Supplementary Material

Introduction

Sulphate aerosols are currently the largest source of uncertainty to evaluate climate's sensitivity responses, with the main reason behind it coming from their both direct and indirect effects on the climate. However, in including such relevant processes onto a modelling scheme, another source of uncertainty has to be accurately and carefully accounted for, namely its spatio-temporal scale, as this aspect can have a further impact in the modelled climate system responses and future projections.

Many scientist and policy-interested research groups have developed future forcing pathways in accordance with desired scenarios, as those under the Representative Concentration Pathways (RCPs) or Shared Socio-economic Pathways (SSPs). Some pathways still being studied, nevertheless, are developed without downscaling or as ungridded time-series, for example if direct outputs from Integrated Assessment Models (IAM) are utilized (see the public databases under https://iiasa.ac.at//). Most research so far has not focused in evaluating the role the model inclusion choices regarding spatio-temporal scales have, as well as their impacts for applicable and relevant scientific and political decision-making.

In the current study we analyse distinct aerosols implementations, focusing on changing the temporal and spatial detailing of the radiative forcing, and evaluate the uncertainty for future temperature development, the carbon cycle and heat uptake processes. Opting for aerosol in this investigation topic is a straight-forward decision, as this component is responsible for the largest source of uncertainty to climate sensitivity, as mentioned beforehand, and as it is a component known to show high regional variability.

Methods

The current study simulates the different scenarios with an Earth system model of intermediate complexity (UVic-ESCM 2.10 - Weaver et al. 2001; Eby et al. 2009; Mengis et al. 2020), which has a 3.6° x 1.8° spatial grid, 19 ocean vertical levels and 14 levels in the terrestrial soil module, as well as dynamic vegetation with 5 plant functional types, and a permafrost module. It shows a good representation of Earth's carbon cycle and heat exchanges.

In terms of the scenarios utilized, we chose a highly ambition mitigation scenario aiming at global mean temperature stabilization, namely the Adaptive Emission Reduction Approach (AERA -Terhaar et al. 2022; Silvy et al. 2024). This approach iteratively calculates the fossil fuel CO_2 emissions necessary for reaching and stabilising at a defined temperature target, here 1.5°C (Frölicher et al. 2022). In addition, the model accounts for land use changes and non-CO_2 greenhouse gases following ambitious mitigation pathways (SSP1-2.6).

In UVic-ESCM 2.10, aerosol forcing is introduced as monthly maps of atmospheric optical depth (AOD), which interact with radiation and affect the incoming short-wave radiation and derived processes. As stated previously, the used pathway follows SSP1-2.6 for the aerosol radiative forcing. To obtain the distinct aerosol implementations we either averaged the default AOD over the seasons at each year (annual spatially resolved – asr), or over the globe for each month (seasonal global – sg), or both simultaneously (annual global – ag). The forcing from further components was the same in the different implementations.

Results

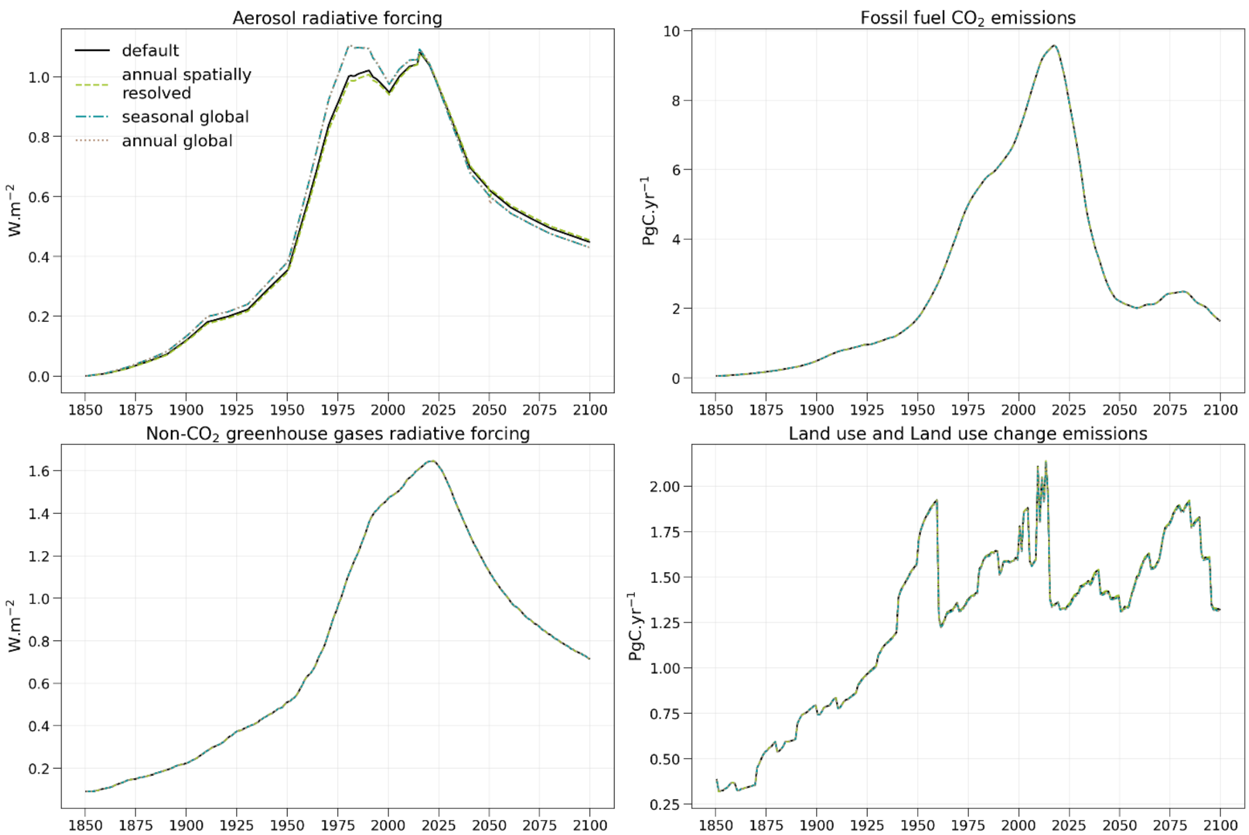

Figure 1. Radiative forcing from aerosols and non-CO_2 greenhouse gases, as well as emissions of CO_2 from fossil fuels and land use activities for the different aerosol implementations (see legend for colors and line style) throughout the simulations.

The anthropogenic radiative forcing, from fossil fuels emissions, land use emissions, non-CO_2 greenhouse gases and aerosols, is the same across the different simulations (Figure 1). The small mismatch between spatially -averaged and -resolved aerosols forcing around 1980 does not play a significant role in altering the temperature or atmospheric CO_2 content (not shown) in the simulations, since this component has a short lifetime in the atmosphere, making this brief mismatch the cause to only a small impact in the climate responses development.

An overall distinct implementation of aerosols optical depth, however, causes surface air temperature to be 0.08 °C higher when an using a globally-averaged forcing (Figure 2).

Changes in the temporal resolution of the forcing, from seasonal to annual, seem to play a minimal role (*ca.* 0.012 °C – not shown).

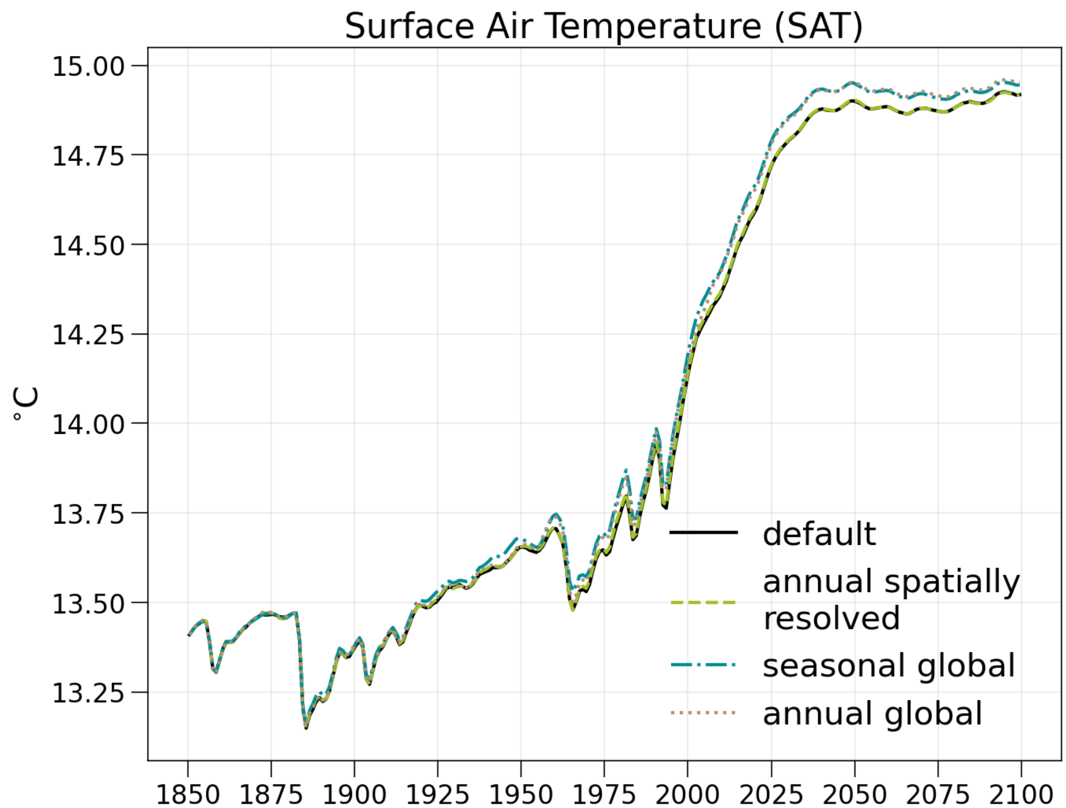

Figure 2. Historical and future air temperature for simulations with seasonal spatially-resolved (default), annual spatially resolved, seasonal globally-averaged and annual global aerosol implementations

Using a new framework to comprehensively describe forcing contributions onto temperature responses (FROT - Monteiro et al. submitted), we can easily observe each component's role in relation to one another for each individual simulation (Figure 3). Moreover, the impact these components have on the temperature development is clear. The largest forcers are those that alter the carbon burden on the atmosphere (blue bars), which, however, become less dominant in terms of leading temperature variability as the simulation progresses towards temperature variability.

Another benefit of FROT is to easily compare distinct simulation implementations and obtain information on the relative importance of the forcings to observed temperature responses. Here we have highlighted the differences from spatially -averaged and -resolved aerosols implementations, either with annual or seasonal optical depths (Figure 4). In both cases, the main causes for a higher temperature when implementing spatially-averaged forcing are the responses from the climate system in terms of land carbon uptake and ocean heat uptake, both reduced in these simulations.

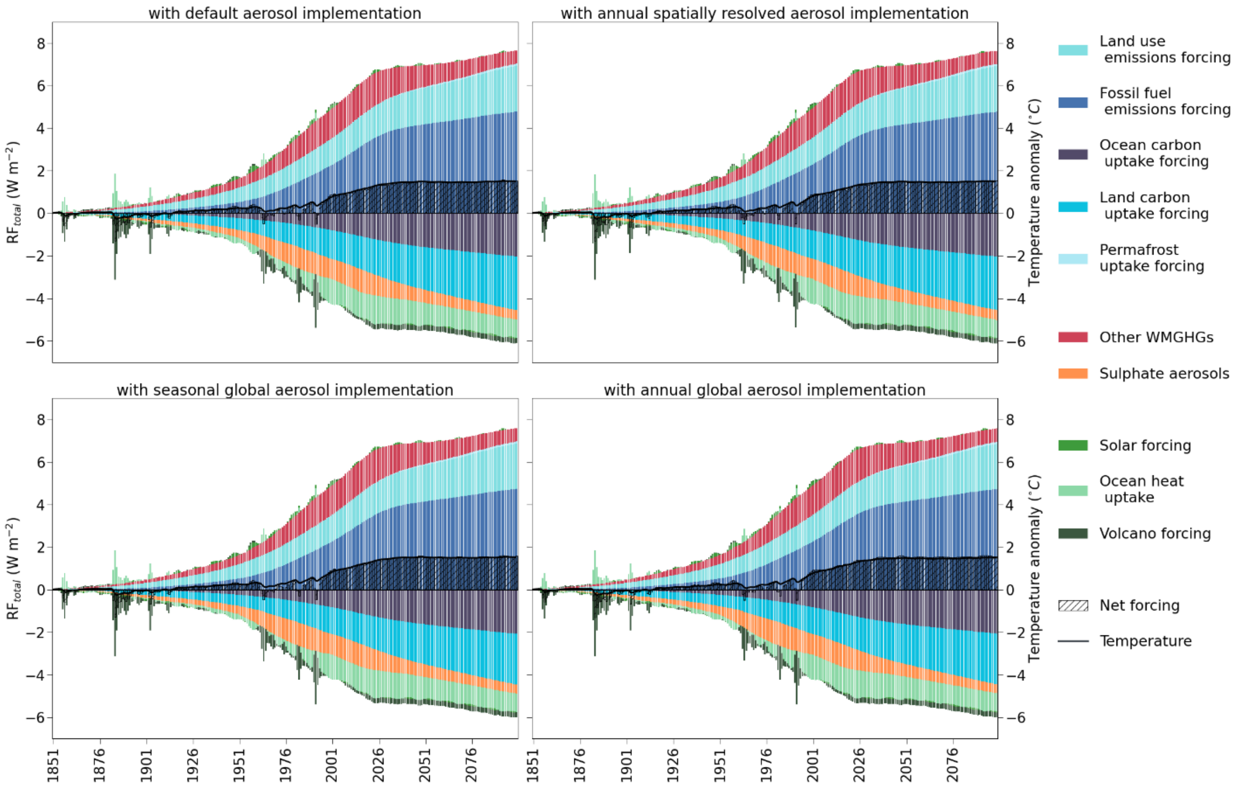

Figure 3: Stacked radiative forcing in terms of cumulative fluxes from all individual components (colored bars – see legend) between 1950 and 2100. The black hatched bars indicate the net forcing from the sum of the contributors considered. The black line represents the temperature variability (referring to right y axis).

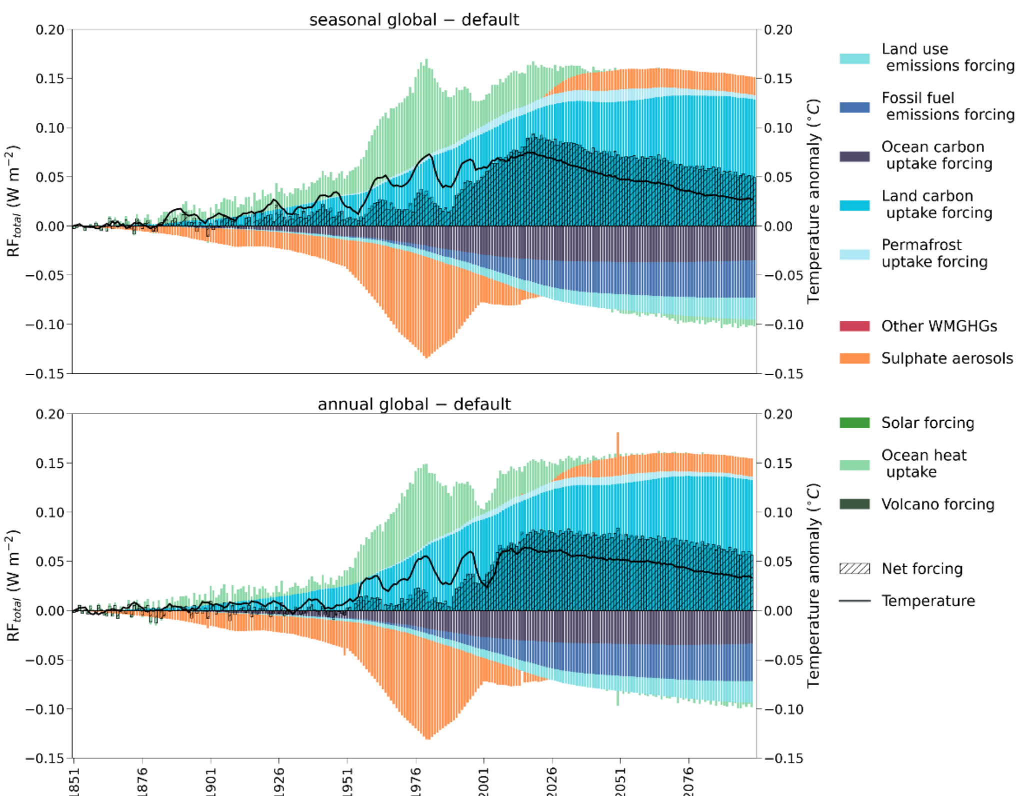

Figure 4: Stacked radiative forcing in terms of cumulative fluxes from all individual components (colored bars – see legend) between 1950 and 2100. The black hatched bars indicate the net forcing from the sum of the contributors considered. The black line represents the temperature variability (referring to right y axis).

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