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Climatic Effects of Hygroscopic Growth of Sulfate Aerosols in the Stratosphere

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Motivation

- Deliberate climate intervention by injection of sulfate aerosols in the stratosphere is a method proposed to counteract anthropogenic climate warming.
- We use idealized climate model experiments to study the climate effects of a specific microphysical property of sulfate aerosols in the stratosphere: the hygroscopic growth.
- The larger relative humidity in the lower stratosphere causes an increase in the aerosol size through hygroscopic growth that leads to an increase in scattering.
- We investigate if sulfate aerosols, for a fixed mass, cause more cooling when prescribed at the lower levels of the stratosphere because of the hygroscopic growth.

Climate Model

- NCAR CESM 1.0.4 is used in this study with CAM4 coupled to CLM4 and a slab ocean model.
- Model has a horizontal resolution of 1.9° x 2.5° with 26 vertical layers.
- The aerosols are prescribed with uniform concentration globally in single model layers with a pressure thickness of ~15.5±1.0 hPa.
- Processes such as chemistry, transport, and sedimentation are not included, and the aerosol layer remains fixed throughout the simulations.

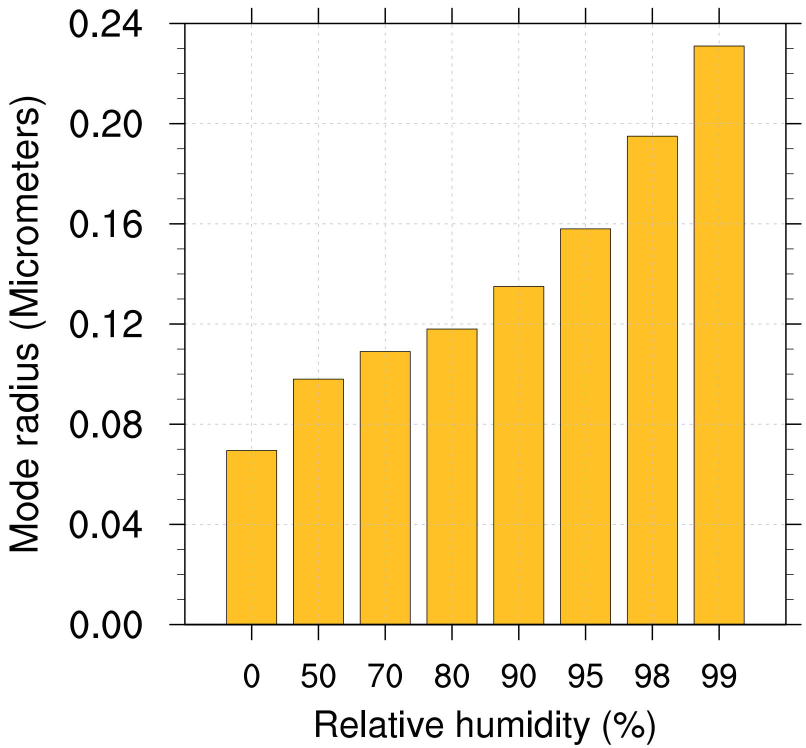
Stratospheric sulfate aerosols in CAM

- We use “background sulfate aerosols” in the CAM4 which is in the form of ammonium sulfate ($(NH4)_2SO_4$).
- The hygroscopic growth of sulfate aerosol is parametrized as a function of relative humidity in the model.
- The optical properties of sulfate aerosols such as specific extinction, single-scattering albedo and asymmetry parameter vary depending on relative humidity.
- For the aerosol experiments, we add an additional amount 20 Mt-SO4 of background sulfate aerosols in the stratosphere.

Model Experiments

- 1xCO2 - 100-year preindustrial control simulation, where CO_2 concentration is prescribed at the preindustrial value of 284.7 ppm.
- 2xCO2 - CO_2 concentration is doubled to 569.4 ppm to simulate climate change.
- Aerosols are added to the 2xCO2 experiment. We chose three different altitudes for additional aerosol layers – 100, 70, and 37 hPa (experiments are referred to as Bg_100hPa, Bg_70hPa, and Bg_37hPa). Hygroscopic growth is allowed.
- Another set of experiments are conducted where the hygroscopic growth is not allowed in the stratosphere. The non-hygroscopic growth simulations (nHG), are referred to as Bg_100hPa_nHG, Bg_70hPa_nHG, and Bg_37hPa_nHG.

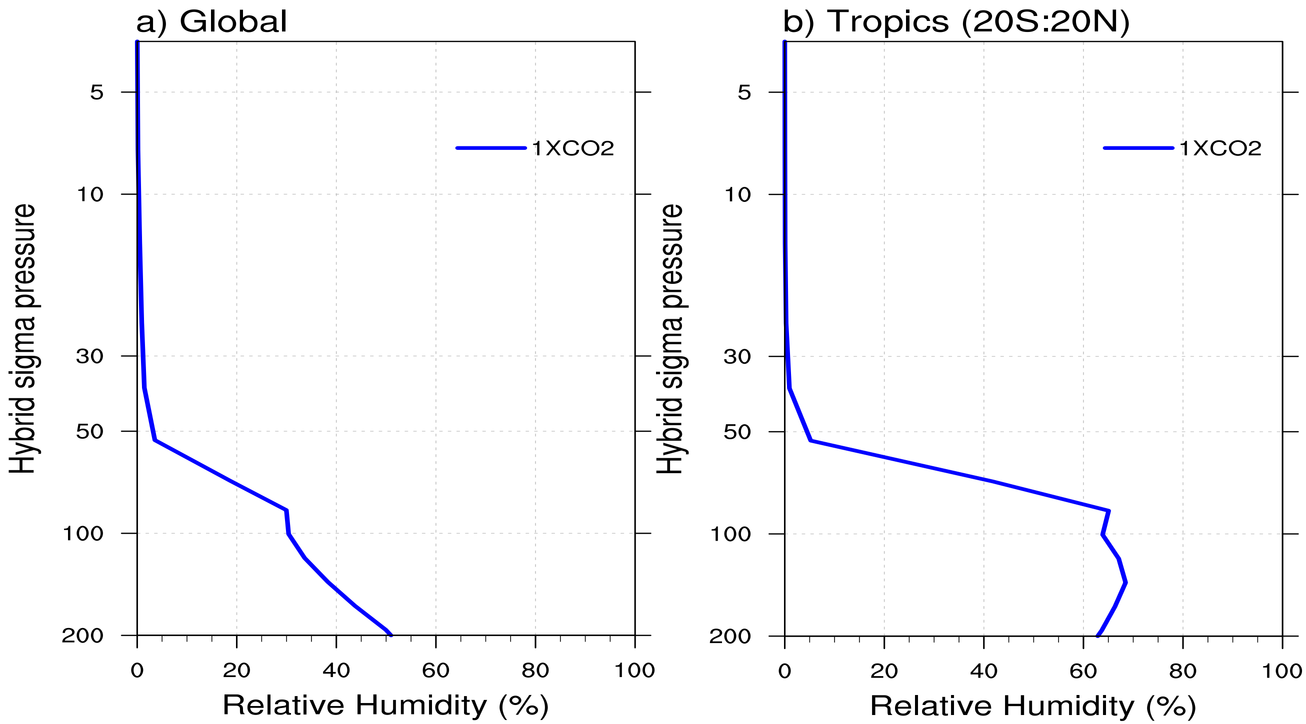
Hygroscopic growth of sulfate aerosols



- **As relative humidity increases, sulfate aerosols grow to new equilibrium sizes.**
- **This leads to an increase in SW scattering because of the increase in particle scattering coefficient.**

Data obtained from the Optical Properties of Aerosols and Clouds (OPAC) dataset (Hess et al., 1998)

Stratospheric relative humidity

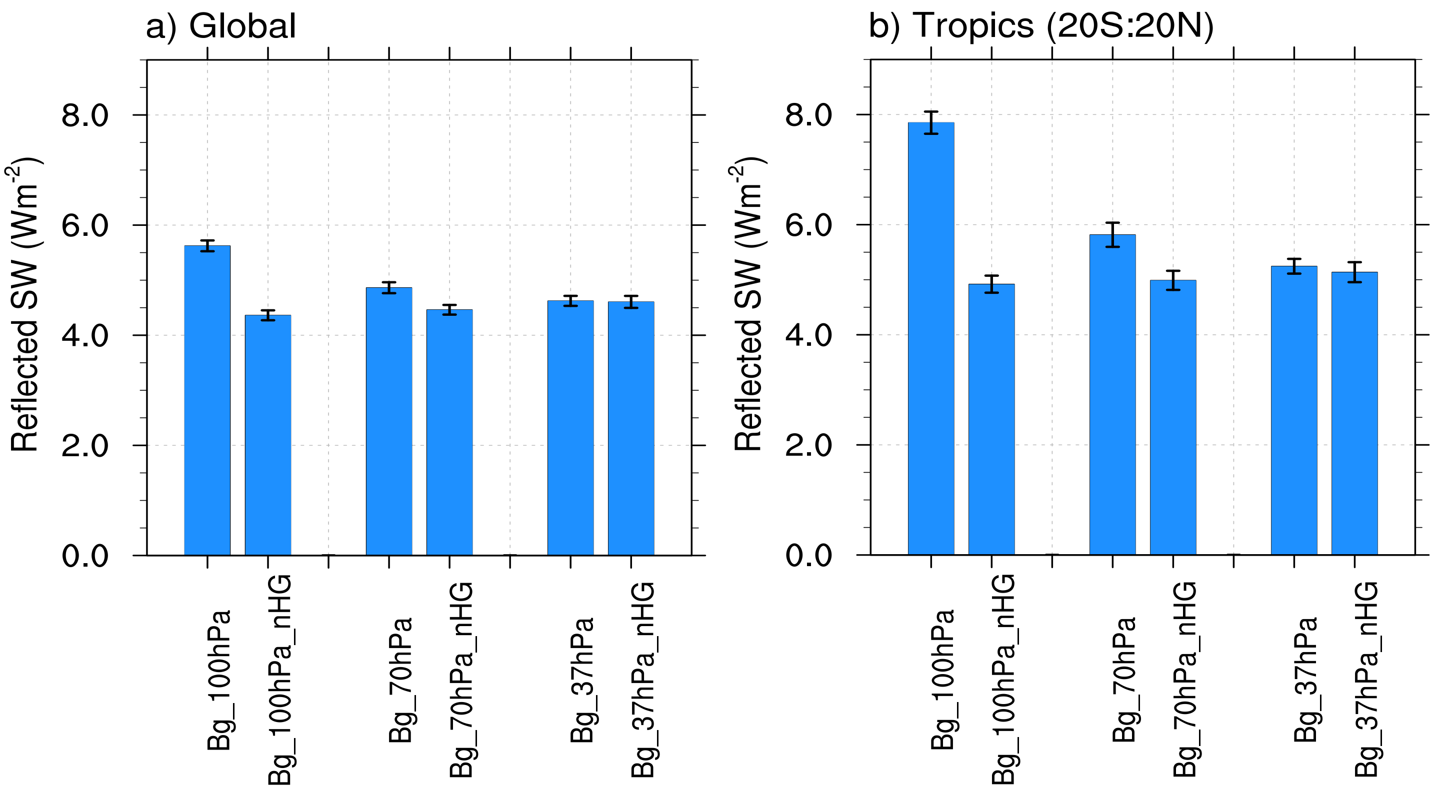


Data from 1xCO2

- **In the control (1xCO2) simulation, relative humidity decreases rapidly with increasing altitude in the stratosphere.**
- **The changes in relative humidity with height are more prominent in the tropics.**

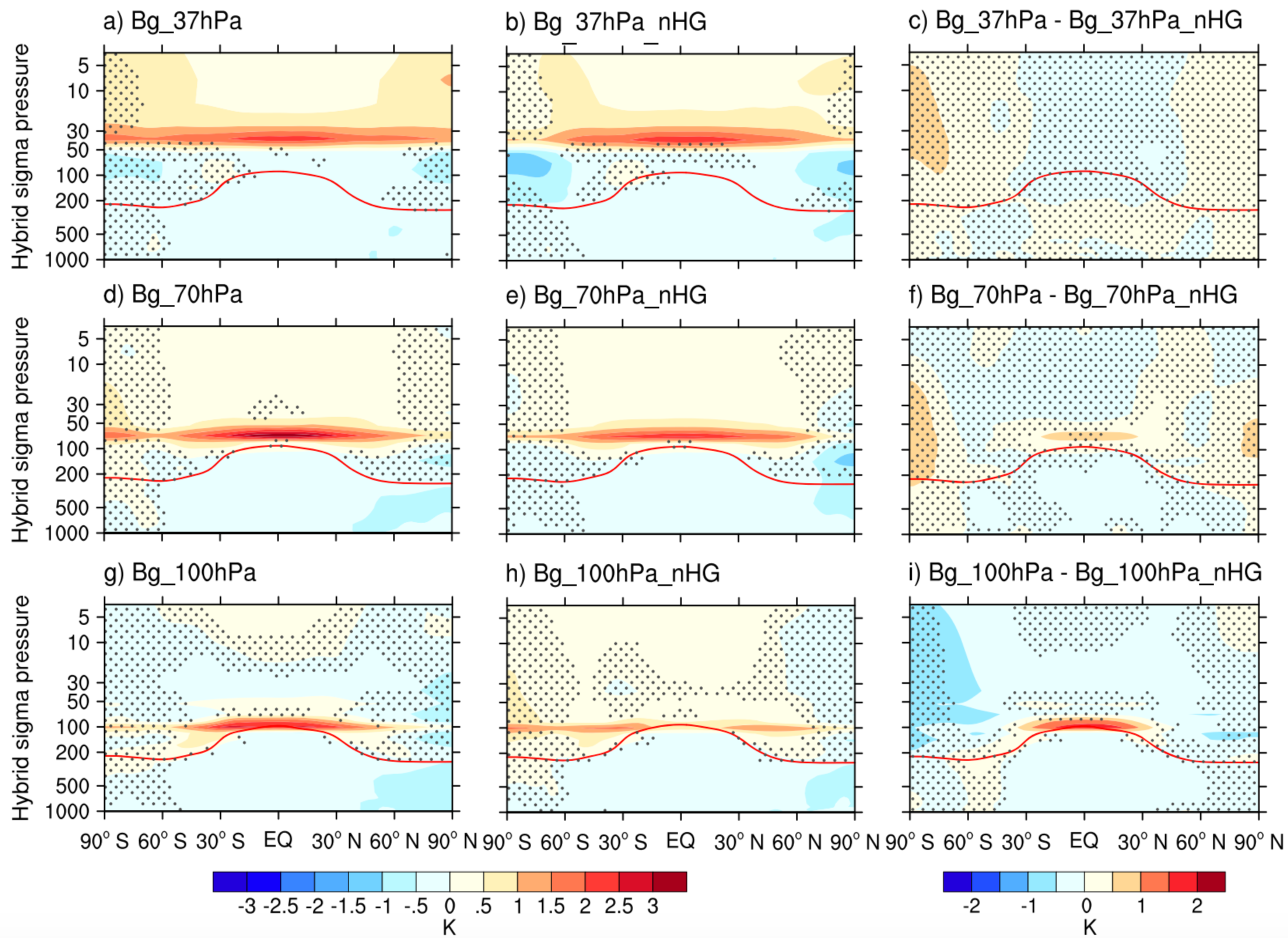
Changes shown in the following slides are relative to the 2xCO2 experiment

Changes in reflected SW radiation



- **The reflected SW radiation increases in hygroscopic growth experiments relative to the non-hygroscopic experiments.**
- **As the relative humidity values are larger in the tropics, the changes in reflected SW radiation are larger in the tropics.**

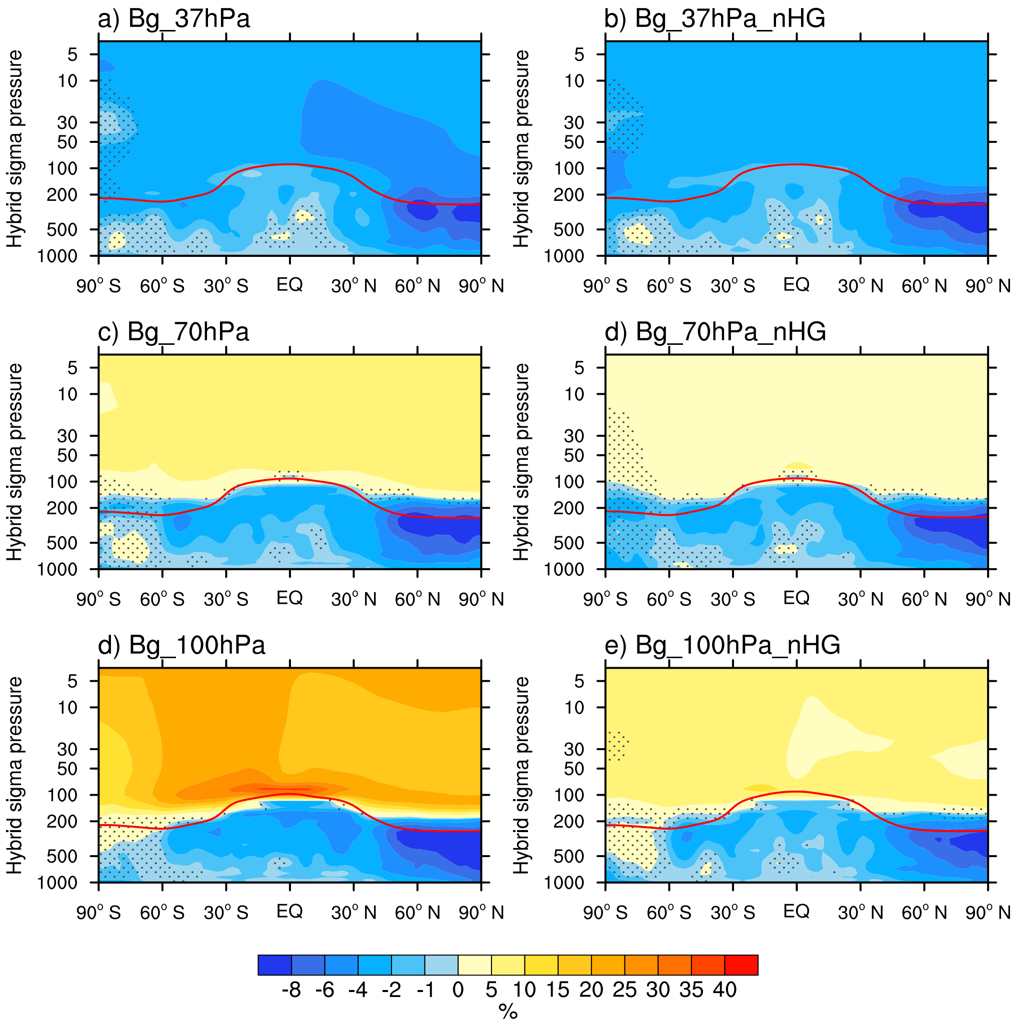
Vertical Temperature changes



- **The aerosols absorbs radiation and warm the layer where they are prescribed.**
- **The warming is more in the experiments which allow hygroscopic growth.**

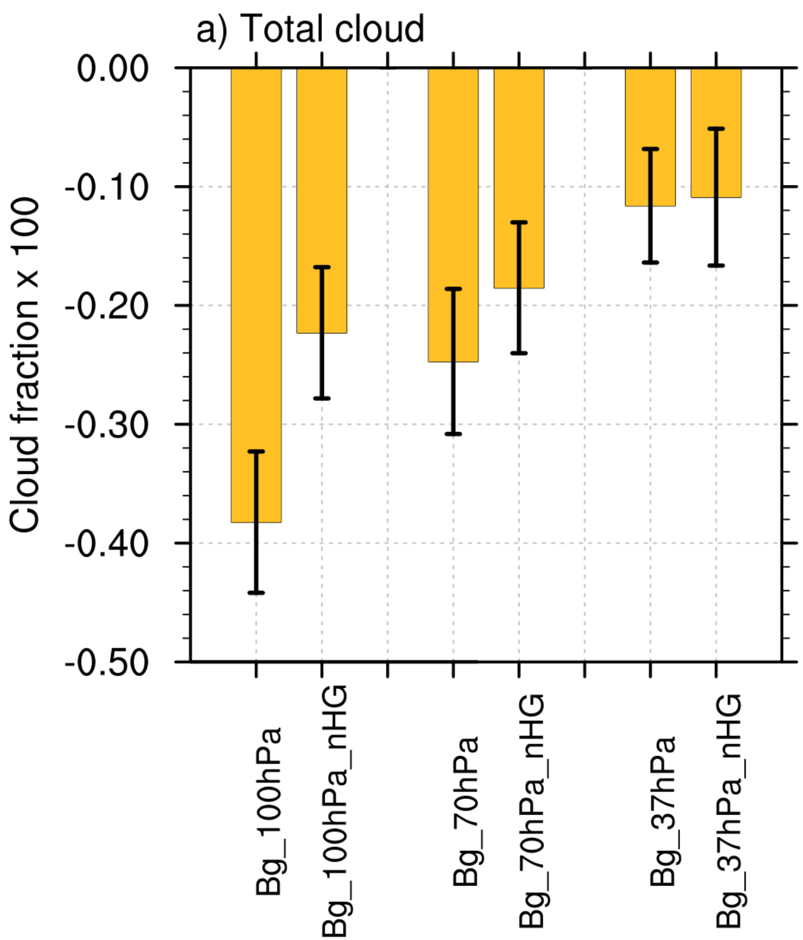
Water vapor changes

Percentage changes in specific humidity



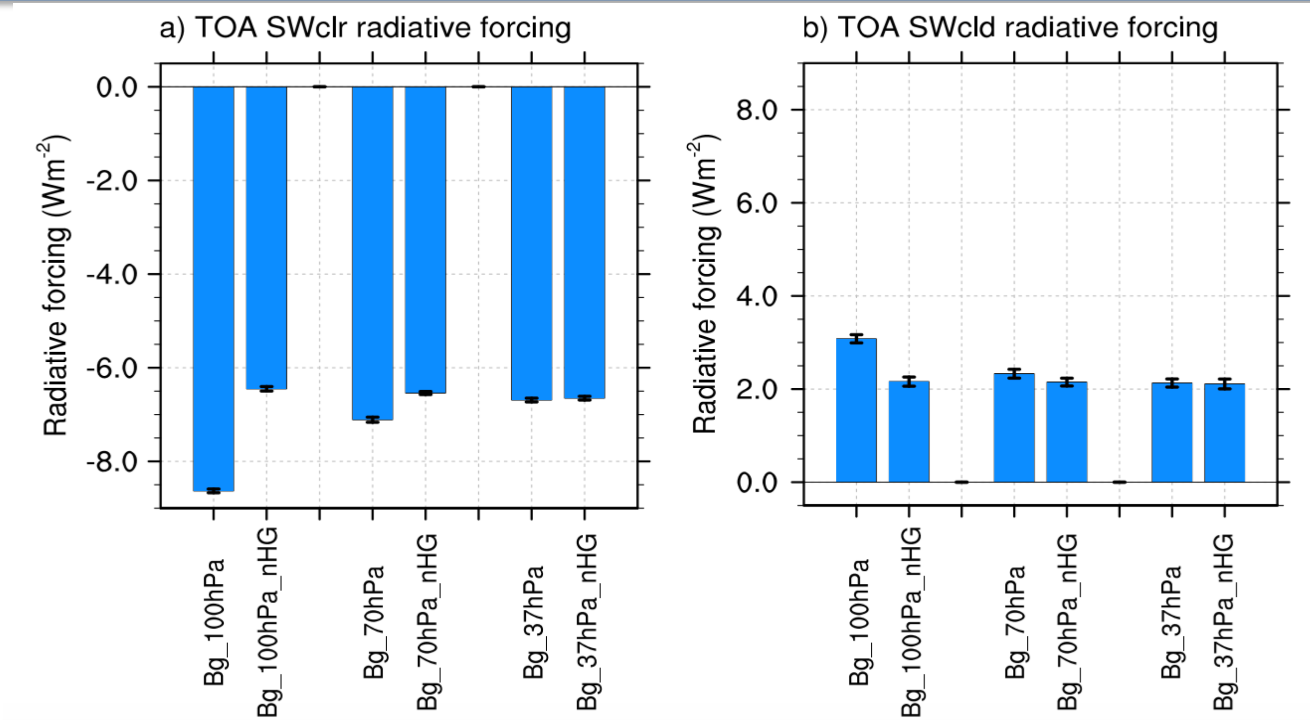
- **The aerosol-induced warming leads to enhancement in the water vapor transport from the troposphere to the stratosphere.**
- **The amount of additional water vapor in the stratosphere decreases as the aerosol layer is moved away from the tropopause.**

Cloud fraction changes



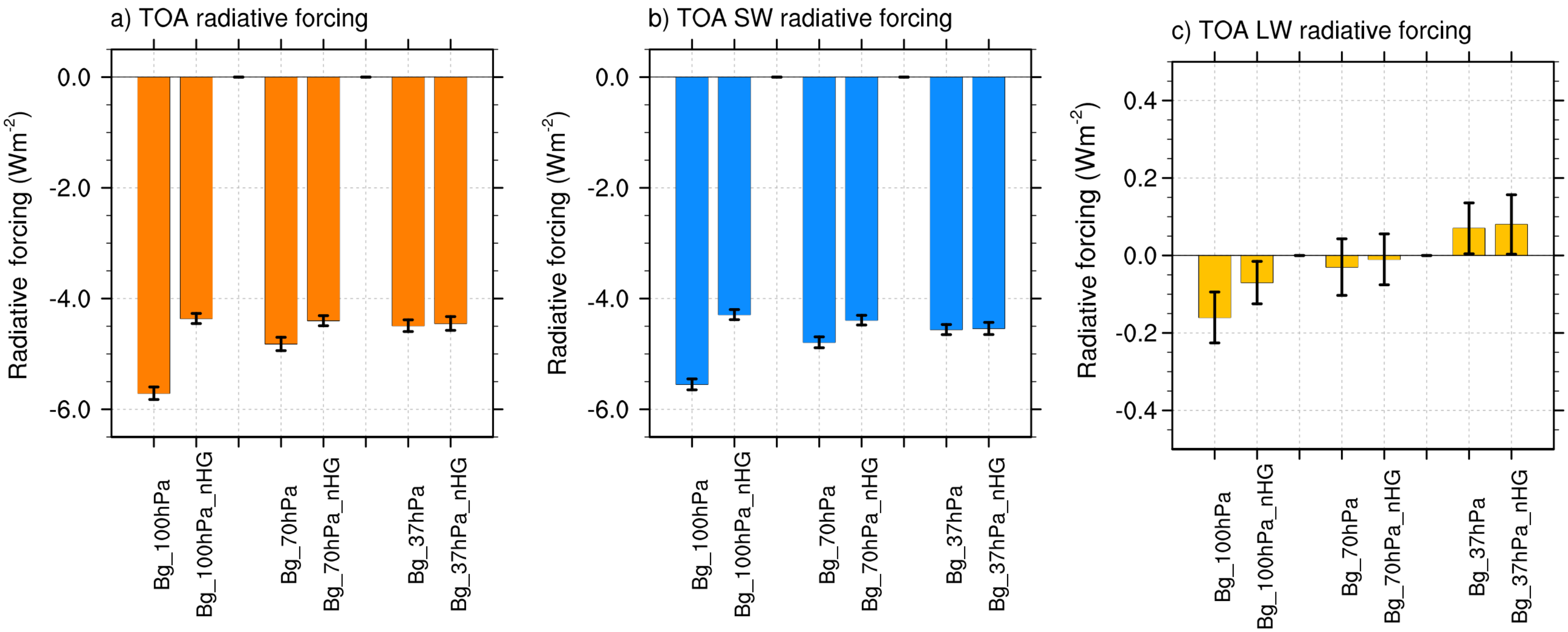
- A reduction in total cloud cover is simulated in all experiments, as the stratospheric warming by aerosols increases the stability of the troposphere leading to a reduction in total cloud cloudiness.
- The reduction is larger in the hygroscopic experiments where the warming is larger.

TOA SW radiative forcing



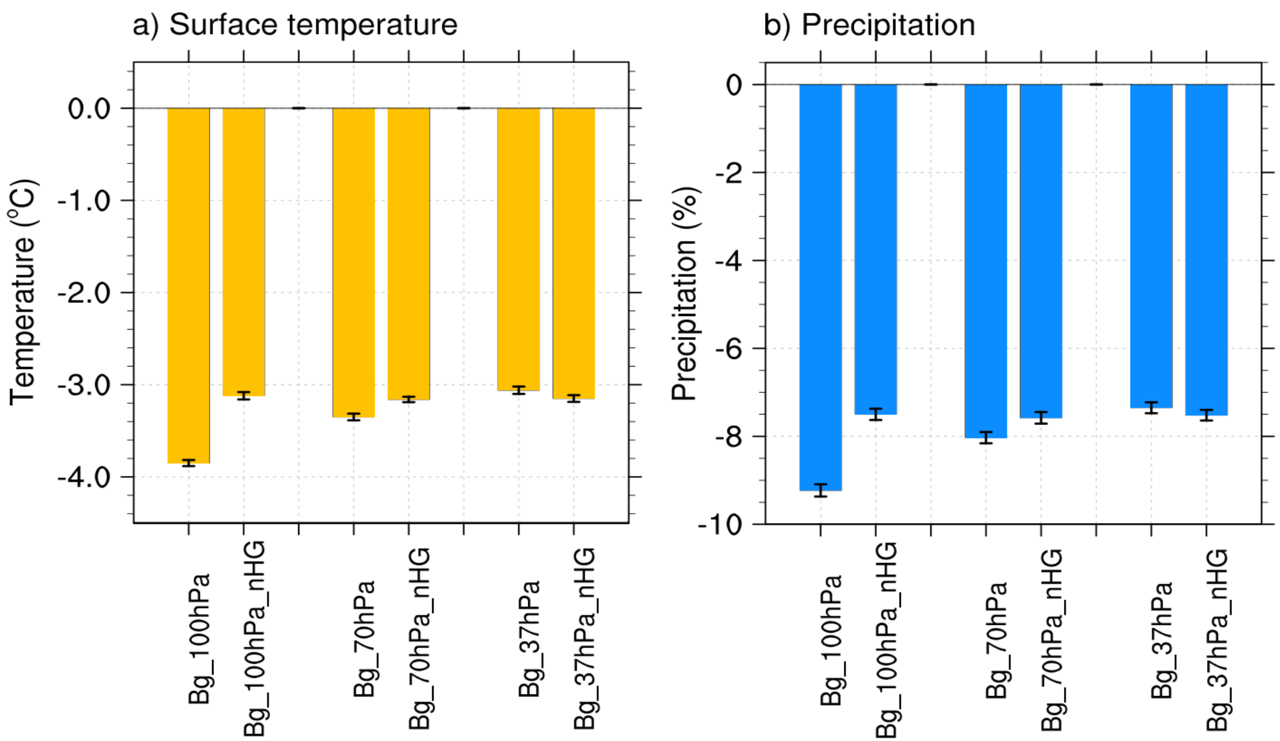
- **The shortwave (SW) radiative forcing is negative, and its magnitude is larger than longwave (LW) forcing in all cases.**
- **SW clear-sky forcing is related to scattering by aerosols (-ve) and increased absorption of SW by the additional water vapor (+ve).**
- **SW cloudy-sky forcing is related to decrease in cloudiness (+ve).**

TOA effective radiative forcing



The magnitude of effective radiative forcing is largest when aerosols are prescribed lower in the stratosphere and when hygroscopic growth is allowed (1.3 W/m^2 difference between 100 hPa hygroscopic and non-hygroscopic case).

Global Climate change



We simulate more surface cooling and consequently larger reduction in precipitation when hygroscopic growth is allowed in the model and when sulfate aerosols reside in the lower levels of the stratosphere.

Take Home Messages

- We have analysed the effect of the hygroscopic growth of sulfate aerosols on climate using idealized climate model simulations with prescribed aerosol distributions.
- Hygroscopic growth could lead to increase in the size of the aerosols and consequently an increase in scattering.
- The aerosols also heat the stratospheric layers where they reside, altering stratospheric water vapor content, tropospheric stability and clouds, and consequently the effective radiative forcing.
- As the relative humidity (and hence the hygroscopic growth) is larger in the lower stratosphere, we find that the cooling efficiency of a fixed mass of sulfate is larger when they reside in the lower levels of the stratosphere.

Publication

Krishnamohan, K. S., Bala, G., Cao, L., Duan, L., & Caldeira, K. (2020). The Climatic Effects of Hygroscopic Growth of Sulfate Aerosols in the Stratosphere. Earth's Future, 2019EF001326. https://doi.org/10.1029/2019EF001326