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Systemic swings in end-Permian climate from Siberian Traps carbon and sulfur outgassing

Benjamin A. Black[1], Ryan R. Neely[2,3,4], Jean-François Lamarque[3], Linda Elkins-Tanton[5], Jeffrey T. Kiehl[6], Christine A. Shields[3], Michael Mills[3], Charles Bardeen[3]

[1] City University of New York, New York, NY, USA

[2] National Centre Atmospheric Science, University of Leeds, Leeds, UK

[3] National Center for Atmospheric Research, Boulder, CO, USA

[4] School of Earth and Environment, University of Leeds, Leeds, UK

[5] School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA

[6] University of California, Santa Cruz, Santa Cruz, CA, USA

Siberian Traps flood basalt magmatism coincided with the end-Permian mass extinction approximately 252 million years ago. Proposed links between magmatism and ecological catastrophe include global warming, global cooling, ozone depletion, and changes in ocean chemistry. However, the critical combinations of environmental changes responsible for global mass extinction are undetermined. In particular, the combined and competing climate effects of sulfur and carbon outgassing remain to be quantified. Here we present results from global climate model simulations of flood basalt outgassing that account for sulfur chemistry and aerosol microphysics with coupled atmosphere and ocean circulation. We consider the effects of sulfur and carbon in isolation and in tandem. We find that coupling with the ocean strongly influences the climate response to flood basalt-scale outgassing. We suggest that sulfur and carbon emissions from the Siberian Traps combined to generate systemic swings in temperature, ocean circulation, and hydrology within a longer-term trend towards a greenhouse world in the early Triassic.

Geochemical proxies record profound shifts in carbon cycling, sea surface temperature (SST), ocean chemistry and circulation, and weathering during the Permian-Triassic transition. In particular, equatorial SST increased by 5-10 °C[1-4] in less than 100 kyr[5]; seawater $^{87}Sr/^{86}Sr$, which reflects weathering of crustal material, underwent the most rapid increase in the Phanerozoic[6, 7]; and carbon isotope data record a sharp negative excursion at the onset of the end-Permian mass extinction, while boron isotope data record a pulse of ocean acidification several tens of thousands of years after the carbon isotope excursion[8].

Flood basalt provinces are enormous magmatic foci that recur at intervals of ~10^7 years on Earth[9], emplacing magma volumes of 10^5-10^7 km^3 accompanied by intense outgassing. In the case of the Siberian Traps, ~7-15 $\times 10^6$ km^3 intrusive and extrusive magmas were emplaced

beneath, into and on top of volatile-rich sedimentary basins[10]. Hypothesized environmental consequences of flood basalts include release of toxic metals[11], ozone depletion from halogen emissions[12, 13], enhanced weathering of fresh volcanic rocks[14], and climate perturbations from outgassing of sulfur and magmatic and sedimentary carbon [10, 15-17].

We use the Community Earth System Model (CESM1), a three-dimensional (3-D) global coupled climate model, to investigate the competing effects, on different timescales, of sustained sulfur emissions and increases in atmospheric CO_2 (Figure 1c). Previous 3-D modeling examined the atmospheric chemistry effects of Siberian Traps emissions alone[13]. Prior modeling of the climate effects of flood basalt sulfur has employed present-day geography and offline surface temperature calculation[17], precluding investigation of the coupled atmosphere-ocean response. Here we focus on climate consequences including hydrology and ocean circulation. Our simulations include latest Permian paleogeography and the Community Aerosol and Radiation Model for Atmospheres (CARMA), a sub-model of detailed aerosol microphysics within the CESM1 framework, to capture sulfur aerosol growth and sedimentation (Methods; Fig. ED2); both processes critically influence the climatic effects of volcanic aerosols[17].

Tempo and scale of Siberian Traps sulfur and carbon release

The tempo and magnitude of outgassing are major sources of uncertainty. Sulfur concentrations in Siberian magmas are recorded in melt inclusions (see Methods). Geochemical evidence for pulsed magmatism from other flood basalt provinces suggests that time-averaged magma discharge rates vary substantially[18]. Comparison with recent fissure eruptions[19] and paleomagnetic data[20] suggest that during especially intense intervals, magma flux may have

exceeded the longer-term flux implied from geochronology[21] by 1-2 orders of magnitude, with 10^3-10^4 km^3 of magma erupting in as little as 100 years. A unique aspect of flood basalt eruptions is thus the potential for intervals of sustained, intense sulfur emissions lasting tens to hundreds of years[17]. Eruption plume modeling indicates that during episodes of very high eruption rate, columns could reach 13-17 km in height[22]. We consider upper troposphere-lower stratosphere (UTLS; 12−14 km altitude) injection of 2000 Tg SO_2/yr, spanning 10-200 years (each year of emissions represents ~100× the SO_2 emissions of the Mount Pinatubo eruption in 1991). Our simulations span 4500 years, in contrast to the ~800 kyr duration of Siberian magmatism[21]. Because the effects of sulfur outgassing are not cumulative beyond the lifetime of sulfur in the atmosphere, stresses due to the most intense episodes of outgassing may be most relevant to global biota[23]. We therefore focus on the climate response to such episodes, which may have been repeated with varying intensity during the overall history of the large igneous province.

A central quandary of flood basalt carbon is that paleoclimate and geochemical records are best explained through massive release of carbon with a temporally evolving isotopic signature[1, 8, 24], but carbon outgassing related to lavas, deep and shallow intrusive magmas, and heating of surrounding rocks remains much more challenging to quantify than sulfur emissions. This is in part because CO_2 saturation can occur deep in the magmatic system and carbon solubility decreases strongly towards Earth's surface, partitioning CO_2 into an exsolved volatile phase[10]. While there are few direct petrologic constraints on Siberian Traps magmatic carbon, comparison with Icelandic and Hawaiian basalts supports flood basalt magmas carrying up to ~1 wt% CO_2[10, 25], in addition to cryptic degassing from intrusive magmas[26] and CO_2 release through metamorphism and assimilation[27]. Recent measurements of CO_2 release during continental

89 rifting[28] also point to the continental lithospheric mantle as a potentially important, but poorly
90 known, source of carbon during flood basalt magmatism.

91 Motivated by pCO_2 proxy data and inverse modeling of the carbon cycle[2], we consider
92 progressive increases in pCO_2 going from 710 to 2800 and then 5600 ppmv CO_2 (see Methods).
93 Such increases would each require 20,000-30,000 Pg of CO_2 release (Fig. ED3), consistent with
94 the carbon available from extraction of carbon from ~10^5-10^6 km^3 magma on decamillenial
95 timescales[10, 24] or from smaller magma volumes that also tap crustal carbon reservoirs. Only a
96 fraction of any such eruption interval would likely be sufficiently intense to inject sulfur into the
97 UTLS[22]. Furthermore, substantial assimilation or metamorphism of country rocks will enrich
98 gases more strongly in carbon than sulfur species[27, 29]. Thus, our combined sulfur and carbon
99 simulations encapsulate the effects of UTLS injection of sulfur during the most intense volcanic
100 activity (10-100 years) synchronized with more prolonged intervals (10^3-10^4 years) during which
101 carbon accumulated rapidly in the atmosphere due to volcanism, intrusion, and metamorphism.
102 To account for uncertainty in the tempo of Siberian Traps outgassing and the degree to which
103 sulfur and carbon outgassing are synchronized, we present simulations in which sulfur and
104 carbon are considered independently before examining the potential combined effects.
105
106 **Climate response to Siberian Traps outgassing**
107
108 Our simulations demonstrate that as pCO_2 reached ~2800 ppm, annually averaged
109 equatorial sea surface temperatures were 29-30°C; at ~5600 ppm CO_2 annually averaged
110 equatorial sea surface temperatures were ~32°C. Surface air temperatures were significantly
111 hotter on land, in places reaching annual mean temperatures of ~38°C at 2800 ppm CO_2 and

almost 45 °C at 5600 ppm CO_2 (Figure 2b). The model reproduces the observed (Fig. 3) +8-10°C anomaly in Permian-Triassic sea surface temperatures[1, 4] under the highest CO_2 levels we consider, after ~3 doublings of CO_2. Oxygen solubility is inversely related to salinity and water temperature, but evidence for end-Permian anoxia is most prevalent at high latitudes[30]. While high latitude SST is lower than tropical SST in all simulations, increasing pCO_2 results in sharper relative decreases in oxygen solubility at high latitudes due to a diminished equator-to-pole temperature gradient (Fig. ED4). More sluggish ventilation under greenhouse conditions, especially in the Tethys, would exacerbate oxygen depletion[31].

In contrast to greenhouse gases, volcanic sulfur emissions quickly form sulfate aerosols that exert a net cooling effect on climate[17]. Because Siberian Traps eruptions occurred at ~60 °N, most sulfate aerosols remain in the northern hemisphere[32]. For UTLS injection of 2000 Tg/yr SO_2 under constant baseline greenhouse levels, we find a maximum northern hemisphere optical depth of ~5. Increased optical depth results in a global mean temperature decrease of 1.5-3 °C (Fig. ED5b) after 10 years of emissions, with annual mean temperature decreases of ~10-15 °C in the northern hemisphere on land (Fig. ED5a). While cooling of northern hemisphere landmasses is severe, global mean cooling is more moderate than previous estimates of flood basalt cooling (Fig. ED5b). We attribute this partly to the high paleolatitude of the Siberian Traps, and partly to the strong ocean response to carbon and sulfur emissions.

We find that changes in ocean circulation play an important role in mediating changes in surface temperature due to prolonged flood basalt sulfur emissions. Changes in mixed layer density and the equator-to-pole thermal gradient due to changes in surface temperature and hydrology translate to changes in the strength of ocean overturning, with vigorous overturning in the sulfur-dominated climate mode and weaker overturning in the carbon mode. Strengthened

meridional overturning circulation (MOC) has been demonstrated due to cooling and diminished high-latitude runoff after eruptions of the past millennium[33]. The ocean circulation response to flood basalt-scale sulfur emissions in our simulations is more pronounced by an order of magnitude, probably due to prolonged cooling and correspondingly larger effects on ocean heat content. A caveat is that the strength of the MOC response to volcanic eruptions has been shown to vary across models[34]and to depend on background conditions[35]. Changes in ocean circulation also affect the patterns of surface temperature change. For example, enhanced Panthalassic overturning and poleward heat transport due to prolonged sulfur emissions cause regions of warming in the northern Panthalassic ocean (Fig. 2a, Fig. ED5a). Within a year after sulfur emissions cease, maximum northern hemisphere optical depth decays to less than 0.1. In contrast, ocean circulation takes several decades to recover after sulfur emissions wane (Fig. 1), indicating that changes in ocean circulation and heat content can extend the climate effects of flood basalt sulfur emissions well beyond the lifetime of aerosols in the atmosphere.

Finally, it is well-known from the present day that aerosols and CO_2 cause competing effects on the hydrological cycle due to the positive Clausius-Clapeyron slope of water vapor, which indicates that to first order, increases in surface temperature correspond to increased atmospheric water vapor concentrations[36]. Consequently, global greenhouse conditions lead to an intensification of the hydrological cycle[37] on longer timescales (Fig. 2d). During intervals with vigorous sulfur release, the patterns of precipitation shift in the opposite direction (Fig. 2c).

Predicted climate swings and comparison with the proxy record

The coupled changes in surface temperature, ocean circulation, and hydrology lead us to identify a cooler 'sulfur mode' that characterizes intervals of intense UTLS sulfur injection, and a warmer 'carbon mode' that prevails on longer timescales when high-altitude sulfur injection wanes. Multiple episodes of intense magmatism imply repeated swings between these sulfur and carbon modes. Given the idealized forcing and compressed timeline of our simulations, comparison of model and proxy data (Fig. 3) is performed to assess consistency of magnitude, sign, and dynamics, rather than to establish detailed alignment.

The maximum temporal resolution of available temperature proxy records from the PT interval[4] is ~10^4 years, too coarse to confidently resolve swings on the timescales discussed here (Fig. 4). In this context, our results serve as predictions that could be most reliably tested with higher resolution proxy records. However, significant evidence already exists for repeated shifts in environmental conditions during flood basalt magmatism. Evidence for initial cooling followed by warming during other flood basalt eruptions has been attributed to early liberation of sulfur from cratonic lithosphere[38]. While release of sulfur and carbon from the mantle lithosphere may well be an important process during continental flood basalt magmatism, our results show it is not necessary to explain such apparent swings between sulfur-dominated and carbon-dominated climate modes. Uranium isotope-based records of marine redox conditions also show marked fluctuations through the end-Permian mass extinction interval[30, 39]. Sulfur isotope variations have been interpreted as evidence for variations in overturning vigor during this time[40]. Such fluctuations are consistent with swings in oxygen solubility, runoff, ventilation, and productivity. As with oxygen isotope records from the end-Permian, the temporal resolution of available U-isotope datasets[39, 41] is limited to ~10^4 years. If these records reflect the swings

described here, the signal must be sufficiently large that it is robust even with time-averaged records, or individual data points represent snapshots of shifting conditions.

Over the long-term, our model predicts strong warming-induced increases in runoff, especially at high latitudes as the equator-to-pole temperature gradient diminishes, providing a mechanism to explain the steep increase in seawater $^{87}Sr/^{86}Sr$ from the latest Permian to the early Triassic (Figure 3). The increase in $^{87}Sr/^{86}Sr$ has been interpreted as a consequence of intense continental weathering at this time[6, 7]. In the northern high latitudes, eruption of the Siberian Traps emplaced millions of square kilometers of fresh volcaniclastic rocks and early lavas enriched in radiogenic ^{87}Sr, likely acquired through interaction with ancient Siberian continental material[42, 43]. Consequent ocean fertilization and enhanced productivity may have contributed to ocean anoxia[44].

Punctuated environmental stresses from Siberian flood basalts

Even given uncertainties in the tempo of flood basalt outgassing and the origins of the carbon that caused the end-Permian $\delta^{13}C$ excursion and elevated pCO_2[2], our results strongly support several conclusions. The atmospheric residence time of sulfur aerosols is very short relative to that of CO_2[15, 17], and flood basalt eruption column modeling[22] demonstrates that high-altitude sulfur injection is only possible during intense episodes that span a small fraction of the overall duration of the extinction interval. Therefore, we predict swings between a cooler sulfur-driven climate mode during intervals of intense Siberian Traps fire-fountaining and a warmer carbon-driven climate mode on longer timescales. Our modeling demonstrates that these swings in climate encompass ocean circulation, marine oxygen solubility, and precipitation and runoff

patterns. Available temperature proxy data from the end-Permian mass extinction[1, 3, 4] are insufficiently high-resolution to directly test for rapid swings in surface temperature, though other proxies record fluctuations in ocean circulation[40] and redox[30]. If future very high-resolution data from the end-Permian do not show the predicted climatic swings, this implies that most Siberian Traps sulfur did not reach the UTLS or that fundamental gaps exist in understanding of the climate response to flood basalt outgassing.

Extinction depends on the rapidity of environmental change relative to organisms' capacity to adapt[45]. Variations in magma emplacement rate, volatile sources, and volatile concentrations over the life cycle of flood basalt provinces, along with differences in atmospheric lifetime, imply that environmental changes due to magmatism should be evolving rather than monotonic. By quantifying the contrary effects of CO_2 and SO_2 on different timescales, our simulations relate Siberian Traps magmatism to the punctuated deterioration of global ecosystems during the end-Permian mass extinction.

Figures

Figure 1. **Outgassing scenarios and changes in global surface temperature and ocean circulation.** (**a**). Global temperature anomalies for increases in pCO_2 alone (panel c, blue curve) and for combined sulfur and carbon emissions (panel c, black and blue curves). Time intervals shown in Fig. 2 are indicated. (**b**). Maximum zonal mean strength of the meridional overturning circulation (MOC) at greater than 500 meters depth in the northern hemisphere. (**c**). SO_2 emissions scenarios and pCO_2 levels considered here.

Figure 2. **CO_2 and SO_2 cause competing effects on surface temperatures and hydrology.** (**a**). Annual mean surface temperature anomalies relative to 710 ppm CO_2 simulation with combined CO_2 increase and 2000 Tg/year SO_2. Warming in northern Panthalassa results from enhanced overturning and increased northward heat transport. (**b**). As in **a**, but with no sulfur emissions and ~3 doublings of atmospheric CO_2 to 5600 ppm CO_2. Estimates of peak SSTs (circled numbers) as noted in Table ED4. (**c**). Annual mean precipitation change on land (relative to 710 ppm CO_2 simulation) with combined CO_2 increase and 2000 Tg/year SO_2. (**d**). As in **c**, but with no sulfur emissions and ~3 doublings of atmospheric CO_2.

Figure 3. Summary of end-Permian proxy data and comparison with model results. (**a.**) proxy data[3, 4, 6, 8, 39, 41] originating from Tethyan sections in Turkey, U.A.E., Iran, and South China. Error bars for $\delta^{238}U$ are two standard deviations. Due to uncertainties in Permian-Triassic seawater $\delta^{18}O$, relative temperature anomalies from $\delta^{18}O$ proxy estimates may be more robust than absolute temperatures[3, 4]. (**b.**) Reconstructed localities for proxy data. (**c.**) Changes in sea surface temperature, salinity, O_2 solubility, and runoff for simulations shown in Fig. 2a and 2c. Tethys and Panthalassa water temperatures are averaged across the extent of each at the sea surface and 750 meter depth.

Figure 4. Conceptual illustration of how combined flood basalt SO_2 and CO_2 emissions cause repeated climate swings. This illustration shows an example eruption-climate history. The sulfur mode triggered by intense UTLS sulfur injection during the most intense eruptions swings to a carbon mode on longer timescales. Swings can occur repeatedly. Such swings are not expected to be preserved in a proxy record with a temporal resolution of ~10^4 years, but will rather average out to reflect the long-term shift towards carbon-dominated conditions. TS is surface temperature.

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460 **Corresponding author**

461 Please address correspondence and requests for materials to Benjamin Black

462 (bblack@ccny.cuny.edu).

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473 **Data availability**

474 Model outputs used to generate Figures 1-3 have been archived at PANGAEA (PDI 18756).

475 Output files exceeding 100MB are available from the authors. Proxy data are available from

476 original sources as cited in the text.

477

478 **Code availability**

479 The CESM code is available at cesm.ucar.edu.

480

481 **Author contributions**

BAB conceived the research and analyzed the results. BAB and RRN designed and performed the simulations with input from JFL, JTK, CAS, MMM, CB, and LTET. All authors contributed to writing the manuscript.

Methods

Sulfur and CO_2 forcing levels

Sulfur loading

Maximum pre-eruptive sulfur concentrations in Siberian Traps melt inclusions from lavas are ~0.18 wt% [29]. During episodes of intense magmatism, studies of paleomagnetic secular variation suggest packages of 5-15 flows encompassing 10^4 km^3[20, 46, 47] erupted in 100 years or less. Assuming a magma density of ~3000 kg/m^3 and a magma mass eruption rate of 265 km^3/year (comparable to the ≥216 km^3/year mass eruption rate estimated by [47]) yields a total sulfur budget of 2900 Tg SO_2/year. The tropopause altitude is lower at high latitudes, and is sensitive to climate, with increasing tropopause altitude as pCO_2 increases [22]. In our simulations, the altitude of the tropopause above the Siberian Traps is ~11-13km (Fig. ED8, ED10). This altitude is higher in our microphysical simulations than at present due to the warmer climate (3550 ppm CO_2) assumed in our microphysical simulations. Plume modeling indicates that during episodes of very high eruption rate, flood basalt eruption columns can reach 13-17 km in height [22]. Assuming that during episodes of intense volcanism, ~70% of total dissolved SO_2 is released and reaches 12-14 km altitude (through gas release at the vent during vigorous fire fountaining and lofting in buoyant columns) we obtain our applied injection rate during magmatic pulses of 2000 Tg SO_2/year. Because our assumed injection altitude straddles the tropopause, a large fraction of the sulfur emissions remain in the troposphere, which is reflected in a sulfur mean atmospheric residence time of several weeks, comparable to previous upper tropospheric simulations[17]. While the precise SO_2 flux is subject to uncertainties given the limited available information on volcanic tempo, our assumed flux is consistent with previous estimates [17, 47-49], and is further consistent with our goal of investigating the effects of representative combined SO_2 and CO_2 emissions during the most intense magmatic pulses. The pace and timing of gas release within eruptive pulses is uncertain; we therefore assume steady SO_2 injection spread evenly annually and over the course of the eruption episode. Between episodes of peak magmatic intensity, we assume much more modest SO_2 injection at the same altitude but a rate of 20 Tg SO_2/year (Extended Data Table 2). To explore the sensitivity of our results to the applied sulfur release rates, the continuity of emissions, and to emissions altitude, we performed sensitivity simulations as listed in Extended Data Table 3 and as illustrated in Extended Data Figure 9.

CO_2 levels

Evidence for very rapid, dramatic increases in atmospheric greenhouse gas levels (and most likely in atmospheric CO_2 levels) includes: (i) Oxygen isotopes, which suggest that low-latitude Sea Surface Temperatures (SSTs) increased by 6−10 °C during the extinction interval [1, 3, 4], (ii) the pattern of marine extinction, which was particularly severe among poorly buffered or heavily calcified organisms, implying that ocean acidification, warming, and anoxia contributed to the extinction [50-52], (iii) the brevity of the major negative marine carbon isotope excursion, which had a duration of 2-18.8 kyr [5], and (iv) a transient drop in ocean pH interpreted as the result of a ~10,000 year pulse of CO_2 release (Extended Data Figure 3). Although the source of increasing greenhouse gas levels remains the subject of discussion [53], the overwhelming evidence for rapid increases (on millennial timescales) in atmospheric pCO_2 motivates our

simulations of stepped increases in pCO_2. The specific levels we consider (710, 2800, and 5600 ppmv CO_2) are subject to some uncertainty, but are consistent with: (i) the stomatal index proxy for pCO_2 across the PTB [54-56], (ii) carbon cycle modeling of transient spikes in pCO_2 due to injection of carbon [53, 57], and (iii) pCO_2 levels required for the model to reproduce proxy constraints on paleo-temperature (Extended Data Table 4 and 5).

As discussed in the main text, classic volcanological estimates suggest flood basalt magmas do not release sufficient mantle carbon to cause the observed changes [58-60], leading to the hypothesis that volatile-rich sedimentary rocks supply the bulk of the carbon [27, 61]. However, recent estimates suggest that the mass of carbon released from the mantle could be much larger than previously thought[10, 62, 63]. To achieve pCO_2 increases similar to those we model requires release of $>10^4$ Gt of CO_2 on decamillennial timescales (Fig. ED3), constituting ~10-50% of the estimated Siberian Traps mantle-derived CO_2 budget of 64,000-320,000 Gt CO_2[10, 12, 62]. In this context, the observed Permo-Triassic greenhouse conditions[1, 3, 4, 64] can be achieved primarily through elevated CO_2 via a combination of the following possibilities: (1) mantle-derived CO_2 release at the high end of estimates, (2) large additional quantities of CO_2 released due to assimilation, thermal metamorphism, and other interactions with Siberian coal, carbonates, and hydrocarbon-bearing sedimentary rocks, or (3) a mechanism that is unknown or unrelated to magmatism.

The specific timescales we consider (2000 years of model time after each pCO_2 increase) are designed to allow investigation of transient effects rather than equilibrium climate. The timescale for the atmosphere to equilibrate with the ocean is 10^2-10^3 years [65]. Therefore a pulse of CO_2 release lasting $<10^3$ years will result in a transient peak in atmospheric pCO_2, followed by an exponential decline in pCO_2 as equilibration—first with the ocean, then with sediments, then through weathering—proceeds[59, 66]. For simplicity, and to investigate the specific, transient Earth system response to a step change in atmospheric pCO_2, we choose not to model this decline. Instead, we fix atmospheric pCO_2 between pulses of outgassing.

Ultimately, the step changes in pCO_2 in our simulations are representative of and allow us to investigate the effects of several emissions scenarios: pulsed emissions of magmatic CO_2 if magmas are CO_2 rich; pulsed emissions of metamorphic CO_2 and CH_4 if metamorphic gas release occurs rapidly during brief intrusive and extrusive magmatic pulses; or pulsed emissions of CO_2 and CH_4 from the deep ocean and/or from clathrates, if changes in ocean temperature and circulation due to initial magmatic outgassing result in a follow-on release of gas from the ocean as proposed here. Because all of these emissions scenarios are fundamentally related, changes in atmospheric CO_2 probably in reality result from some combination of these processes. Our idealized pCO_2 history is intended to investigate the climate response to rapid changes in pCO_2 (with or without concomitant SO_2 release) due to any or all of these scenarios.

As noted in the main text, we report greenhouse forcing in CO_2-equivalent levels of greenhouse gases. Release of methane and other greenhouse gases may have been significant during the end-Permian[27, 55]. From a radiative perspective (neglecting the potential effects of methane on atmospheric chemistry) our simulations can equally represent CO_2 dominated greenhouse conditions or outgassing of CO_2 in lower abundances along with significant, sustained quantities of methane (sustained because the lifetime of methane in the atmosphere is ~10 years, barring significant drawdown of OH concentrations). While methane and other greenhouse gases may have played a significant role, the relatively rapid oxidation of methane favors CO_2 as a greenhouse gas, because greenhouse conditions were relatively long-lived[1, 3, 4,

[64], and oxidation of realistic quantities of methane leads to only several hundred ppm increases in CO_2 [67].

Modeling methods

Our modeling approach has been adapted from that of [13, 31, 68]. The Community Earth System Model (CESM1) is a global climate model that tracks the coupled interactions between the Earth's atmosphere, ocean, land, and sea ice to yield a comprehensive view of coupled Earth systems[69, 70]. In order to combine detailed microphysical simulations with long atmosphere-ocean coupled simulations, we utilize the modeling approach illustrated in Extended Data Figure 2, in which we use two configurations: the Community Atmosphere Model (CAM4) with the Community Aerosol and Radiation Model for Atmospheres (CARMA), and CAM4 with interactive ocean. We describe the model components and calculations of oxygen solubility based on model outputs in more detail below.

CARMA

Robust aerosol size distributions are critical to accurate assessment of radiative effects, and such size distributions can vary significantly for different styles of eruption[17, 71]. We therefore employ the Community Aerosol and Radiation Model for Atmospheres (CARMA, a sectional aerosol microphysical model[72] that includes processes such as nucleation, growth and settling[72-74]. In our work, CARMA has been configured with 35 aerosol size bins, from 0.003 microns to 7 microns, and has been coupled to CESM1(CAM4) to permit the simulation of the aerosol plume in three dimensions through time[72, 75, 76]. All size bins are included as tracers within CESM1(CAM4). Heating of sulfates from tropical eruptions can influence the dispersal of the sulfates[77, 78], a process that is not accounted for in our simulations. The expected consequences of aerosol heating might include self-lofting, slower removal of stratospheric aerosols, and increased transport into the southern hemisphere. Therefore the climate effects we consider are representative, though conservative, given the assumptions involved.

CESM1(CAM4)

The configuration of CESM1(CAM4) used in this study has 26 vertical levels that extend to ~40 km altitude with 1.9° × 2.5° horizontal resolution. CESM1(CAM4) handles the representation of dynamics, physics, atmospheric chemistry, and coupling to the land and prescribed SSTs within CESM while CARMA simulates only the sulfate aerosol microphysics.

The equilibrium climate sensitivity of CESM1(CAM4) is 3.2 °C for a doubling of CO_2, while that of CESM1(CAM5) is 4.0 °C[79]. The CESM2 was just released to the community and its equilibrium climate sensitivity is 4.2 °C. Importantly, these are model estimates of Earth's climate sensitivity. Analysis of paleoclimate data, present day observations and a hierarchy of climate models yield an estimated range of climate sensitivity from 2.0 to 4.5 °C, in which the probability distribution of all of these estimates peaks at around 3 °C[80]. Given uncertainty in the precise observational value of Earth's climate sensitivity, and given that our model falls well within the estimate range and agrees with the most probable value, CESM1(CAM4) is well suited for investigation of end-Permian climate. If the true end-Permian climate sensitivity is

closer to 4.0 °C per doubling of CO_2, rather than 3.0 °C per doubling of CO_2, then lower levels of atmospheric carbon dioxide would yield similar changes to those we simulate.

We use a version of CAM4 with extended sulfur chemistry to allow for the accurate transformation of the volcanic SO_2 plume into sulfate. The conditions for all simulations presented here are summarized in Table S2. Appropriate boundary conditions and paleogeography for the latest Permian were used to force the simulations (Extended Data Table 1). Stratospheric circulation is slightly slower in the CAM4 model compared with WACCM and CAM5/6, resulting in an aerosol lifetime that is slightly longer in CAM4[81].

Prescription of CARMA results in CESM1(CAM4) under end-Permian conditions

In our simulations with interactive ocean circulation, an atmospheric model with a horizontal resolution of 3.75° × 3.75° was used to enable the relatively long simulations presented here. The radiative properties of the sulfate aerosol plume calculated by CARMA were coupled to CESM1(CAM4) by calculating the optical properties of the plume from the output of WACCM-CARMA simulations. To accomplish this, we first calculate the wet aerosol mass and size from the dry sulfate radius and mass output by CARMA by accounting for temperature and water activity[72, 82]. Mie calculations are performed using this information to determine the radiative properties of the plume required by CESM1(CAM4) [83]. CESM1(CAM4) uses this input and the CAM-RT (*71)* radiative transfer scheme to determine the full radiative effects of the sulfate aerosol distributions in four dimensions (space and time) during fully coupled simulations with latest Permian paleogeography[31].

Ocean model

We use prescribed SSTs based on a climatology derived from our equilibrium simulations with CESM1(CAM4) in our CESM1(CAM4)-CARMA simulations. All other simulations include the fully interactive Parallel Ocean Program (POP2) model[69, 84], with bathymetry from Kiehl and Shields[31].

Land dataset

The latest Permian land surface dataset used in our simulations is from Kiehl and Shields [31], based on the surface types of Rees et al. [85]. The land surface types are illustrated in Figure ED 11.

Oxygen solubility

We compute oxygen solubility (Figure 3, Figure ED4) using Eqn. 8 in Garcia and Gordon [86] in conjunction with temperature and salinity predictions from our model.

The role of methane clathrate

Recent work on the Paleocene-Eocene Thermal Maximum[24] has suggested clathrate dissociation due to volcanogenic warming could amplify carbon release and explain an excursion in $\delta^{13}C$. Oxidation of methane in seafloor sediments and in the water column limits methane

clathrate release to the atmosphere[87]. However, clathrate methane need only reach the water column to cause an isotope excursion, and high methane fluxes due to rapid dissociation may enable a larger fraction of methane to bypass the sediment filter and enter the ocean[87]. During a swing from a sulfur- to carbon-dominated climate regime, enhanced overturning continues for around 50 years after the conclusion of a 200-year pulse with 2000 Tg/yr SO_2 injection even as the surface ocean warms. Under these conditions, bottom water temperatures increase at rates that briefly reach 0.1-0.5 °C/year at the seafloor on continental margins. This rate of seafloor warming is much more rapid than under increasing pCO_2 alone (Figs. ED6 and ED7), potentially catalyzing a clathrate-driven drop in the $\delta^{13}C$ of the end-Permian ocean (and eventually the atmosphere through air-sea exchange of carbon). The magnitude of the isotope excursion requires ~4000 Gt C with $\delta^{13}C \approx -60$[67]. An estimated 1800-5000 Gt C is stored in clathrate and methane bubbles in modern marine sediments[87]. Suboxic conditions like those that prevailed leading into the end-Permian[30, 52] enhance clathrate accumulation[87], suggesting that the latest Permian clathrate inventory may have been larger than the modern inventory despite late Permian warmth, which is further supported by persistently high carbonate $\delta^{13}C$ prior to the extinction transitioning to lower long-term carbonate $\delta^{13}C$ after the extinction[67]. Indeed, the release of large quantities of methane into the ocean and subsequent oxidation in the water column would have promoted anoxic conditions. This scenario, which depends on synchronization of carbon and sulfur outgassing, explains abrupt carbon cycle perturbation near the onset of warming[4, 5], coincident with expansion of anoxia[41], and agrees with evidence for increases in methane abundance in seawater from enclaves in brachiopod shells[88].