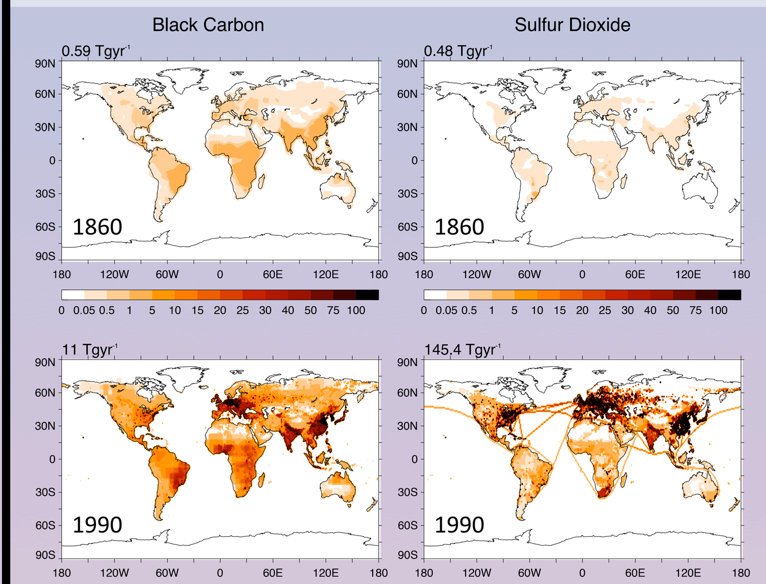
Offsetting and Complementary Characteristics of Sulfate and Soot Direct Radiative Forcings

Ilissa Ocko, *Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, New Jersey*
V. Ramaswamy and Paul Ginoux, *NOAA Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey*

Abstract

- This study investigates the competing and complimentary aspects of anthropogenic sulfate and soot direct radiative forcing (DRF) in the context of a successful climate model – GFDL CM2.1
  - Results show that sulfate and black carbon global-mean DRFs evenly offset one another (0.87 W/m^2 black carbon; -0.96 W/m^2) at the top-of-atmosphere (TOA) , whereas surface direct radiative forcings are both negative and additive, exerting a combined forcing of -2.12 W/m^2
- We focus on factors governing the scattering-absorbing aerosol balance for the global-mean and geographically – clouds, relative humidity, surface albedo
  - Results show that without clouds, sulfate would dominate the aerosol TOA DRF balance, and without sulfate hygroscopic growth from high relative humidity, black carbon would dominate the balance

Introduction



Annual Emissions (10^{-12} kgm^{-2}s^{-1})

- Aerosols directly perturb Earth's radiative balance by scattering and absorbing shortwave and longwave radiation
  - All aerosols decrease amount of radiation reaching surface, which can reduce the strength of the hydrological cycle
  - Aerosols have competing warming/cooling characteristics at top-of-atmosphere, which can affect Earth's temperature
    - Scattering aerosols (e.g. **sulfate**) enhance planetary albedo
    - Absorbing aerosols (e.g. **black carbon**) trap energy in climate
- Concentrations of aerosols have risen considerably since pre-industrial times
- RF is uncertain since aerosols are short-lived and vary spatially; therefore, offsetting characteristics may change regionally

Model Description

- The GFDL CM2.1 model is used in conjunction with MOZART to simulate the global distribution and radiative forcing of black carbon and sulfate aerosols
- Horizontal resolution of MOZART is 2.8° by 2.8°, aerosols are remapped to the 2° by 2.5° resolution of CM2.1 with 24 vertical levels
- Emissions are taken from inventories compiled for IPCC AR4 [*Horowitz*, 2006]
- CM2.1 radiation code used to calculate radiative forcings, with the shortwave radiation algorithm adapted from *Freidenreich and Ramaswamy* [1999] and the longwave radiation algorithm from *Schwarzkopf and Ramaswamy* [1999]
- Aerosol optical depth, single scattering albedo and asymmetry parameter calculated as a function of hygroscopic growth and optical properties derived from Mie theory

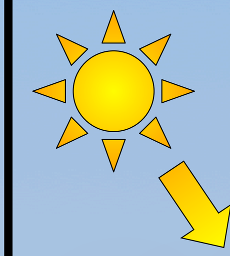
Model Simulations

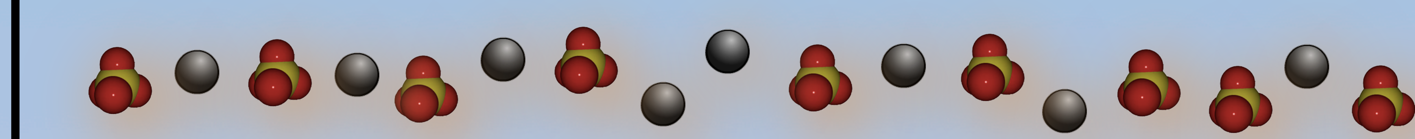
Control Case – *Radiative forcing calculations derived using realistically simulated climate conditions, including typical geographical distributions of horizontal and vertical cloud cover and relative humidity, surface albedo, and insolation*

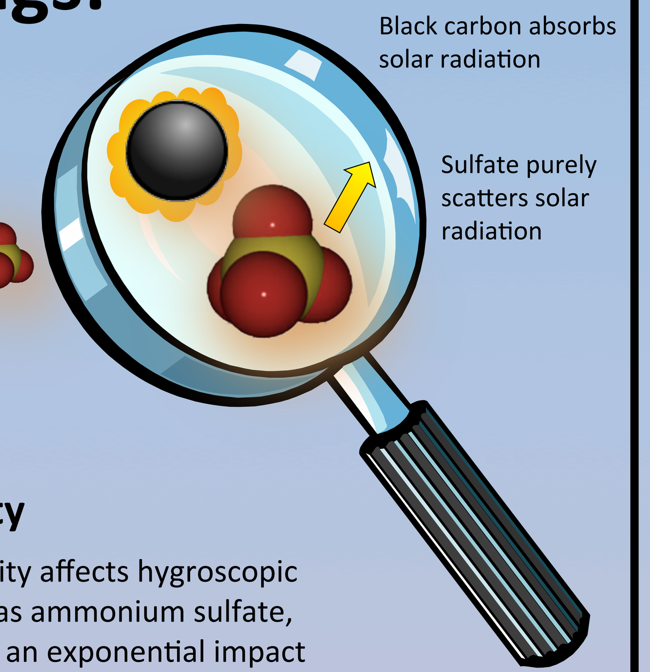
Experiments – *sensitivity studies of governing factors*

1. **Cloud Impact** – *DRFs were calculated for clear-sky conditions (zero clouds) and subtracted from the control case to determine the impact from the presence of clouds*
2. **Relative Humidity Impact** – *DRFs were calculated for dry sulfate conditions (30% relative humidity) and subtracted from the control case to determine the impact from hygroscopic sulfate*
3. **High Albedo Impact** – *DRFs were calculated for constant low surface albedo conditions (0.1) and subtracted from the control case to determine the impact from presence of high surface albedos*

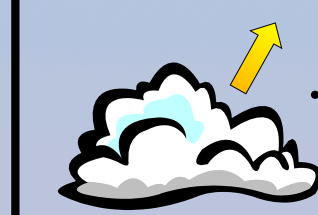
Aerosol Direct Radiative Forcings: physics and governing factors





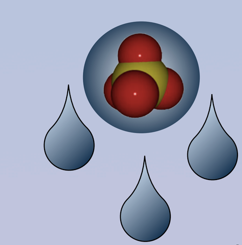


1. Cloud Coverage



- Relationship depends on the vertical distribution of the clouds and aerosols in the atmospheric column
- When clouds exist above the aerosol layer, they block radiation from penetrating through
- When clouds are below the aerosol layer, radiation is scattered back into the aerosol layer, allowing absorbing aerosols to interact with more radiation and therefore enhancing positive DRFs

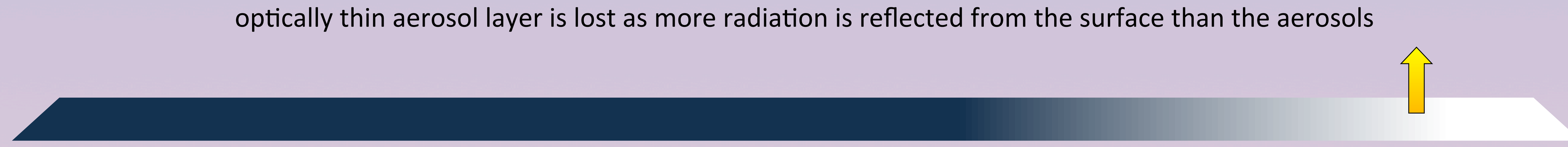
2. Relative Humidity



- Relative humidity affects hygroscopic aerosols, such as ammonium sulfate, and introduces an exponential impact on the specific extinction of sulfate as humidity increases and the sulfate particles swell
- The larger the size of the particle, the more radiation it scatters or absorbs

3. Surface Albedo

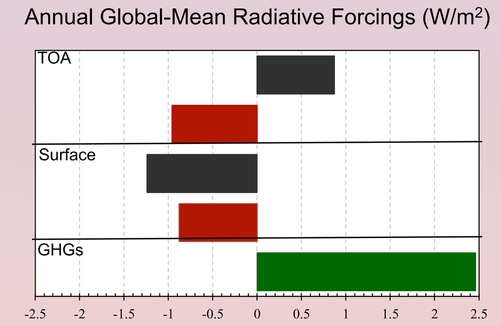
- Similar to the impact from low clouds, high albedo surfaces (deserts, snow and ice) reflect more radiation into the aerosol layer, significantly enhancing positive DRFs from absorbing aerosols
- DRFs from scattering aerosols are reduced since the contrast between a low albedo surface and an optically thin aerosol layer is lost as more radiation is reflected from the surface than the aerosols

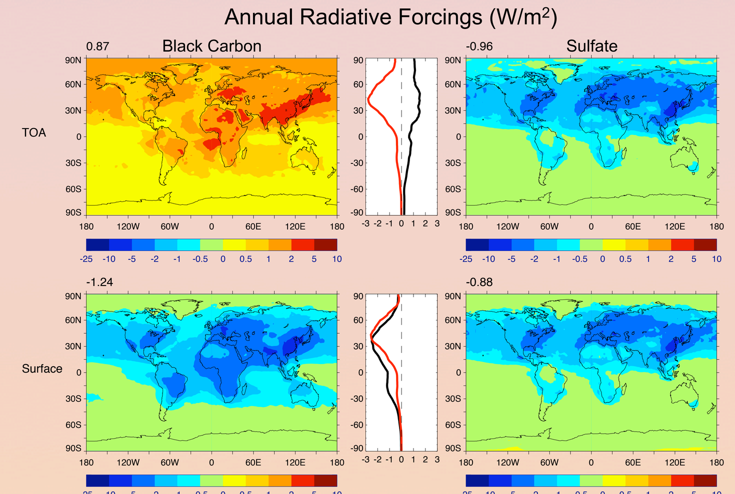


Results

KEY: Black Carbon; Sulfate

Control Case



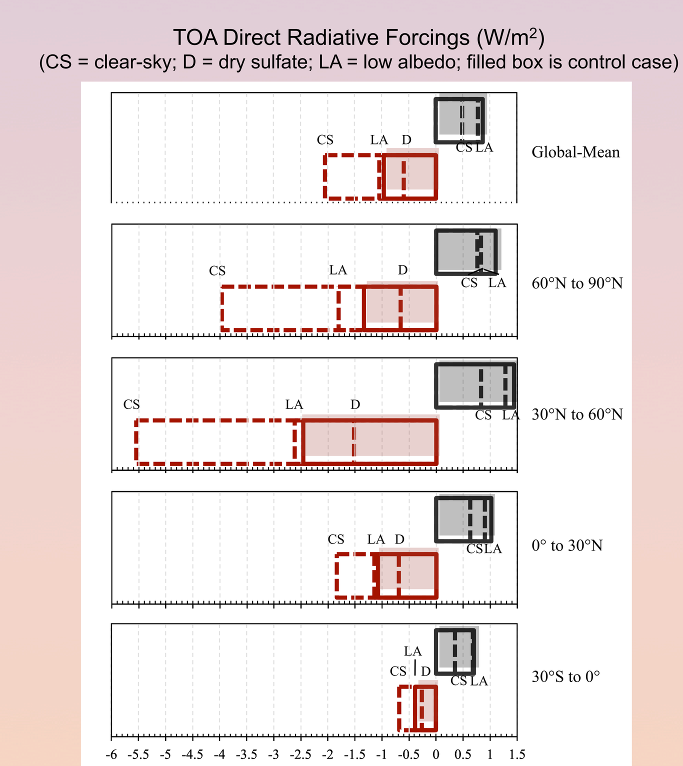


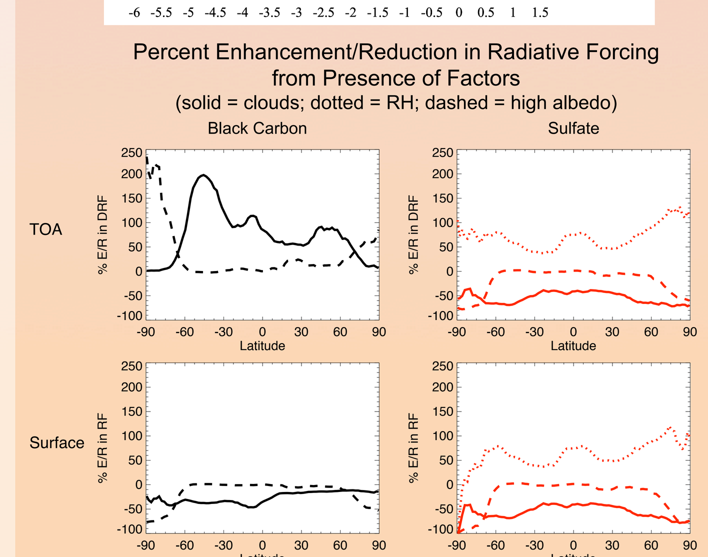
Annual Radiative Forcings (W/m^2)

	TOA			Surface		
	BC	SO_4	BC+SO_4	BC	SO_4	BC+SO_4
Global-mean	0.87	-0.96	-0.09	-1.24	-0.88	-2.12
60°N to 90°N	1.1	-1.33	-0.23	-0.7	-1.03	-1.73
30°N to 60°N	1.44	-2.46	-1.02	-2.11	-2.25	-4.36
0° to 30°N	1.02	-1.08	-0.06	-1.75	-1.01	-2.76
30°S to 0°	0.7	-0.39	0.31	-1.1	-0.37	-1.47
75°N to 90°N	0.89	-0.58	0.31	-0.29	-0.31	-0.60
60°N to 75°N	1.20	-1.70	-0.50	-0.89	-1.37	-2.26

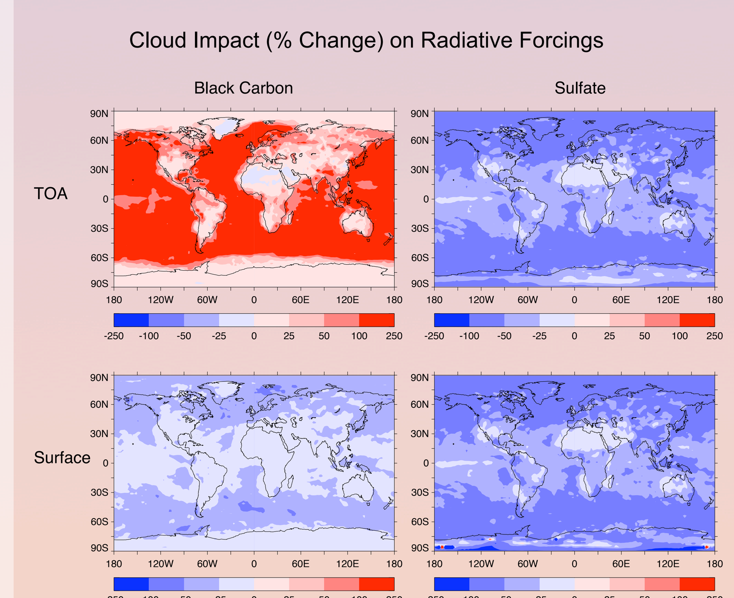
- Near-complete offset for TOA global-mean
- RFs peak where emissions peak, sulfate dominates offset
- BC TOA DRF high and constant in Arctic, offset flips signs

Experiments



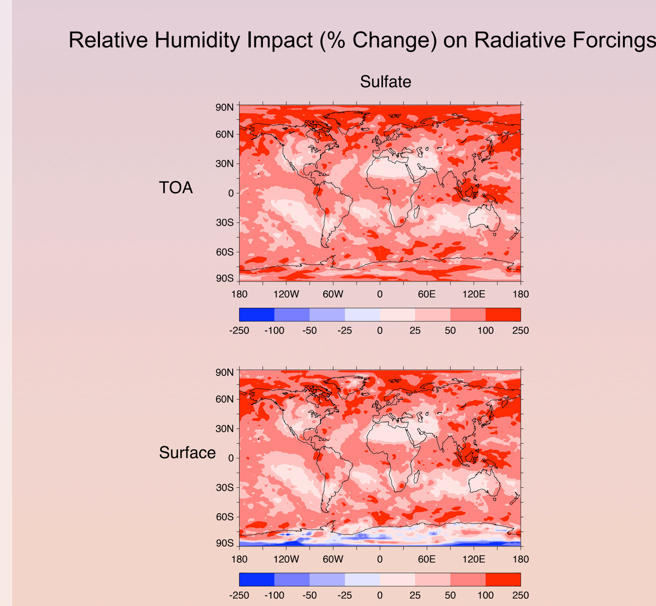


1. Cloud Impact



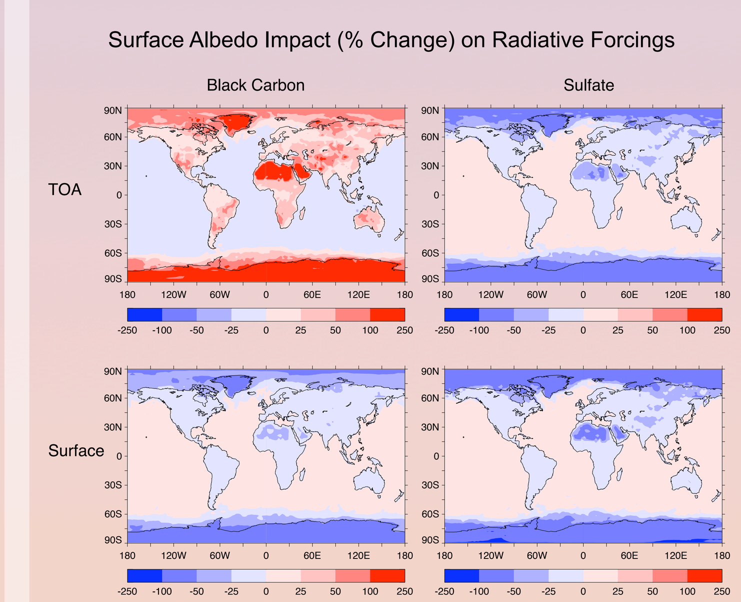
- Globally averaged annual SO_4 TOA DRF is reduced by roughly half when clouds present
- Globally averaged annual BC TOA DRF is enhanced by double when clouds present
- Clouds play minor role in changing BC TOA DRF in polar regions (close to 0% change)
- Clouds reduce SO_4 SFC DRF more than BC SFC DRF; but enhance BC TOA DRF more than reducing SO_4 TOA DRF

2. Relative Humidity Impact



- Relative humidity enhances SO_4 DRFs by over 60% for global average
- Relative humidity enhances SO_4 DRFs by over 100% in the Arctic
- BC DRFs would dominate aerosol forcing if SO_4 was not hygroscopic

3. Surface Albedo Impact



- High albedo surfaces enhance BC TOA DRFs, reduce all other DRFs
- As large of an impact on SO_4 DRFs as BC, larger for SFC DRFs
- Comparable impacts in Arctic and Antarctica, but magnitudes increased much more in Arctic
- Impact on magnitude of DRFs approximately increases with latitude in Northern Hemisphere

Conclusions

- Sulfate and black carbon top-of-atmosphere DRFs are offsetting
  - BC DRF (+0.87 W/m^2): ⅓ of all GHG RF; ½ of CO_2 RF
  - SO_4 DRF (-0.96 W/m^2)
- Sulfate and black carbon surface DRFs are additive and negative (BC: -1.24 W/m^2; SO_4: -0.88 W/m^2)
  - May decrease strength of hydrological cycle
- Sulfate DRF enhanced by relative humidity (63% globally) and reduced by clouds (~50% globally) and high albedo (8% globally)
- Black carbon DRF impacts different for top-of-atmosphere and surface – TOA affected more
  - TOA – BC DRF enhanced by clouds (78% globally) and high albedo (10% globally)
  - SFC – BC DRF reduced by clouds (22% globally) and high albedo (3% globally)

Percent Change in Annual Global-Mean Radiative Forcing

	TOA		Surface	
	BC	SO_4	BC	SO_4
Cloud cover	78%	-53%	-22%	-52%
High albedo surfaces	10%	-8%	-3%	-8%
High relative humidity		63%		63%

Future Work

- Include internal mixtures, black carbon deposition in snow, and indirect effects on clouds
- Perform sensitivity studies on the vertical distribution of clouds and aerosols in relation to one another
- Implications for policy and climate will be explored

Acknowledgments:

I would like to thank my graduate advisor, V. Ramaswamy, for all of his guidance and brilliant insight; Paul Ginoux and Larry Horowitz for being incredible resources to me throughout my work, of whom my success would not have been possible without; My colleagues, especially Amanda O'Rourke and Andrew Ballinger, for our stimulating discussions; Joseph Roy-Mayhew for constantly challenging me; and Greg Seroka for supporting and inspiring me always.