



Supplement of

Using reduced-complexity volcanic aerosol and climate models to produce large ensemble simulations of Holocene temperature

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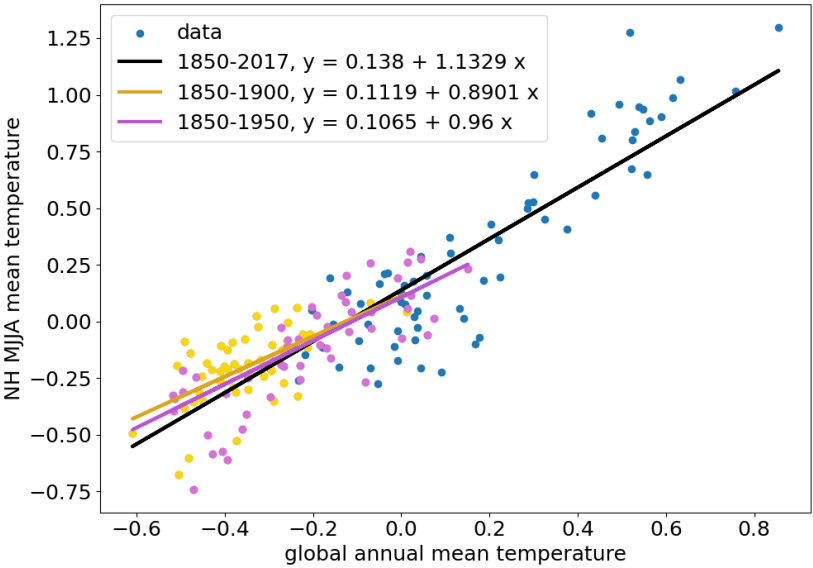
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Table S1: List of SO₂ injections for which we used an eruption match. Matches are determined by geochemical identification of cryptotephra in the ice cores or the coincidence of a known eruption and an ice core signal. Isopleth heights are corrected following Aubry et al. (2023).

Volcano	Eruption date	Ice Core date	VEI	S mass (Tg of S)	Match method	Same match as eVol _v 2k /HoI _{Vol}	Latitude (°N)	Injection height (km)	Method and reference
Okataina	1886	1886	5	0.74	Coincidence	Yes	-38.12	24	Isopleth, Carey & Sigurdsson (1989)
Krakatau	1883	1883	6	9.3	Coincidence	Yes	-6.1	35	Observations, Self & Rampino (1981)
Askja	1875	1875	5	0.67	Coincidence	Yes	65.03	23	Isopleth, Carey et al. (2010)
Kie Besi	1861	1861	4	4.5	Coincidence	Yes	0.32		
Hokkaido-Komagatake	1856	1856	4	1.3	Coincidence	Yes	42.06		
Toya	1853	1853	4	1.4	Coincidence	Yes	42.54		
Hekla	1845	1846	4	0.97	Coincidence	No	63.98	19	Isopleth, Guðnason (2017)
Cosiguina	1835	1835	5	9.5	Coincidence	Yes	12.98	24	Isopleth, Self et al. (1989)
Galunggung	1822	1822	5	2.0	Coincidence	Yes	-7.25		
Tambora	1815	1815	7	28	Coincidence	Yes	-8.25	30	Isopleth, Sigurdsson & Carey (1989)
Grimsvotn	1783	1783	4	21	Geochemical	Yes	64.4	9-18	Scaled on the observed height of phase 6, Thordarson & Self (2003)
Hekla	1766	1766	4	2.5	Coincidence	Yes	63.98	12	Isopleth, Janebo et al. (2018)
Kie Besi	1760	1762	4	4.8	Coincidence	No	0.32		
Katla	1755	1755	5	1.2	Coincidence	Yes	63.63	16	Derived from total mass, Schmith (2017)
Huaynaputina	1600	1601	6	19	Geochemical	Yes	-16.61	26	Isopleth, Prival et al. (2019)
Bardarbunga	1477	1477	6	5.1	Geochemical	Yes	64.63	14	Isopleth, Larsen (2005)
Samalas	1257	1258	7	59	Geochemical	Yes	-8.42	29	Isopleth, Vidal et al. (2015)
Changbaishan	946	946	7	1.7	Geochemical	Yes	41.98	25	Isopleth, Wei et al. (2003)
Eldgja	939 ± 1	939	4	16	Geochemical	Yes	63.63	12.5	Isopleth, Moreland (2017)
Bardarbunga	877 ± 1	879	4	3.0	Geochemical	Yes	64.63		
Churchill	853 ± 1	853	6	2.5	Geochemical	Yes	61.38	31.5	Isopleth, Lerbekmo (2008)
Katla	823	822		3.9	Geochemical	No	63.63		
Illopongo	432 ± 2	433	6	14	Geochemical	No	13.67	45	Machine learning simulation of tephra

									deposit, Smith et al. (2020)
Taupo	232 ± 10	236	6	5.8	Geochemical	Yes	-38.82	22	Isopleth, Houghton et al. (2014)
Okmok II	-43	-43	6	48	Geochemical	No	53.43		
Aniakchak II	-1628	-1628	6	52	Geochemical	Yes	56.88		
Mazama	-5624 ± 35	-5624	7	162	Geochemical	Yes	42.93	35	Inversion of tephra deposit using tephra2, Buckland et al. (2022)
Khangar	-5922 ± 41	-5923	6	30	Geochemical	No	54.76		

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10 **Figure S1: conversion global annual mean temperature to NH ET MJJA temperature using linear regression over the Cowtan and Way dataset; in gold 1850-1900 datapoints, pink 1900-1950 datapoints and blue 1950-2017 datapoints.**

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Table S2: regression slopes for volcanic and non-volcanic years for different models from Marshall et al., 2025

Models	Slope for volcanic years	Slope for non-volcanic years
UKESM1	1.654	1.237
CESM2(WACCM6ma)	1.544	1.418
MRI-ESM2	1.190	1.046
MPI-ESM1-2-LR	1.397	0.999
MIROC-ES2L	1.722	1.137
IPSL-CM6A-LR	1.244	1.524
Mean	1.459	1.227

Table S3: Temperature difference between the Medieval Climate Anomaly and the Little Ice Age for different start and end dates, unless specified, the temperature is the global mean surface temperature.

Temperature timeseries		[950-1250] – [1450-1850]	[900-1200] – [1250-1850]	[950-1150] – [1350-1750]
Global annual mean temperature	Simulations (LU = KK10)	0.14 ± 0.05	0.11 ± 0.04	0.12 ± 0.04
	Simulations (LU = HYDE 3.2)	0.05 ± 0.03	0.03 ± 0.03	0.05 ± 0.03
	Simulations (LU = HYDE 3.3)	0.10 ± 0.04	0.09 ± 0.04	0.10 ± 0.04
	PAGES 2k	0.16 ± 0.12	0.16 ± 0.11	0.14 ± 0.12
	LGMR	–	–	0.15 ± 0.19
	Holocene data assimilation	0.011 ± 0.007	0.015 ± 0.005	0.015 ± 0.005
	Van Dijk et al. (2024) simulation	0.09	0.07	0.06
	Lücke et al. (2023) simulations	0.12 ± 0.08	0.09 ± 0.06	0.09 ± 0.07
NH ET MJJA temperature	Simulations (LU = KK10)	0.18 ± 0.06	0.14 ± 0.06	0.15 ± 0.06
	Simulations (LU = HYDE 3.2)	0.07 ± 0.04	0.04 ± 0.04	0.04 ± 0.05
	Simulations (LU = HYDE 3.3)	0.13 ± 0.06	0.12 ± 0.05	0.11 ± 0.05
	King et al	0.23 ± 0.02	0.19 ± 0.04	0.15 ± 0.03
	Schneider 2015	0.04	0.00	-0.03
	Guillet 2017	0.20	0.10	0.10
	Büntgen 2021	0.15	0.15	0.14
	NTREND 2015	0.32	0.30	0.25
	Van Dijk et al. (2024) simulation	0.10	0.08	0.10
	Lücke et al. (2023) land only	0.11 ± 0.08	0.07 ± 0.06	0.08 ± 0.07

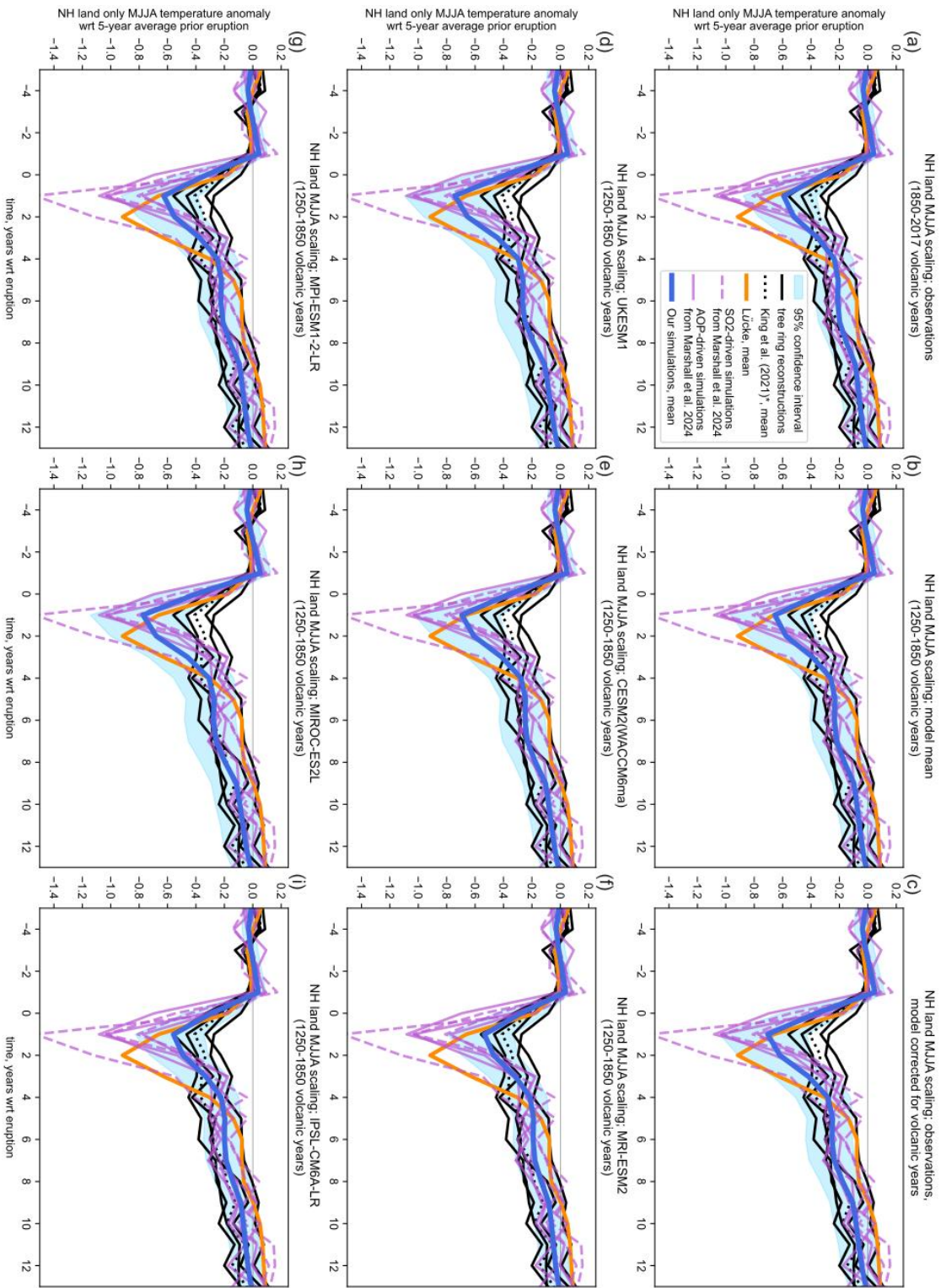


Figure S2: SEA for different scaling factors used to convert our simulated GMST into a NH MJJA land only temperature. a) our simulations are scaled using a scaling factor determined by linear regression over 1850-2017 observations from Cowtan and Way (2014); b) using a scaling factor corresponding to the mean slope for volcanic years over six ESM simulations for 1250-1850 from Marshall et al. (2025); c) using the scaling factor from Cowtan and Way, multiplied by 1.19, which is the model-mean ratio between the factor derived from volcanic years and from non-volcanic years, where we used again the Marshall et al. 2025) model simulations; d-i) using a scaling factor determined by linear regression over the volcanic years for each model (summarized in table S2).

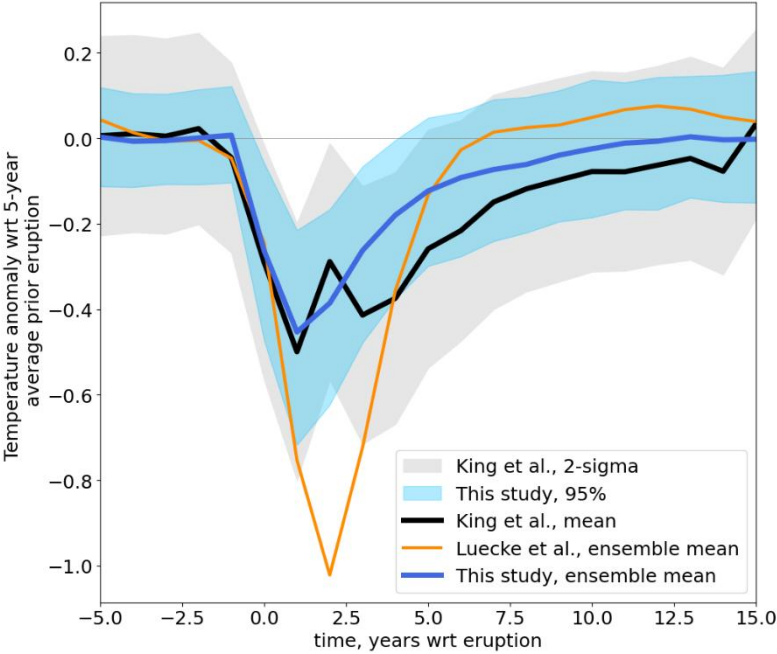


Figure S3: Superposed Epoch Analysis excluding clustered eruptions (eruptions considered: 939, 1108, 1230, 1345, 1600, 1640, 1695, 1783, 1883)

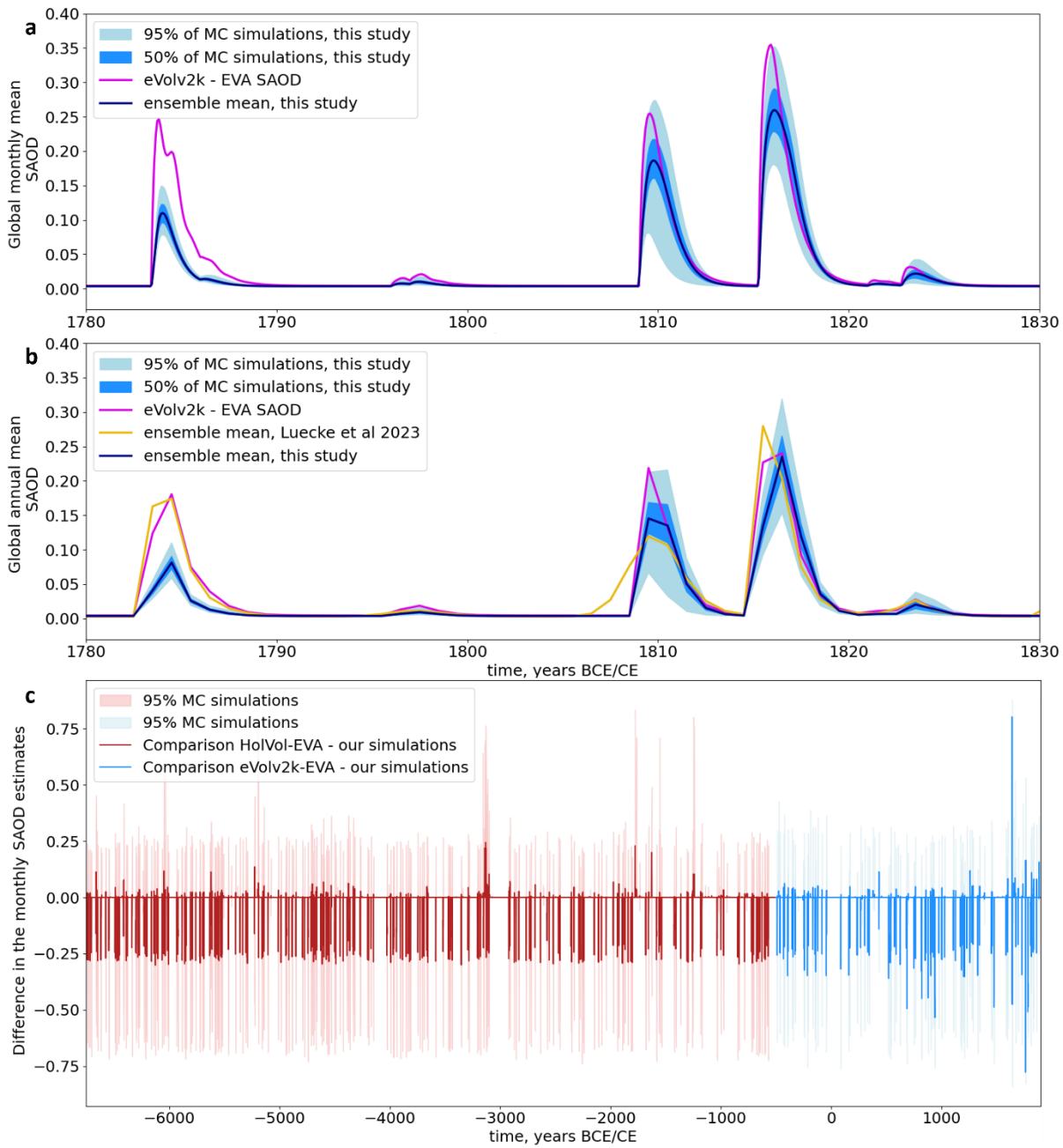


Figure S4: a. Global monthly mean SAOD for the period 1780 – 1830 CE modelled using eVolv2k and EVA (Toohey and Sigl 2017) in purple, or eVolv2k and EVA_H (this study, in blue); b. Global annual mean SAOD modelled using eVolv2k and EVA (Toohey and Sigl (2017) in purple and Lücke et al. (2023) in yellow) or eVolv2k and EVA_H (this study, in blue); c. Relative difference between our simulations using EVA_H and other simulations using EVA (Sigl et al. (2022) in red, Toohey and Sigl (2017) in blue)

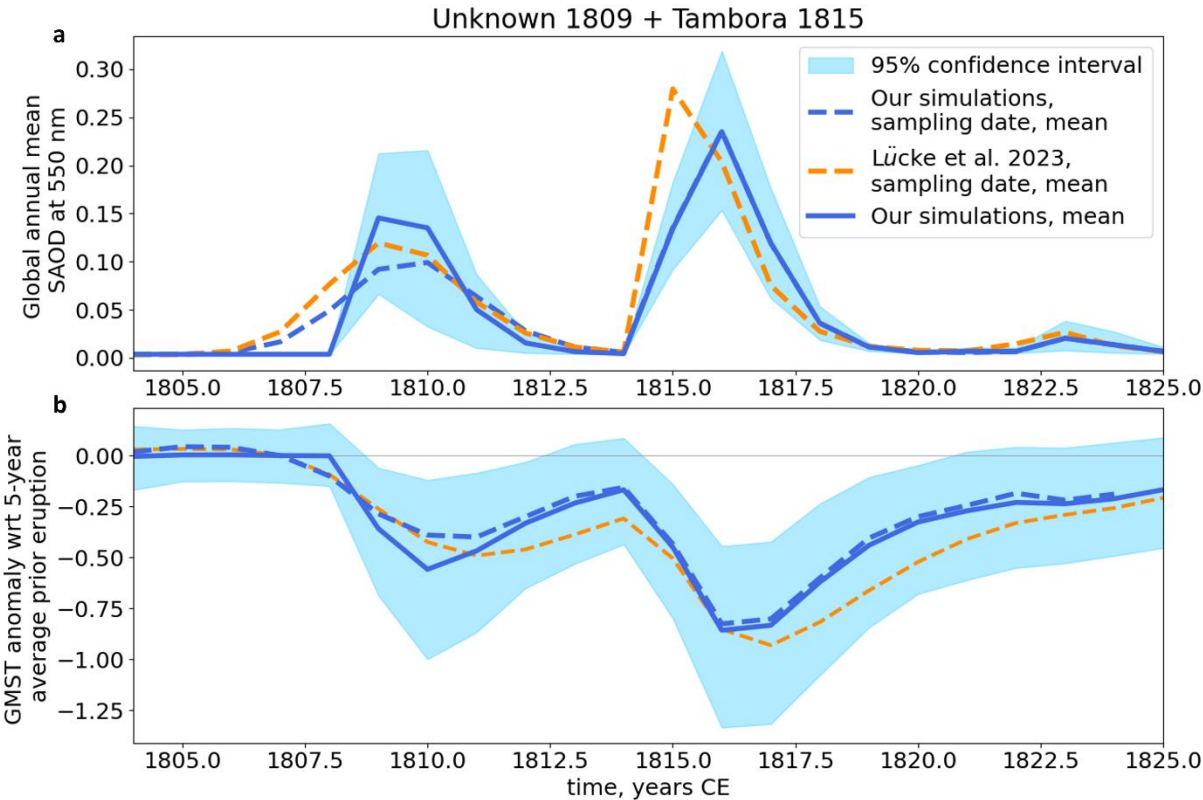
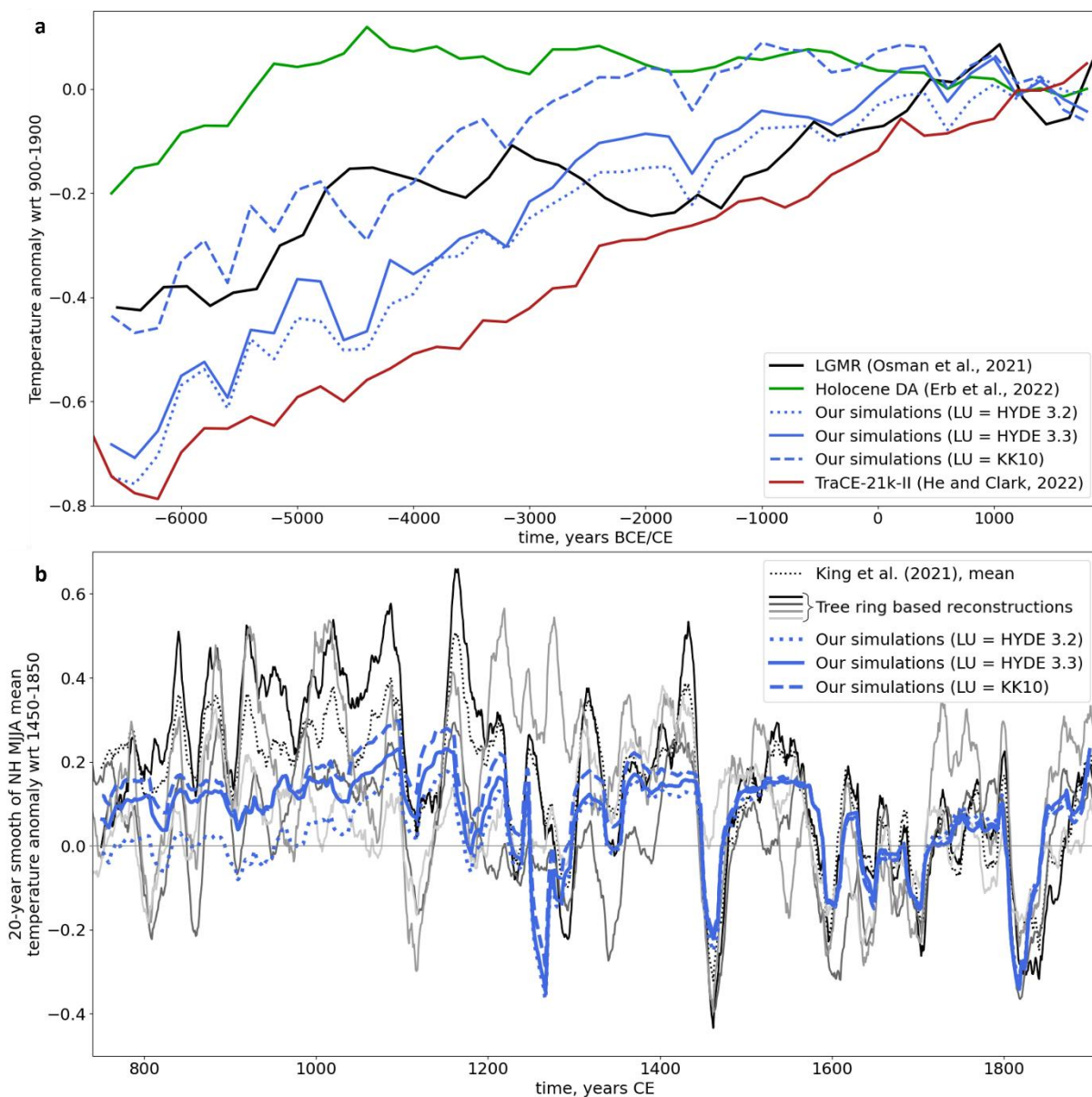


Figure S5: a. Comparison of our simulated global annual mean SAOD for 1809 and Tambora 1815 eruptions when sampling the eruption date for unknown eruptions (dashed line) or not (solid line) and simulations from Lücke et al. (2023); **b.** corresponding GMST responses.



50 **Figure S6: a. Comparison of the Last Glacial Maximum Reanalysis with our simulations for different land-use forcing; b. Comparison of the tree ring-based reconstruction with our simulations for three different land-use forcing, with a 20-year smoothing.**

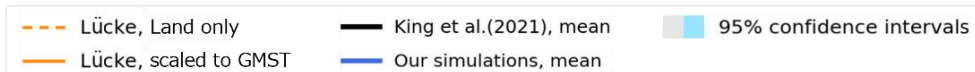
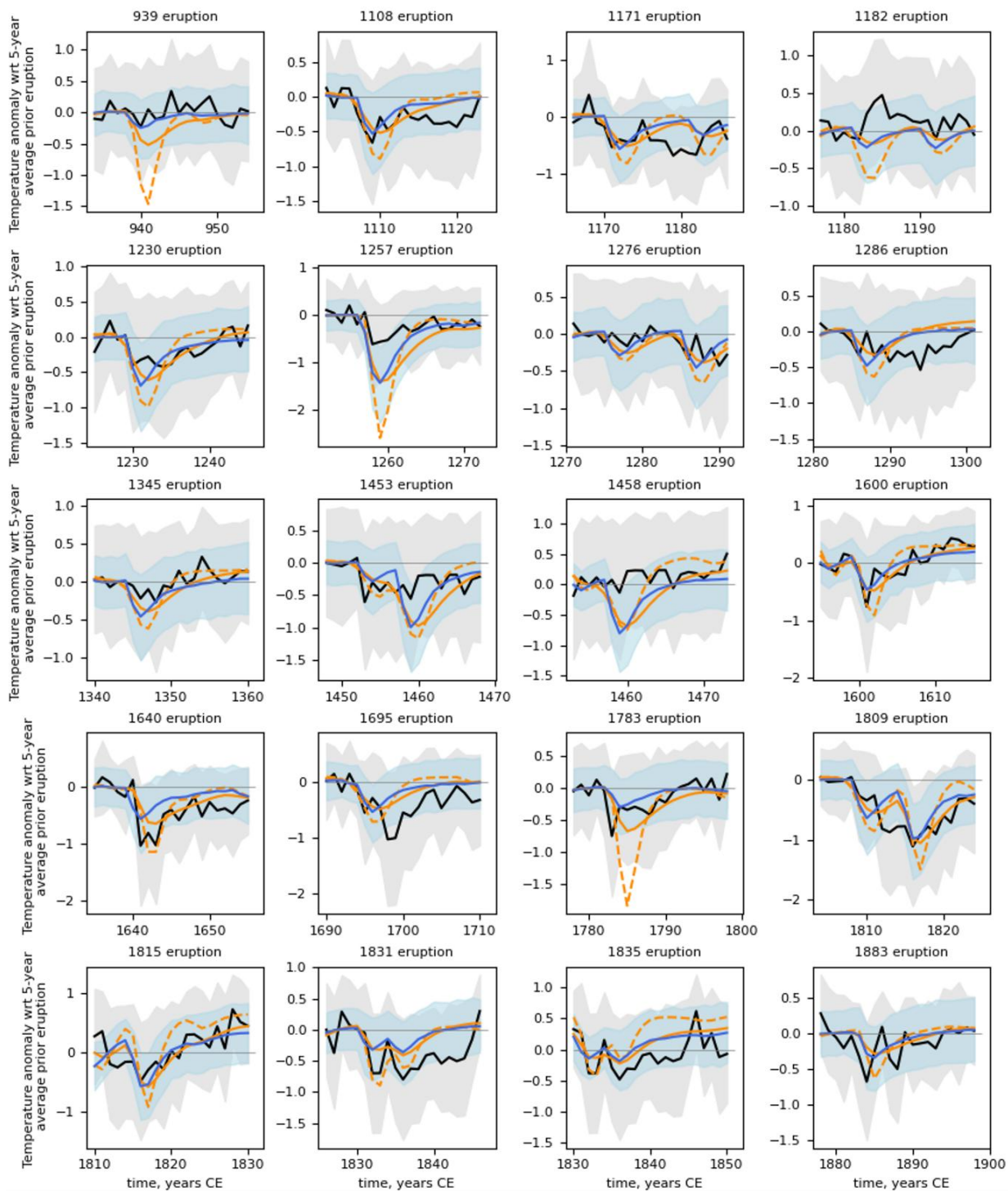
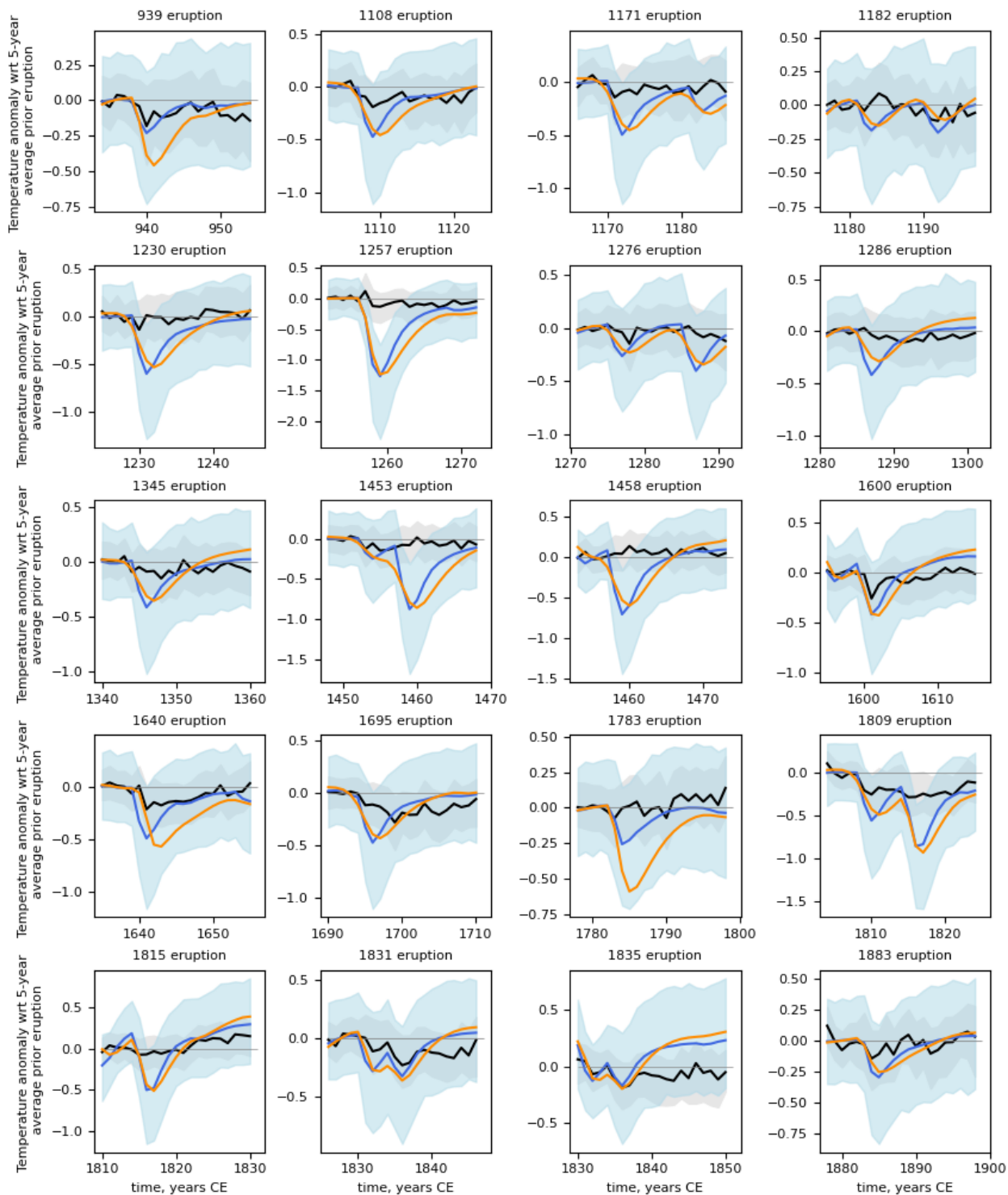


Figure S7: Comparison NH MJJA temperature simulated in this study, in Lücke et al. for land only temperature (dashed) and scaled from GMST (solid line), and reconstructed in King et al., for the 20 largest eruptions between 885 and 1900 CE.



65 **Figure S8: Comparison GMST simulated in this study (blue line and light blue confidence interval), in Lücke et al. (orange line), and reconstructed in PAGES 2k (Black line and grey confidence interval), for the 20 largest eruptions between 885 and 1900 CE.**

70 **Table S4: Integrated response of the superposed epoch analysis (Fig.7.d) *Note that King 2021 corresponds to land and sea mean temperature, whereas other reconstruction are land only.**

Temperature timeseries	Interval after eruption			
	0-3 years	0-5 years	0-10 years	0-15 years
NTREND 2015	-0.26 K	-0.32 K	-0.32 K	-0.27 K
Schneider 2015	-0.18 K	-0.18 K	-0.12 K	-0.06 K
Guillet 2017	-0.31 K	-0.33 K	-0.28 K	-0.20 K
Büntgen 2021	-0.15 K	-0.20 K	-0.23 K	-0.20 K
King 2021 *	-0.23 K	-0.21 K	-0.26 K	-0.21 K
Our simulations	-0.34 ± 0.08 K	-0.35 ± 0.08 K	-0.27 ± 0.07 K	0.20 ± 0.06 K
Marshall et al., 2025 AOP driven	-0.49 K	-0.43 K	-0.32 K	-0.23 K
Marshall et al., 2025 SO2 emission driven	-0.55 K	-0.49 K	-0.31 K	-0.20 K
Lücke et al., 2023	-0.40 ± 0.04 K	-0.49 ± 0.03 K	-0.29 ± 0.03 K	0.17 ± 0.02 K

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