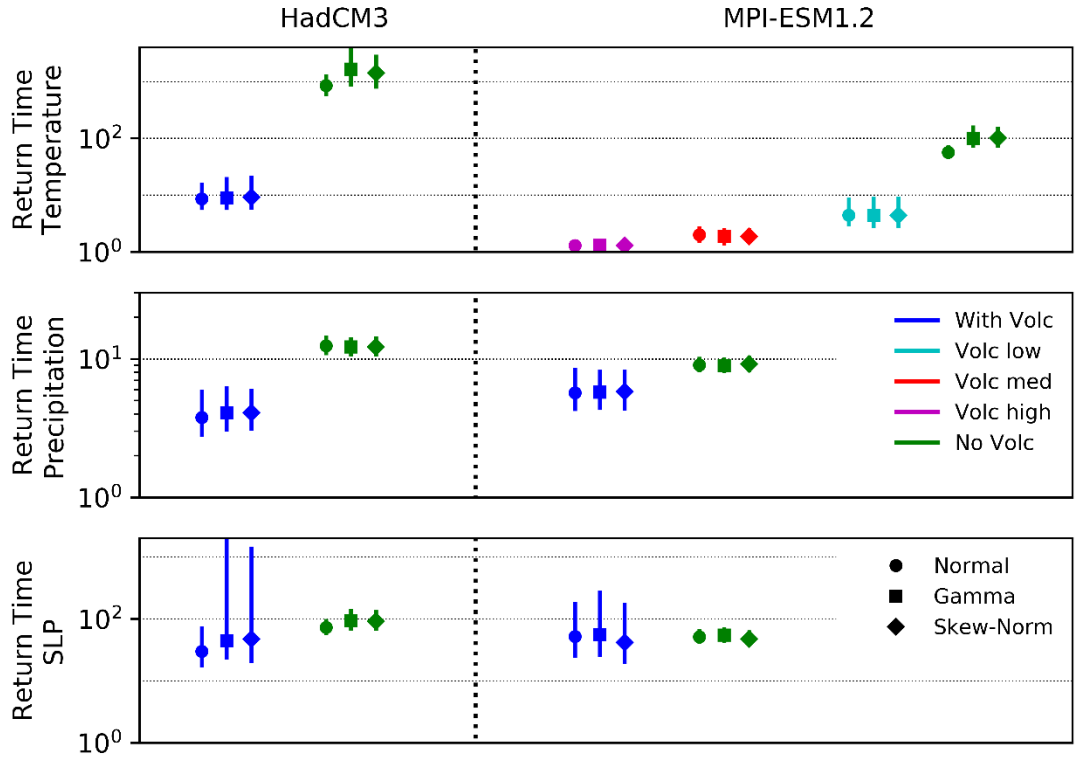
Supplementary figure 8. Epoch analysis of summer temperature after tropical eruptions. *Panels show mean temperature anomalies following volcanic eruptions relative to proceeding 5 years. The methodology is that of ref 9, with timings of eruptions taken from this publication. The figure highlights the sensitivity to the number of eruptions chosen which explains the discrepancy between the large post-volcanic cooling shown in ref 9 (which is identical to panels a and b) and the blue dots in our Fig. 1, which display only a slight cooling and use the eruptions shown in panels e and f. As in ref 7 data is taken from Luterbacher et al.[10].*



Supplementary figure 9. Epoch analysis of summer precipitation after tropical eruptions. *Panels show mean precipitation anomalies following volcanic eruptions relative to proceeding 5 years. The methodology is that of ref 9, with timings of eruptions taken from this publication. As in ref 7 data is taken from Pauling et al.*[5].



Supplementary figure 10 – Distributions fitted to the piControl data for the two models used. *Three distributions: normal (which is used in the main paper), gamma and skew-normal are shown. The p-value of the fit, given by a Kolmogorov–Smirnov test, is given for each distribution in the top right corner, smaller values indicate a worse fit. No distribution can be rejected with any great confidence.*



Supplementary figure 11 –Return values calculated using three different distributions to fit the model data. *The results using the normal distribution are those shown in figure 4 and table 1.*

References

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