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Carbon-climate feedback responses to spatial aerosol model implementation variations

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Aerosols have played an important role in defining the climate over the historical period, due to their net cooling effect in the atmosphere. However, as their emissions are expected to decrease in upcoming decades, they will be associated with reduced cooling, i.e. future warming, of the planet. Despite their importance and high uncertainty associated with their radiative forcing, aerosols inclusion in simple climate models, impact models and carbon-based climate assessment metrics requires simplifications and assumptions. Typically, interactions between physical and biogeochemical processes are disregarded by such. By varying the spatial implementation of aerosols in an intermediate complexity model we explore the variability in Earth system responses under an ambitious mitigation scenario due to aerosols-radiation interactions. When aerosols are implemented disregarding their spatial distribution, surface air temperature is higher by almost 0.1 °C when compared to a regionally heterogeneous implementation, corresponding to an uncertainty of ca. 200 GtCO₂ of remaining carbon budgets. The main processes driving these responses are the land surface temperature and its effect on soil respiration, as well as changed ocean heat fluxes due to differences in incoming shortwave radiation at the surface. The spatial distribution of aerosols triggers important climate-carbon feedbacks, which should be specifically considered when assessing climate evolution and simulated Earth system responses. Even if aerosol-cloud interactions aren't explored, the results already indicate that aerosols should be deliberately accounted for in simple models and assessment tools, as their triggered feedbacks will be instrumental in defining pathways for temperature stabilisation and evaluating, for example, remaining carbon budgets.

Aerosols are currently the largest source of uncertainty in evaluating the Earth's climate feedbacks to anthropogenic forcing¹. Overall, aerosols' contribution is estimated as a net negative forcing of -1.1 [-1.7 to -0.4] W m^{-2} between 1750 and 2019¹, the largest negative contribution to a change in effective radiative forcing. The magnitude of aerosols contribution is similar to, for example, that of non-CO₂ well-mixed greenhouse gases (GHGs) in the same period, which are responsible for a warming forcing of 1.16 [1.05 to 1.17] W m^{-2} ¹. Over the historical period, aerosols have contributed to a reduction of the greenhouse gas-led warming², however, current efforts to reduce air pollution, especially in Asia, have caused this signal to be unmasked, and global warming trends to pace up³. In line with these efforts and as a result of emissions reduction efforts, aerosols emissions are expected to decline in the next few decades⁴. From a physical point of view, aerosols have a direct and an indirect effect on atmospheric radiative

properties. Direct effects are due to the absorption and scattering of the incoming solar shortwave radiation, while in the atmosphere, aerosols can also interact with clouds, altering its microphysical characteristics and leading to an indirect effect on the properties of the atmosphere (see, for example^{5–8}).

Furthermore, the aerosols distribution is spatially and temporally heterogeneous. Emission plumes from point sources, commonly associated with human activities, in combination with a short atmospheric residence time cause aerosol optical depth (AOD) to be on average 1.4 times higher over land compared to oceans⁹. This spatial heterogeneity of aerosols and its associated regional forcing are known to lead to nonlinear climate responses, for example regarding precipitation patterns¹⁰.

Despite aerosols importance for both the climate development and its future uncertainty, aerosols spatially heterogeneous character is often times

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disregarded in climate risk and impact assessments¹¹. While integrated assessment models (IAMs), used to develop a multitude of plausible socio-economic scenarios¹², account for the regional aspect of aerosol emissions, the simple climate models (SCM) and emulators that will be employed in risk assessment are typically trained only on global mean aerosol effects, without including its known non-linear and spatially heterogeneous responses¹¹.

Even as current efforts are ongoing to improve emulators ability to handle the spatial heterogeneity of aerosols responses¹³, SCMs depend on various simplifications and assumptions. These involve both their representation of aerosols, with simplified patterns (see, for example¹⁴), parametrization of radiative forcing impacts (e.g.,¹⁵ or scaling factors), as well as limitations on feedbacks between the carbon cycle and the climate¹⁶. Also in SCMs with a more realistic representation of the carbon cycle, interactions between physical and biogeochemical components are not typically present in either these models or the IAMs, being provided only by the Earth system models¹⁶. These simplifications in the coupled components result in a lack of representation of carbon-climate feedbacks.

Climate-carbon cycle feedbacks relate to carbon exchanges between Earth's components and how the efficiency of these processes is interconnected to changes in the climate, which in turn are directly affected by the weakening or strengthening of such fluxes¹⁷. The uptake of carbon by the ocean and the land, as well as permafrost carbon emissions, are among the fluxes included in these feedbacks and contribute to the uncertainty added to future CO₂ development projections and the associated surface air temperature (e.g.,^{18,19}). As a result, carbon cycle feedbacks will play a role in controlling temperature responses to emitted carbon, and add to the uncertainty of transient climate response to cumulative CO₂ emissions (TCRE)²⁰, carbon budgets¹⁸ and ultimately whether temperature targets can be reached or not.

Processes or components that alter these feedbacks are, therefore, of great importance to the assessment of future climate evolution, as is the case with aerosols. The spatially heterogeneous distribution of aerosols can lead to, for example, heterogeneities in regional temperature patterns that enhance or reduce carbon and heat uptake, and have been demonstrate to be capable of affecting net biome production, gross primary production and total ecosystem respiration, via mostly changes in surface air temperature²¹.

The importance of carbon feedbacks to understand the evolution of the climate has been intensely discussed, and disregarding these feedbacks can have implications to evaluation tools and metrics, as for example, for global warming potential (GWP)²². However, metrics and linear models employed for the estimation of the remaining carbon budget commonly combine all non-CO₂ forcing into one globally aggregated value (e.g., for TCRE, TCREff, CO₂-fe^{23–27}), despite aerosols' influence on the climate being intrinsically different from that of CO₂ and other GHGs¹¹. Evaluation metrics and tools typically assume no non-linearities between forcing and carbon cycle responses, and disregard the spatial temporal differences between aerosols and other GHGs, as well as their potential effect on carbon climate feedbacks. While some studies have attempted to include certain aspects of aerosols regional character and its effects on linear metrics, such as for absolute global temperature change potential (AGTP)²⁸, constraining aerosols spatially heterogeneous effects on Earth system responses in a manner that can be useful for improving SCMs, emulators or linear metrics is a topic that still requires further investigation.

In this study, we offer a detailed overview of what Earth system feedbacks are triggered by aerosols-radiation interactions by comparing climate-carbon responses under distinct implementations of aerosols' spatial forcing, in an attempt to disentangle the influence of reduced complexities, such as seen in SCMs, impact models or linear metrics, on possible climate uncertainties for both the historical period and future scenarios. Despite not evaluating the effects of aerosols indirect interactions, associated with cloud microphysics changes, we are already able to show a range of triggered thermodynamic responses to the use of distinct spatial implementations of aerosols. Our results indicate the need for a more comprehensive inclusion

of climate-carbon feedbacks in the context of simplified assessment approaches, especially in the representation of aerosols.

Results

Carbon-climate feedbacks triggered by spatially (un)resolved aerosol implementations

Despite the same global average aerosol forcing (Fig. 1a), the spatially resolved AOD implementation has a distinct radiative forcing pattern compared to the *no plumes* experiment (Fig. 1b), and the associated carbon-climate feedbacks cause differences in the simulated surface air temperature (Fig. 1). Removing the spatial aspect of the aerosol implementation, i.e., moving from *default* to *no plumes*, results in a simulated air temperature that is up to 0.1 °C higher in the latter (Fig. 1d, purple line). The highest surface air temperature differences between the experiments *default* and *no plumes* are simulated, as expected, over the years when aerosols radiative forcing is strongest (negative most values in Fig. 1a). More details on this relation can be found in the Supplementary Information (Fig. S3).

From the individual contributions to the ARB we can see warming and cooling contributions to the temperature difference between the experiments (Fig. 1d; absolute values for all simulations can be found in Table S1). The main warming drivers in terms of Earth system responses are the reduced land carbon and ocean heat uptake in the *no plumes* experiment. The difference in the contributions from the land carbon uptake is responsible for 72% (82%) of the warming burden in 2025 (2100), while the difference in ocean heat uptake contribution causes 18% of the warming burden in 2025 and 5% of the cooling burden by the end-of-century (see Table S2 for detailed information on individual contributions). The *no plumes* experiment simulates a lower land carbon uptake (Figs. 1d and 2a) due to the relative reduction of the aerosol load over land areas, where the plumes are located. The driving process behind this reduced land carbon uptake is the increase in temperature-driven soil respiration (Fig. 2c) due to the relatively lower cooling (i.e., warmer temperatures) by aerosols over land (Fig. S4a), especially in the Northern Hemisphere for higher latitudes during the historical phase and for mid latitude until the end of the century. The lower land carbon uptake is associated with a higher CO₂ concentration in the atmosphere (Fig. 1c), leading, hence, to an increase in temperature. A small increase in vegetation primary production is also seen associated with the warmer temperatures and higher CO₂ concentrations (Figs. 2c and S4b), its contribution to carbon uptake being smaller than the simulated increase in soil carbon and respiration due to its indirect temperature dependency based on the leaf temperature and potential effects of heat stress, resulting in comparatively lower carbon uptake. This reduction in terrestrial carbon uptake is most prominent in mid to high northern latitudes (Fig. 2a), and in tropical and subtropical regions of the globe towards the end of the century. This southern shift corresponds well with the southward shift of aerosol optical depth in the *default* experiment. On a smaller scale, ocean carbon uptake is overall increased, especially in the Southern Hemisphere, towards the end of the simulation (see Fig. S4c).

Additionally, having a globally uniform aerosol forcing implies a higher than default aerosol load over the ocean, which decreases the incoming shortwave radiation at the ocean surface (hatching on Fig. 2d) and accordingly the ocean heat uptake, as well as upper ocean temperature (Fig. 2d). This signal is more pronounced in the Southern Hemisphere, due to its larger ocean areas (see Fig. 2b). The Northern Hemisphere subpolar region shows changing signs in the ocean heat fluxes by the ocean, especially towards the end of the historical period, related to the interplay of incoming shortwave radiation at the surface, changes in ventilation depth and sea ice coverage, with periods of weakened fluxes in the case of globally uniform aerosol implementations. The global aggregated signal is a reduction in ocean heat uptake in the *no plumes* experiment, which contributes to an increase in surface air temperature. An overview of how all the aforementioned components and processes relate to the carbon-climate feedback for the *no plumes* experiment can be found in Fig. S5.

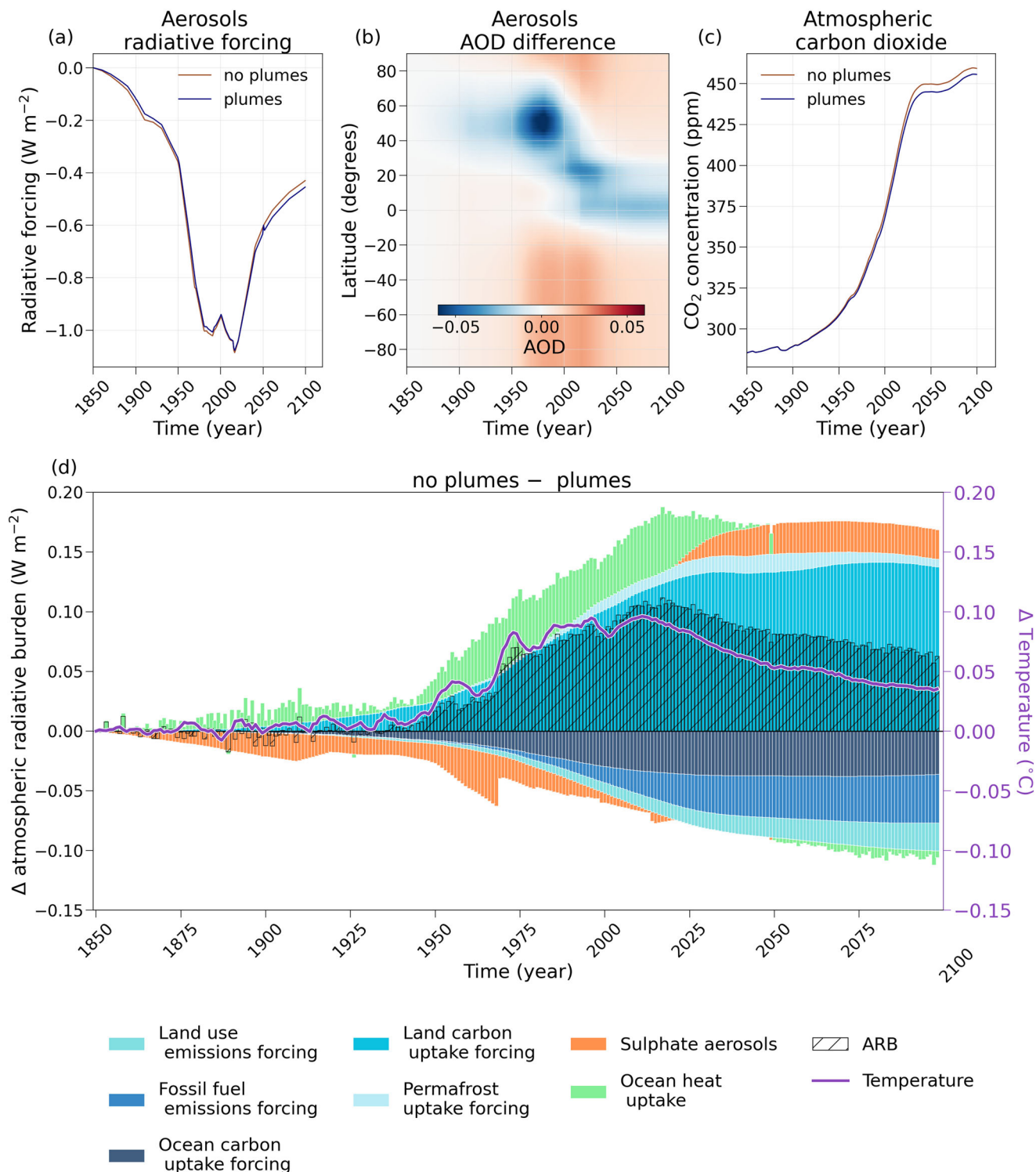


Fig. 1 | Comparison between the default and the no plumes experiments over 1850–2100. a simulated globally averaged aerosols radiative forcing (W m^{-2}), **b** Hovmöller diagram of the difference in aerosol optical depth (AOD) input to UVic ESCM version 2.10 between the no plumes and default experiments and **c** simulated globally averaged atmospheric carbon dioxide concentration (ppm), in (a, c) for the no plumes (brown line) and default (blue line) experiments. **d** Stacked contributions

(coloured bars—see legend) of difference in atmospheric radiative burden (ARB) between no plumes and default experiments from the start of the pre-industrial period in 1850 until the end of the 21st century. The black hatched bars indicate the net ARB difference from the sum of the considered contributions (referring to left y axis), while the purple line represents the temperature difference between the two experiments (referring to right y axis).

Carbon-climate responses from aerosols located only over specific areas

To disentangle the land and ocean carbon-climate responses to spatial aerosol forcing, we constrain the following experiments to exhibit aerosol

forcing only over land or over the ocean, respectively. When aerosols are implemented uniformly over only land with a comparable global mean radiative forcing magnitude, land carbon uptake is increased relative to a globally uniform aerosol implementation (Figs. 3a and 4a). The combined

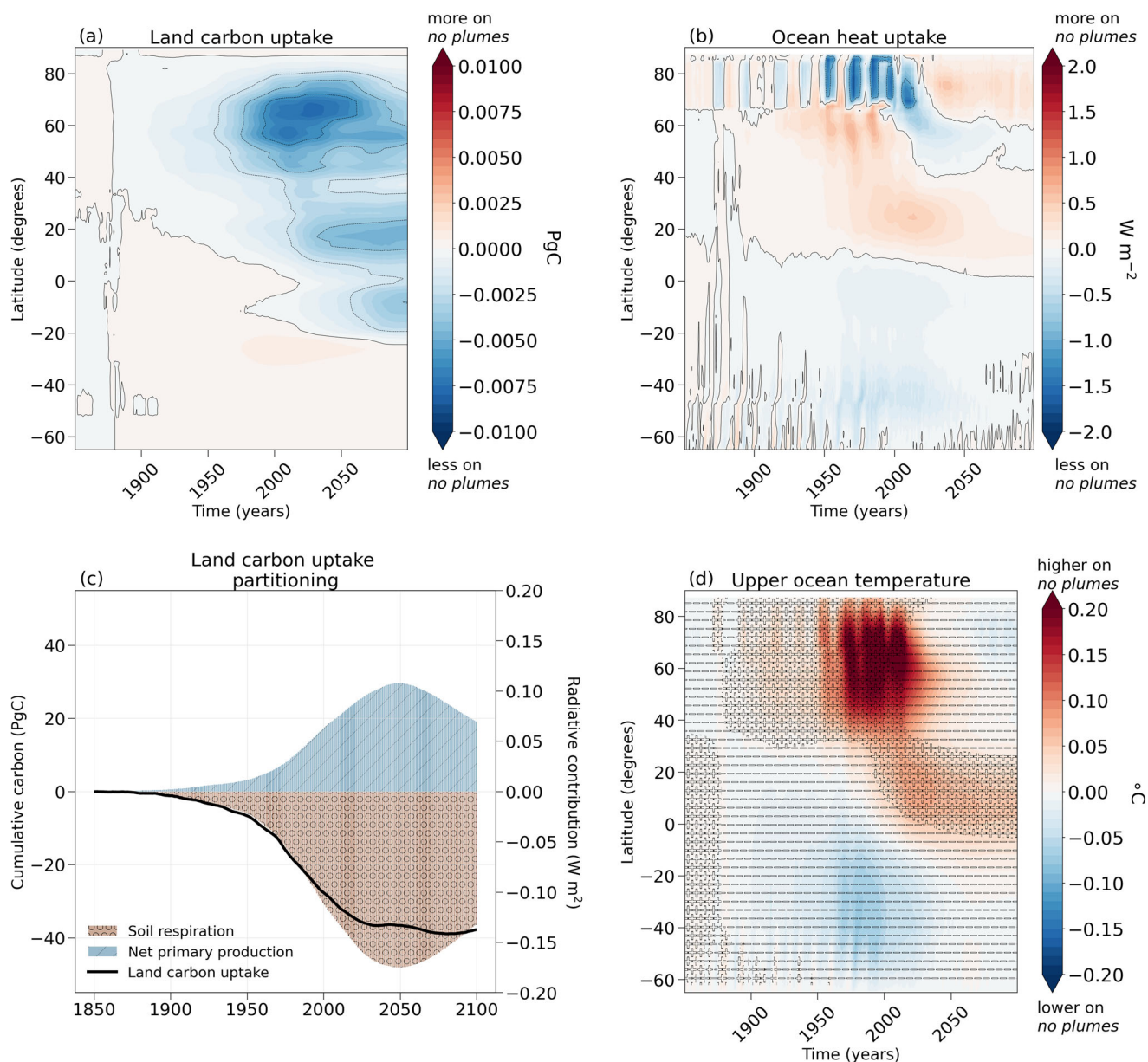


Fig. 2 | Overview of processes dominating differences between experiments. Time-latitude Hovmöller diagram of the difference between experiments no plumes and default. **a** for land carbon uptake anomaly (PgC), **b** for ocean heat uptake anomaly ($W m^{-2}$) and **d** for ocean temperature average for the upper 17.5 m of the water column ($^{\circ}C$), from the start of the pre-industrial period in 1850 until the end of the 21st century. Values are given for a rolling latitude average, and positive values indicate higher fluxes/temperature on the *no plumes* experiment, while negative

values indicate lower fluxes/temperature. In **d**, cross (+) hatching indicates positive difference in incoming shortwave radiation at the surface, while dashed (-) hatching indicates negative differences. Additional details of the difference between experiments *no plumes* and *default* in (c) for soil respiration and net primary production (PgC) (brown hatched circles and blue hatched, respectively, relative to left y axis) and for global land carbon uptake forcing ($W m^{-2}$) (black line relative to right y axis).

effect (Fig. 4c) of decreased soil respiration due to lower temperatures and marginally increased vegetation primary production due to less heat stress drives the land carbon uptake. Consequentially, when aerosols are implemented over *only land* maximum temperature differences to *no plumes* are *ca.* $-0.09^{\circ}C$. The main areas in which higher land carbon uptake can be seen are the mid- to high-latitude regions in the Northern Hemisphere and subtropical areas in the Southern Hemisphere (Fig. 4a). These regional responses on land carbon uptake strengthen in the middle of the 21st century, indicating that, despite the decreasing forcing from the aerosols in the experiments, the climate-carbon effect persists. By the end of century, land carbon uptake differences contribute 94% to the cooling burden in the *only land* experiment in comparison to the *no plumes* experiment (more information in Table S2).

This aerosol implementation with aerosols over *only land* shows an initial increase in ocean heat uptake (Fig. 3a), dominated by an increase in heat uptake over the Southern Hemisphere (Fig. 4b), which turns into a warming contribution in the middle of the 21st century. Additionally, we find a similar feature in this experiment in comparison to the *no plumes*—*default* results, with ocean heat uptake alternating sign in timing and magnitude in the northern high latitudes. We find that the *only land* experiment reinforces the effects seen in a more realistic aerosol implementation, i.e. with plumes.

An interesting characteristic of the heat uptake process is that even if the forcing is implemented without spatial detailing of plumes, a very clear inter-hemispherical difference is present. Heat uptake is mediated by physical processes, which will define areas of release and uptake of heat, as well

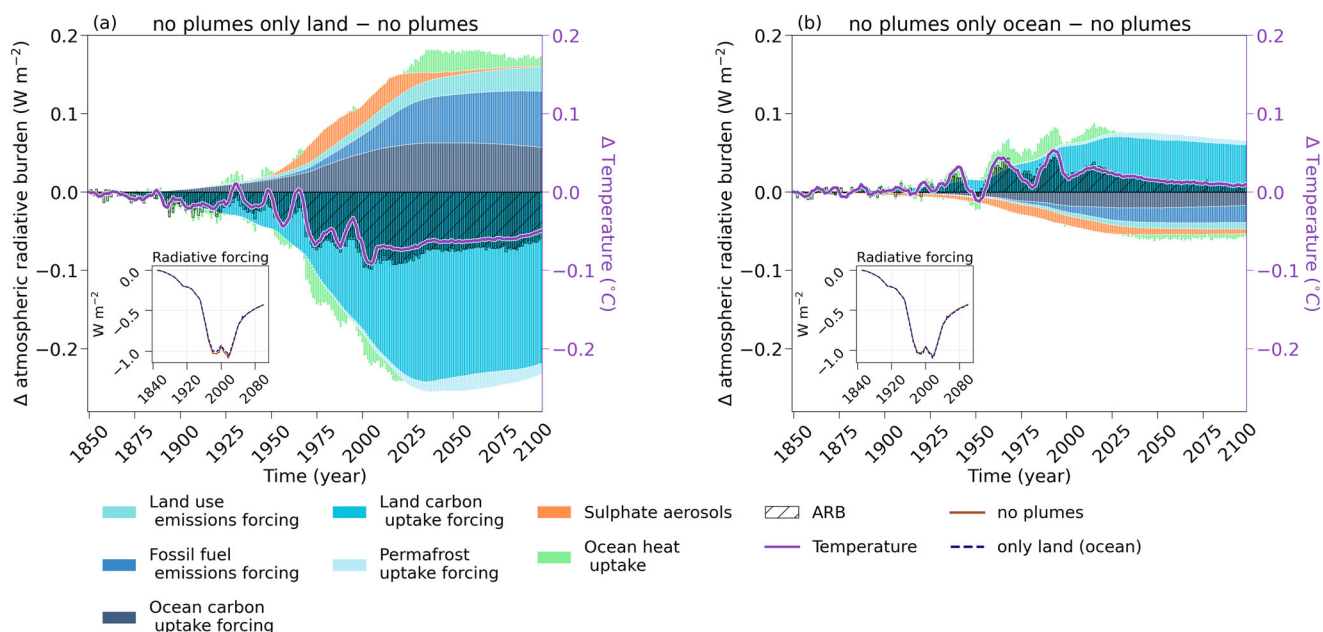


Fig. 3 | Comparison between the experiments with aerosols over only specific areas and the no plumes experiment. Stacked contributions to difference in atmospheric radiative burden (ARB) from all contributors (coloured bars—see legend) between **a** no plumes only land and no plumes and between **b** no plumes only ocean and no plumes, from the start of the pre-industrial period in 1850 until the end of the 21st century. The black hatched bars indicate the net ARB difference from the

sum of the considered contributions (referring to left y axis), while the purple line represents the temperature difference between the two experiments (referring to right y axis). The inset figures show the radiative forcing from aerosol for the no plumes default simulation as a solid brown line, and the respective experiment as a dashed blue line.

as the efficiency in these processes. It is important to highlight that the majority of the ocean areas in the experiments described here do not shift from uptake to release regions, for example, but instead remain with the exchange signature defined by the local physical processes. Once again, the signal from incoming shortwave radiation at the ocean surface is seen to drive the ocean heat uptake and associated ocean surface temperature. However, in this experiment, the signal is less clear, an indication of the effect of the many physical and chemical process at play.

Aerosols implemented over only ocean affect both the carbon cycle and its feedbacks, leading to a decrease in land carbon uptake (Fig. 3b). This response is extremely similar, but in opposite sign, to the only land simulation, with an overall much smaller magnitude. Detailed information on more specific responses for only ocean simulations can be found in the Supplementary Information (Fig. S6 and associated text). The patterns described here highlight the similarity of the only ocean simulation to the no plumes one. In a similar sense, the experiment only land is an imperfect analogue to the real world, presenting an enhanced sensitivity similar to observed historical responses, and expected future changes.

Carbon-climate responses from aerosols over only a hemisphere

This final section explores the development of temperature, as well as carbon and heat responses over hypothetical narratives in which aerosols are only present in one of the hemispheres.

When aerosols are present only over the Northern Hemisphere, small anomalies are seen in ocean and land carbon uptake, as well as in heat uptake (Fig. 5a). As a result, the temperature anomaly to annual no plumes does not surpass $-0.047\text{ }^{\circ}\text{C}$ throughout the simulation, being close to zero over the historical period, and negative by the end of the century. Towards the end of the 21st century, an increase in land carbon uptake dominates the cooling of the climate. The contribution from this difference, however, only accounts for about 70% of the cooling burden compared to no plumes, a smaller percentage than what is observed in other experiments (Table S2). Further discussions on the driving mechanisms behind this simulation are provided in the Supplementary Information (see Fig. S7).

When aerosols are present only in the Southern Hemisphere, surface air temperature is higher than in the default no plumes experiment over both the historical period and future development (Fig. 5b). A strong loss response from the land carbon and permafrost uptake are noticeable, accounting for 71% and 15% of the warming burden by the end of the century compared to the no plumes experiment, respectively (Table S2). Despite a slight increase in net primary production, higher soil respiration in the Southern Hemisphere only experiment causes a decrease in the land carbon uptake (Fig. 6c). Most of the Northern Hemisphere sees such reduction, both in terms of the historical period and future scenario until the end of the century (Fig. 6a). Ocean heat uptake shows overall negative anomalies, i.e. less ocean heat uptake, contributing ca. 14% to the gross warming by the end of the century. This response is driven by a reduced uptake over the Southern Hemisphere (Fig. 6b), directly related to a reduced incoming shortwave radiation at the ocean surface due to higher aerosols load in the atmosphere (see hatching in Fig. 6d). The Northern Hemisphere, on the contrary, shows mostly an increase in heat uptake, associated to a reduced aerosol load in the atmosphere above it. However, high latitudes of the Northern Hemisphere also show short periods of reduced ocean heat fluxes over the historical period. The combined effect from these different ocean areas leads to the lower heat uptake throughout the simulation. The final temperature anomalies to no plumes reach around $0.07\text{ }^{\circ}\text{C}$.

Discussion

In the current study, we have shown that aerosol implementation choices regarding direct aerosol-radiation effects can lead to substantial differences in carbon feedbacks and heat fluxes, resulting in surface air temperature differences of up to $0.1\text{ }^{\circ}\text{C}$, even if the same global mean radiative forcing is achieved. While such anomalies may appear small in magnitude, in an ambitious emissions mitigation setting such contributions are considerable, reducing the effective remaining carbon budget for a given temperature limit by about 200 GtCO_2 (using a TCRE estimate of $0.45\text{ }^{\circ}\text{C}$ per 1000 GtCO_2^{29}). This result indicates that the choice of aerosols emissions spatial characteristics may play a larger role than the simple magnitude of short-lived non- CO_2 species emissions in defining climate targets, since the latter

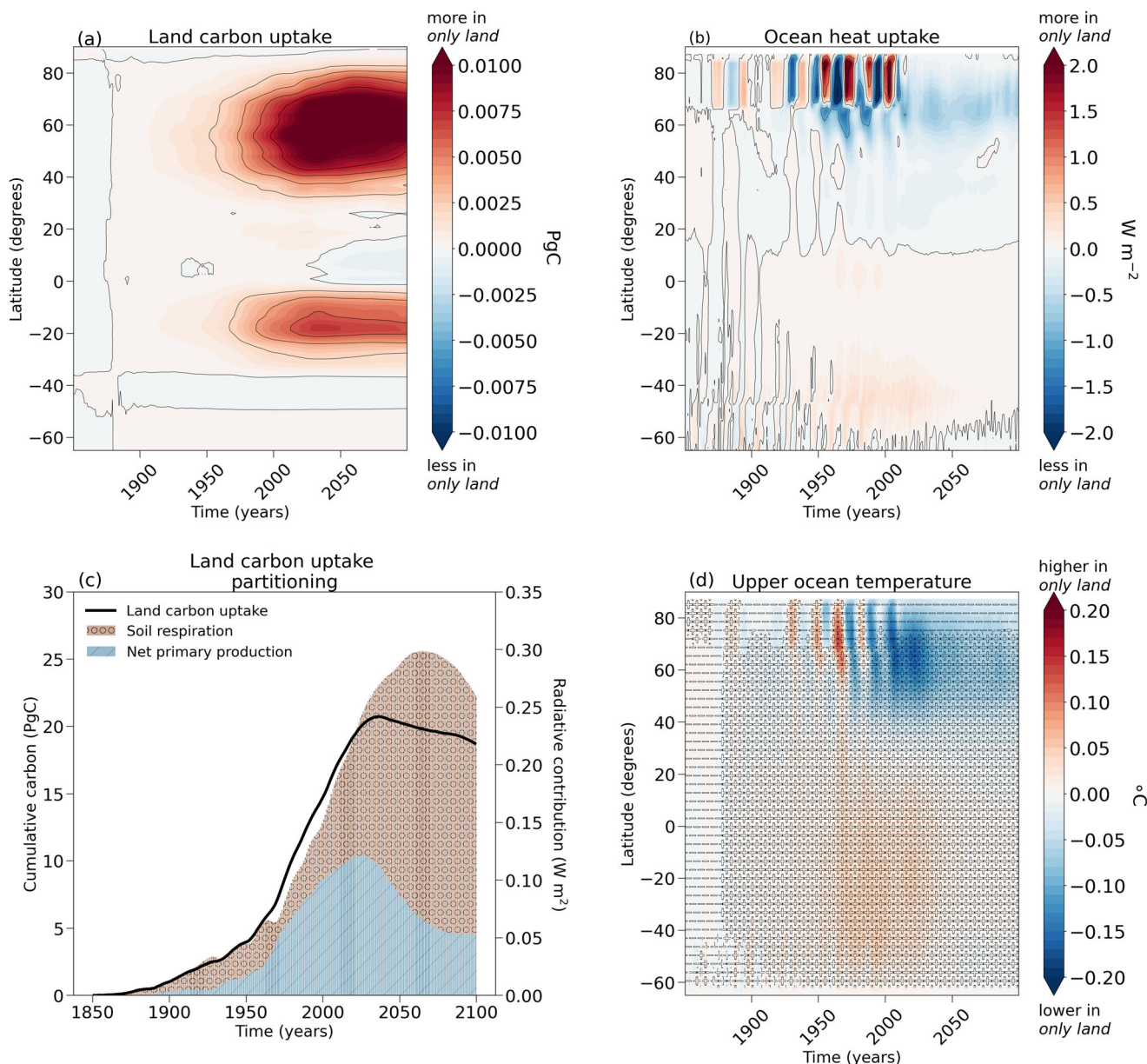


Fig. 4 | Overview of process dominating differences between experiments. Time-latitude Hovmöller diagram of the difference between experiments only land and no plumes. **a** for land carbon uptake anomaly (PgC), **b** for ocean heat uptake anomaly ($W m^{-2}$) and **d** for ocean temperature average for the upper 17.5 m of the water column ($^{\circ}C$), from the start of the pre-industrial period in 1850 until the end of the 21st century. Values are given for a rolling latitude average, and positive values indicate higher fluxes/temperature on the *only land* experiment, while negative

values indicate lower fluxes/temperature. In **d**, cross (+) hatching indicates positive difference in incoming shortwave radiation at the surface, while dashed (-) hatching indicates negative differences. Additional details of the difference between experiments *only land* and *no plumes* in **c** for soil respiration and net primary production (PgC) (brown hatched circles and blue hatched, respectively, relative to left y axis) and for global land carbon uptake forcing ($W m^{-2}$) (black line relative to right y axis).

have been regarded to have only a reduced impact in carbon budgets for highly ambitious mitigation scenarios³⁰. While there is clear utility of simple metrics to help guide policy processes, it behoves the scientific community to build on these to better account for climate-carbon feedback uncertainties, since decisions arising from such metrics will define climate mitigation and intervention efforts, strengthened economic development opportunities, energy source usage and societal transitions (e.g.³¹).

Using more-idealised experiments, we were able to identify the driving processes behind the different Earth System responses, finding changes in the incoming shortwave radiation at the surface and consequently in land surface temperature and soil respiration to dominate the land carbon uptake signal. Changes to this component then drive the

climate-carbon feedbacks, on account of the distinct aerosol implementation choices. We show that since the spatial pattern of aerosols implementation triggers carbon and climate feedbacks, experiments emphasising the current aerosols loads located over the Northern hemisphere and land enhance and reproduce a behaviour of stronger cooling differences (Fig. 7). Conversely, in the experiments with no explicit spatial AOD representation, and where aerosol loads dominate over ocean and the Southern hemisphere, the net forcers lead to a higher ARB and more warming differences in the Earth System. The importance of land carbon uptake forcing in driving the atmospheric radiative burden is evident, with a larger forcing present in experiments where the aerosols implementation is closer to reality, i.e., mostly over northern

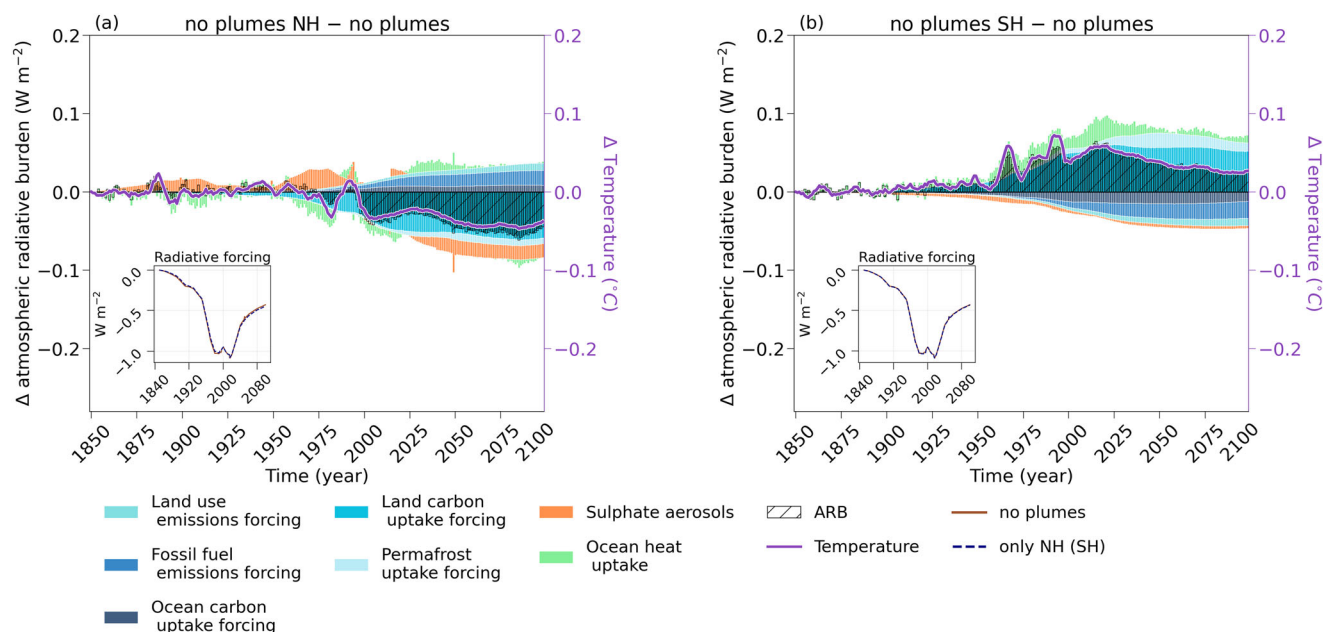


Fig. 5 | Comparison between the experiments with aerosols over only one hemisphere and the no plumes experiment. Stacked contributions to difference in atmospheric radiative burden (ARB) from all contributors (coloured bars—see legend). **a** Between no plumes Northern Hemisphere and no plumes and **b** between no plumes Southern Hemisphere and no plumes, from the start of the pre-industrial period in 1850 until the end of the 21st century. The black hatched bars indicate the

net burden from the sum of the contributors considered (referring to left y axis), while the purple line in represents the temperature variability (referring to right y axis). The inset figures show the radiative forcing from aerosol for the no plumes default simulation as a solid brown line, and the respective experiment as a dashed blue line.

hemisphere land, leading to a smaller radiative burden. This information is crucial to take into account also in the case of spatial shifts in AOD loads in further scenarios.

Considering that simple climate models, emulators and impact models, which are widely used in policy informing efforts, make use of simplifications for the natural system responses, our results show that these assumptions will contribute to an additional source of uncertainty in the aerosol effects. In a similar sense, a potential source of error is introduced when implementing aggregating or carbon-based metrics, as they include aerosols' radiative forcing only in global terms, disregarding its spatial signal and feedback triggers.

We recommend that SCMs add constraints that capture the regional aerosol variations of Earth system models, such that they can inform IAMs and impact models. Our results show that enhancing SCMs to represent aerosol emissions at minimum between hemispheres is important to best capture and parameterize the climatic outcomes of aerosol emissions as represented in IAMs. By capturing this dynamic, IAMs can then make more comprehensive decisions consistent with our understanding of aerosol forcings. It also allows for a more realistic assessment of potential climate risks associated with the triggered feedbacks at different regions of the planet.

The current experiments highlight that an appropriate aerosols implementation that allows for the inclusion of correct biophysical effects of triggered carbon-climate feedbacks will become of higher importance for upcoming model intercomparison efforts. Previous rounds of the Coupled Model Intercomparison Project (CMIP) included mostly concentration-driven experiments, where such impact sensitivities were not considered. However, future efforts are moving towards emissions-driven simulations^{32,33}, for which differences in aerosol forcing in the models will have an additional and non-neglectable effect on the carbon-climate feedbacks, associated processes and estimates of, for example, land and ocean carbon uptake as well as ocean heat uptake.

The aerosols implementations explored here also allow us to better understand aerosols effects on heat uptake by the ocean, for example, by use of the only Southern Hemisphere experiment. For this experiment,

reductions in heat uptake, and in some regions increase in heat release, can be seen especially over the Atlantic and part of the Indian and Pacific sectors of the Southern Ocean (Fig. S8). At the same time, the Northern Hemisphere's subtropics to high latitudes in the Pacific show an increase in uptake, while other areas of release of heat have a decreased signal. This corroborates the hypothesis posed by³⁴ that the larger importance of the Southern Ocean for historical heat uptake compared to carbon uptake is a response to the higher aerosol burden over the global north (see more information on Figs. S8 and S9, and associated text).

A final direct example of policy informing outcomes from the experimental design explored here relates to the use of methods that alter atmospheric burden of aerosols. Aerosols-based solar radiation management (SRM), for instance, encompass techniques that deliberately manipulate the radiation budget of the planet. By changing regional distribution of aerosols, these techniques will have a direct effect on the incoming solar shortwave radiation, but will, as shown here, also trigger carbon climate feedbacks, which are associated with uncertain outcomes and temperature evolution, with even potential regional warming (see Fig. S4a). This effect from aerosols responses of the carbon cycle has received very limited attention when it comes to such techniques. It, therefore, implies that a more thorough assessment of different aerosol injection strategies, including the types of investigation shown here, would be beneficial to further political decisions on climate intervention.

Our results corroborate the need for a less simplified consideration of aerosols effect on the climate-carbon system to take into account associated feedbacks. Caution should be taken, nevertheless, in understanding the temperature variability and individual climate component contributions presented here in a single model experiment.

While UVic ESCM is able to reproduce historical temperature and carbon fluxes, ocean heat fluxes show biases, leading to a simulated higher ocean heat content change than historically observed, and vegetation carbon that is too high mostly over the tropics³⁵. These biases have an impact in the absolute flux values calculated here, for example, leading to a likely exaggerated uptake and release of heat by the ocean.

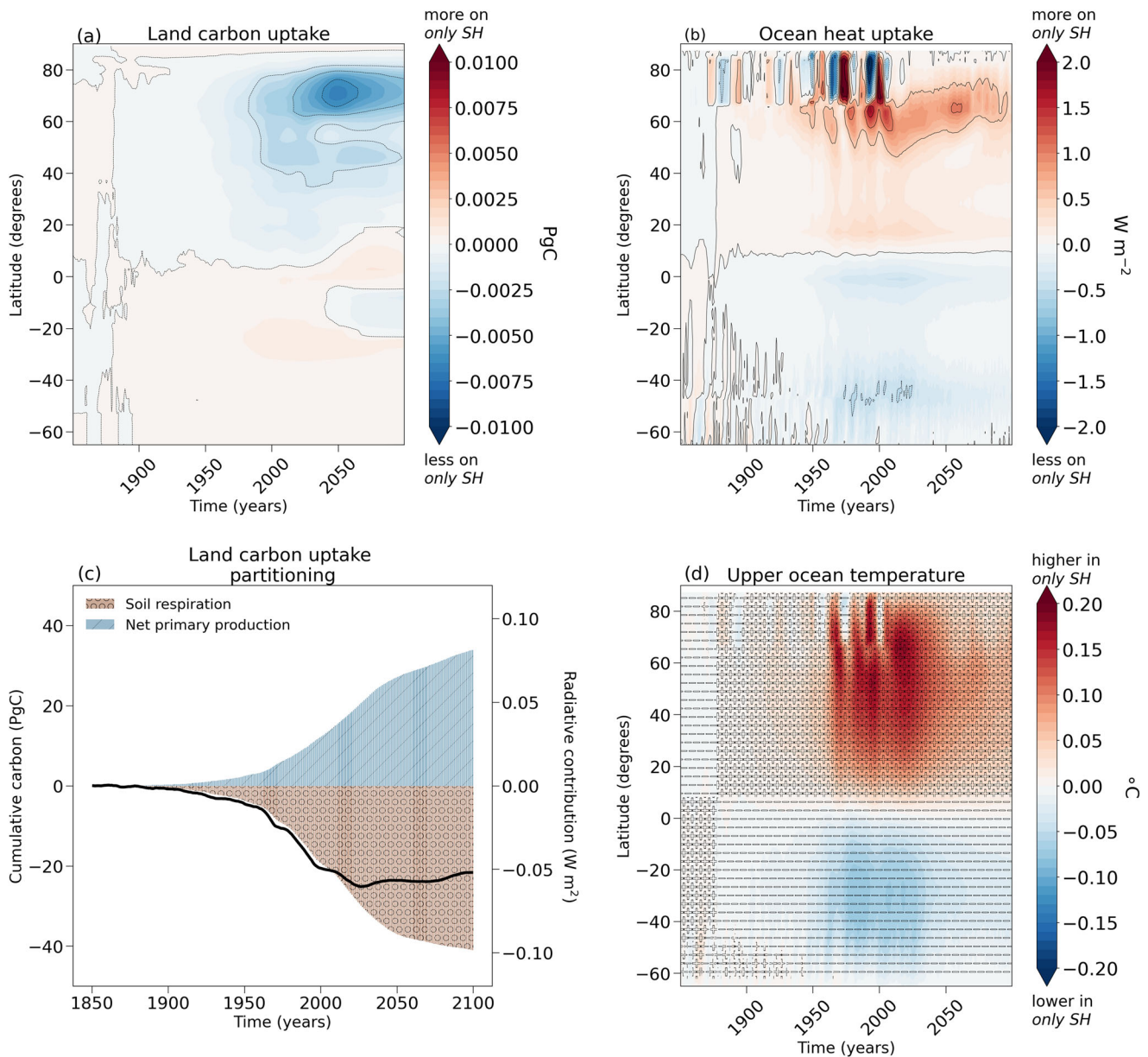


Fig. 6 | Overview of processes dominating differences between experiments. Time-latitude Hovmöller diagram of the difference between experiments only Southern Hemisphere and no plumes. **a** For land carbon uptake anomaly (PgC), **b** for ocean heat uptake anomaly (W m^{-2}) and **d** for ocean temperature average for the upper 17.5 m of the water column ($^{\circ}\text{C}$), from the start of the pre-industrial period in 1850 until the end of the 21st century. Values are given for a rolling latitude average, and positive values indicate higher fluxes/temperature on the *only Southern Hemisphere* experiment, while negative values indicate lower fluxes/temperature. In **d**, cross (+) hatching indicates positive difference in incoming shortwave radiation at the surface, while dashed (–) hatching indicates negative differences. Additional details of the difference between experiments *only Southern Hemisphere* and no plumes in **c** for soil respiration and net primary production (PgC) (brown hatched circles and blue hatched, respectively, relative to left y axis) and for global land carbon uptake forcing (W m^{-2}) (black line relative to right y axis).

The simplified nature of the atmospheric model present in UVic ESCM also restricts the analysis of a few processes and variables that are of interest. Foremost, as the model has non-interactive clouds, it does not include responsive indirect aerosol-cloud forcing. The presence of a cloud mask impacts the atmospheric and surface albedo, but interactions between aerosol atmospheric load and cloud formation processes are overlooked by this analysis. Additionally, while we are able to provide aggregate variables that can be included, e.g., in IAMs, to better understand the role of regional aerosol heterogeneity on global mean temperature, we are not able to provide all climatological information needed by downstream impact model frameworks. For example, variables related to precipitation cannot be reliably provided by the simplified two-dimensional atmosphere implemented in this model.

Even with the expected model caveats and including uniquely aerosol-radiation interactions, through our analyses it is clear that estimating aerosol effects on climate-carbon systems in simple climate models and linear metrics must be accounted for with due caution, including a range of possible sources of uncertainty. Disregarding climate-carbon feedbacks when incorporating or developing aerosols pathways, forcings and impacts may imply wrong estimations of temperature targets, which will account for a considerable headroom under highly ambitious mitigation scenarios, even if only direct radiation effects are considered. The non-linear feedbacks and associated uncertainty are likely to increase when cloud interactions are accounted for, since the forcing related to these remains one of the largest uncertainties in climate sensitivity investigations¹, indicating the importance aerosols will play in defining our future climate.

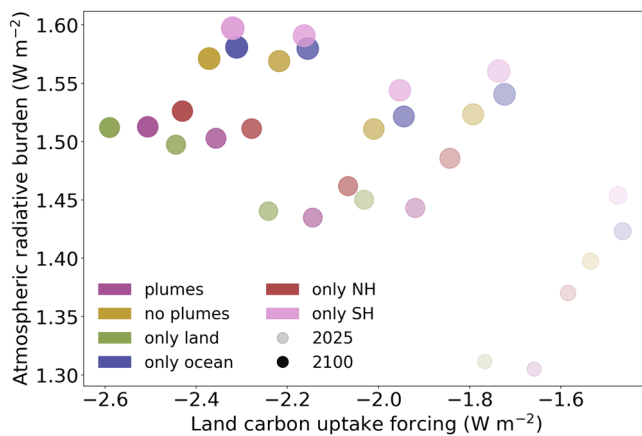


Fig. 7 | Summary of experiments' radiative development. For each experiment (see color-coding in the legend) the land carbon uptake forcing (in W m^{-2}) is related to the ARB (in W m^{-2}), for 2025, 2045, 2065, 2085 and 2100 (from most transparent colour shading to least transparent, respectively). The size of the circles is given by the temperature anomaly to pre-industrial conditions for each experiment and time step considered.

Methods

Employed Earth system model and simulation scenario

The results presented in the Results section are simulated by an intermediate complexity model, the University of Victoria Earth System Climate Model - UVic ESCM version 2.10^{35,36}. It includes 19 ocean vertical levels, 14 terrestrial soil levels, permafrost and dynamic vegetation modules, on a $3.6^\circ \times 1.8^\circ$ horizontal grid. The atmosphere is represented by a two-dimensional energy moisture balance model³⁷, with a cloud mask integrated only onto the atmospheric albedo. This implies that changes in the aerosols' implementations exclude any indirect effects of aerosols on climate. Notwithstanding, the UVic ESCM has been shown to perform well in terms of carbon cycle and temperature responses in historical simulations³⁵, a relevant feature to the exploration of triggered feedbacks included here. In fact, the simplicity of this model in comparison to a comprehensive fully-coupled Earth system model is an advantage that allows us to easily disentangle the effects of the different aerosol implementations.

For the baseline scenario, we follow the CO_2 emissions trajectory from the 1.5°C no overshoot scenario conceived for the Adaptive Emissions Reduction Approach^{38–40}. This approach iteratively calculates the necessary CO_2 emissions trajectory for stabilising surface air temperature at 1.5°C on a 5-year basis, dependent only upon the simulated temperature and the previous radiative forcing and emissions pathways. The aerosol, the non- CO_2 greenhouse gases and the land use change forcings follow the Shared Socioeconomic Pathway 1 (SSP1-1.9⁻⁴¹). The experiments start from the pre-industrial period in 1850, and are simulated until 2100. For all experiments described here, forcing other than aerosols is kept the same.

Aerosols implementation variations

In this default setting, UVic ESCM treats aerosol forcing as spatially masked yearly aerosol optical depth (AOD) data (*default* simulation). The UVic ESCM aerosol forcing is based on the work from⁴², who developed parametrizations of sulphate-like, and in smaller scale nitrate-like, aerosols' optical properties. This is a plume-based model, where aerosol emissions originate from nine spatial plumes in distinct source regions, which are fitted to a present-day climatology, and scaled to match historical anthropogenic emissions in each region. The plumes represent both industrial emissions and biomass burning, with each's respective seasonal cycle (more information on the temporal response component can be found in Fig. S2 and associated text). In the UVic ESCM, aerosols emitted by plumes account only for direct radiative effects, and a scaling factor was implemented in tuning the model to historical period observations³⁵.

To explore the spatial dependencies in aerosol implementations, we design other idealized narratives that support improved understanding of climate-carbon uncertainties:

1) To understand the impact of spatially resolved AOD forcing, we implement an area weighted globally averaged AOD forcing (*no plumes* simulation) resulting in a different spatial temporal forcing (see Fig. 1b). We then adjust the aerosol forcing data utilizing the UVic ESCM aerosol scaling factor, when necessary, to have the final effective radiative forcing with the same magnitude as that for the *default* simulation.

Simulations such as *no plume* can denote implementations of global aerosol emissions forcing derived from integrated assessment models or from future scenarios that provide only the final global mean effective radiative forcing without making assumptions about the source regions.

2) To disentangle ocean and land carbon-cycle impacts, we design a second idealised set of experiments, where we applied aerosol forcing over land or over ocean areas (*only land* and *only ocean* experiments, respectively). The forcing for these experiments is taken from *no plumes* experiment, and once again, in this second set of experiments, the global total aerosol forcing is adjusted to have the final effective radiative forcing with the same magnitude as that in the *default* simulation, applied only over the area of study. The remaining areas in each experiment are assumed to have no aerosols in the atmosphere above them.

3) Finally, to explore the carbon-climate impact of a Northern Hemisphere dominated aerosol spatial distribution compared to a Southern Hemisphere dominated distribution we design the final set of idealised experiments (*North Hemisphere (NH)* and *South Hemisphere (SH)* experiments, respectively), acknowledging, here in a very idealized manner, a likely southward strengthening of aerosol forcing in future scenarios⁴. The opposite hemisphere in each simulation is implemented with zero aerosol content. Finally, for consistency, the global total aerosol forcing from *no plumes* applied to each hemisphere is adjusted to have the final effective radiative forcing with the same magnitude as that in the *default* simulation.

For the second and third experiments (in sections "Carbon-climate responses from aerosols located only over specific areas" and "Carbon-climate responses from aerosols over only a hemisphere"), we used the *no plumes* simulation as a reference as it allows for a clearer distinction of the responses. By prescribing these different narratives of the aerosol spatial implementations, we are able to investigate responses from carbon cycle and climate feedbacks, pointing out missing feedbacks in simplified aerosol representations.

Analysis framework

To analyse the experiments and understand the distinct contribution from all forcings and the carbon cycle, heat fluxes and Earth system responses, we used FROT (Framework for radiative contribution to temperature response⁴³). FROT builds up from the energy balance concept⁴⁴, allowing for a detailed understanding of the transient contributions of all radiative forcings, as well as Earth system dynamical responses defining temperature variability. Under FROT, all radiative forcing as well as system feedbacks are converted to the same metric (in W m^{-2}), expanding from the formulations employed in⁴⁵, which then define the atmospheric radiative burden (ARB). Since ARB includes time varying forcing and radiative responses, this gives rise to a "final burden" in the atmosphere, which drives the surface air temperature variability. Each component has either a positive or negative contribution onto the system and ARB, as applied here, connects these cumulative effects throughout the experiment, using the simulated heat and carbon fluxes. When comparing different experiments, as done in the Results section, the differences in contributions, whether positive or negative, can lead to both a warming or cooling burden, as the different implementations will trigger components or processes to be weaker or stronger depending on the aerosols spatial pattern. Therefore, this framework is ideally suited to compare the individual contributions of distinct processes to the temperature development and climate feedbacks in our different scenarios. More information on the outcomes obtained from applying FROT to an individual scenario is explored in Fig. S1.

Data availability

The data used for the results described in the manuscript is available at <https://doi.org/10.5281/zenodo.17008260>.

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Author contributions

E.A.M. conducted the analyses. E.A.M. and N.M. interpreted the results and were major contributors in writing the manuscript, with added contributions from G.T. and M.J.G. All authors read and approved the final manuscript.

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