

Soot: Air quality and climate

Suies : Qualité de l'air et climat

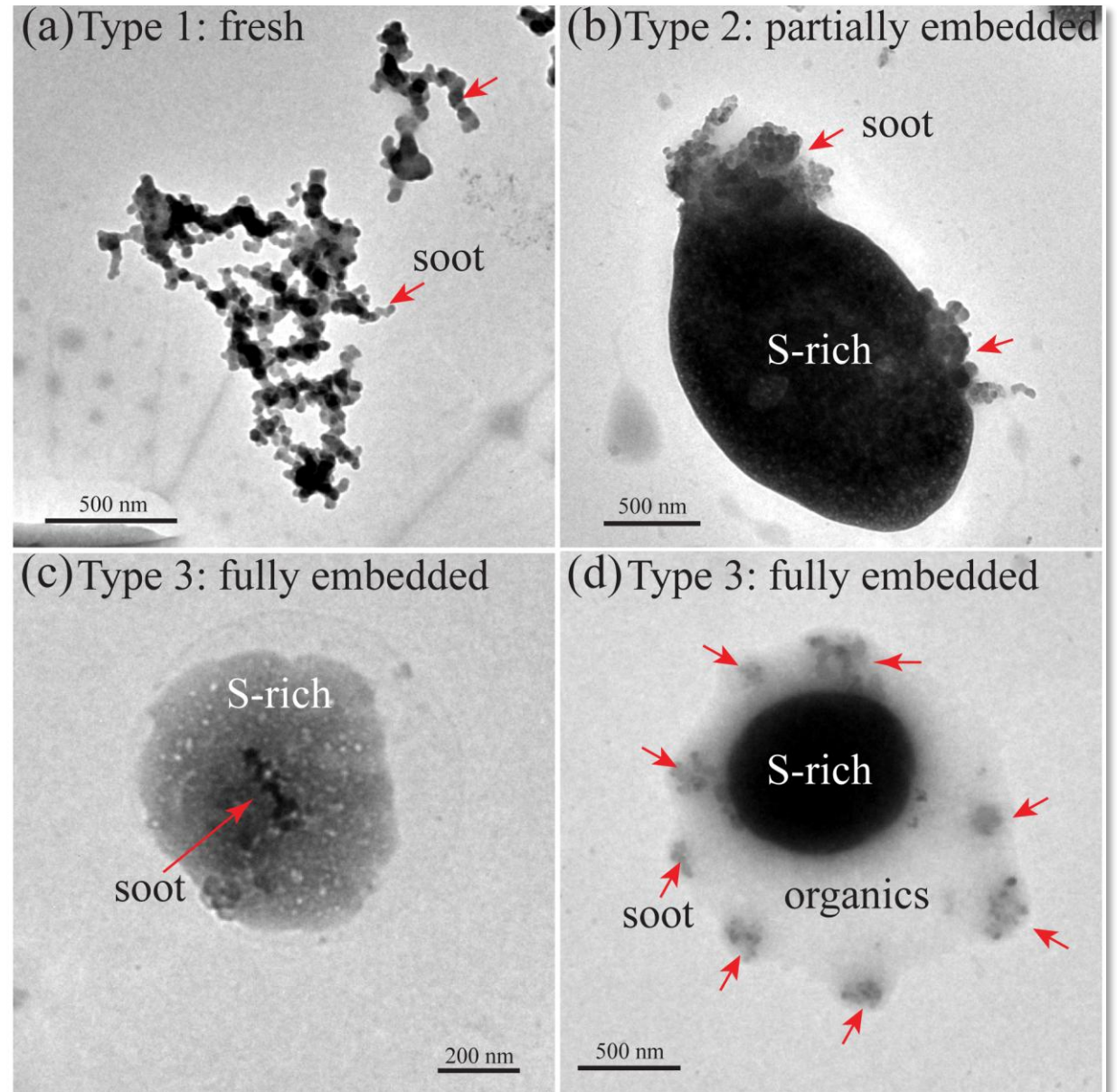
Nicolas Bellouin

Remise de la Grande Médaille de l'Académie des Sciences à V Ramanathan

9 September 2025

Soot

- Particulates emitted into the atmosphere by the incomplete combustion of hydrocarbons and biomass
- Also called “black carbon”
- Absorbs sunlight, but absorption properties change as soot mixes with light-scattering compounds



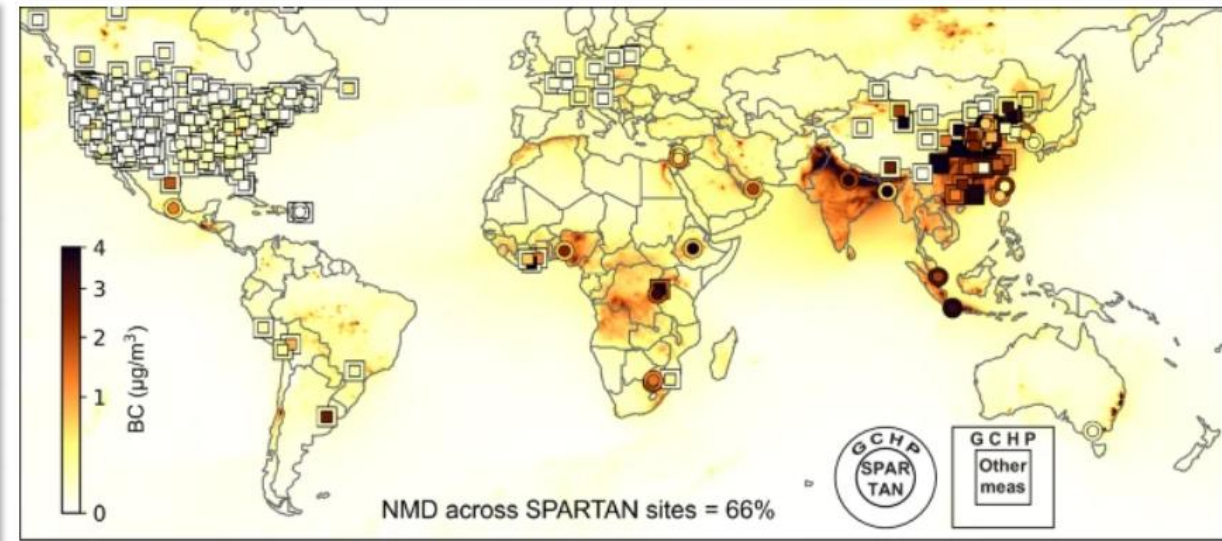
Source: Xu et al. 2020 <https://doi.org/10.5194/acp-20-14321-2020>

Soot emissions by human activities

Emissions

Compound	Type	Approximate emissions Mt yr ⁻¹ , 2024
Sulfur dioxide	Gaseous precursor	71
Ammonia	Gaseous precursor	71
Organic carbon	Particulate matter	36
Soot	Particulate matter	8

Soot concentration (surface)



Average 2019-2023, $\mu\text{g m}^{-3}$



Source: Forster et al. (2025) <https://doi.org/10.5194/essd-17-2641-2025>; Ren et al. (2025) <https://doi.org/10.1038/s41467-025-62468-5>

Particulate matter is harmful to human health

- Particulate matter causes disease.
 - Mostly cardiovascular and chronic respiratory diseases
- Globally, ambient particulate matter pollution contributed to between 3.5 and 5.8 million deaths in 2021
 - Up 31% since 2010, especially in Asia
 - In France, 40,000 deaths, 8 months of lost life expectancy for people over 30





Reduction of Tropical Cloudiness by Soot

A. S. ACKERMAN, Q. B. TOON, D. E. STEVENS, A. J. HEYMSFIELD, V. RAMANATHAN, AND E. J. WELTON [Authors Info & Affiliations](#)

SCIENCE • 12 May 2000 • Vol 288, Issue 5468 • pp. 1042-1047 • DOI: 10.1126/science.288.5468.1042



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Letter | Published: 02 August 2007

Warming trends in Asia amplified by brown cloud solar absorption

[V. Ramanathan](#) & [M. M. Gnanaprakasam](#) [Email](#) [G. Gnanaprakasam](#), [Chul](#)**nature geoscience**[Explore content](#) ▾[About the journal](#) ▾[Publish with us](#) ▾[nature](#) > [nature geoscience](#) > [review articles](#) > article

Review Article | Published: 23 March 2008

Global and regional climate changes due to black carbon

[V. Ramanathan](#) & [G. Carmichael](#) [Email](#)[Nature Geoscience](#) **1**, 221–227 (2008) | [Cite this article](#)**16k** Accesses | **3229** Citations | **285** Altmetric | [Metrics](#)

Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle

V. Ramanathan, C. Chung, D. Kim, T. Bettge, L. Buja, J. T. Kiehl, W. M. Washington, Q. Fu, D. R. Sikka, and M. Wild [-6](#)

[Authors Info & Affiliations](#)

March 4, 2005 | 102 (15) 5326-5333 | <https://doi.org/10.1073/pnas.0500656102>

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Indian Ocean Experiment: An integrated analysis of the climate forcing and effects of the great Indo-Asian haze

V. Ramanathan, P. J. Crutzen, W. Cantrell, G. R. Cass, J. Heintzenberg, A. J. Heyes, T. N. Krishnamurti, D. L. Lawrence, K. Priestley, J. M. Prospero, G. E. Shaw, P. Sheridan

First published: 01 November 2003

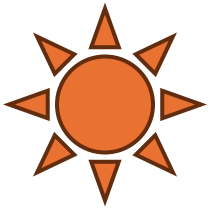
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Letter | Published: 04 May 2000

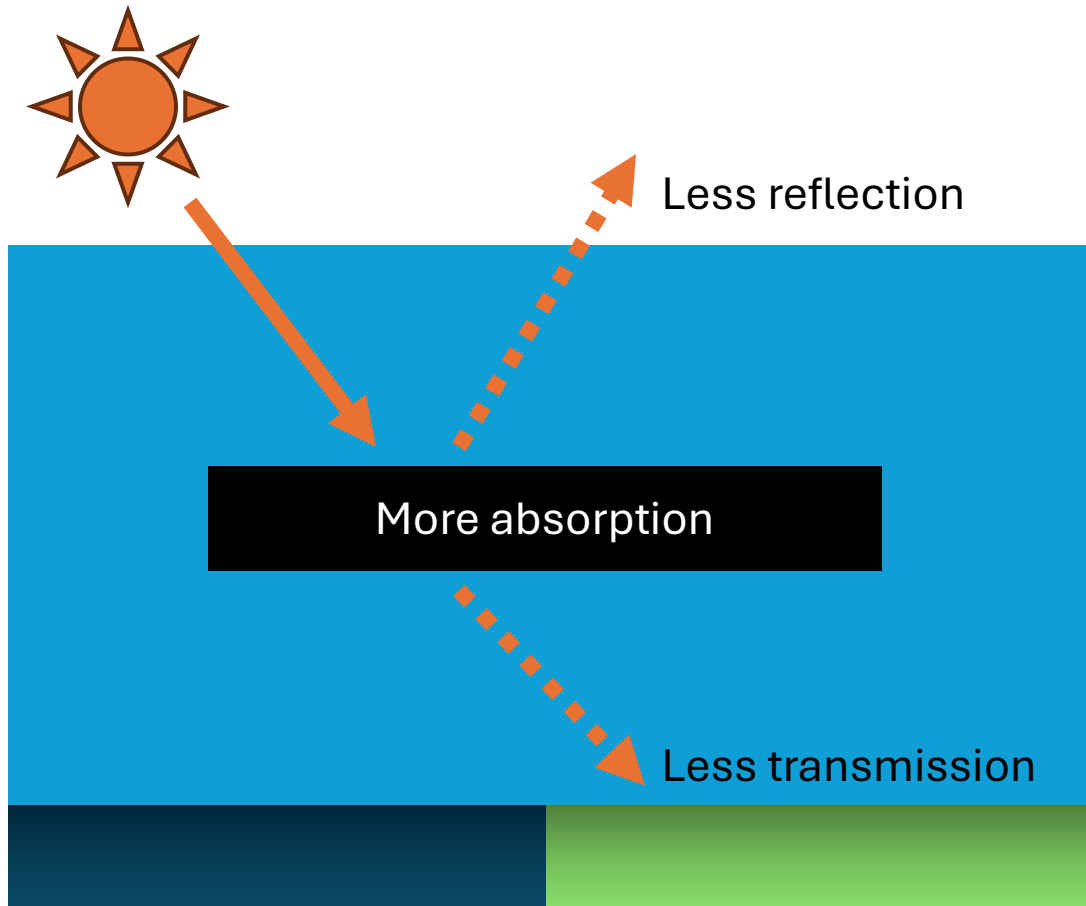
Large differences in tropical aerosol forcing at the top of the atmosphere and Earth's surface

[S. K. Satheesh](#) & [V. Ramanathan](#) [Email](#)[Nature](#) **405**, 60–63 (2000) | [Cite this article](#)**1955** Accesses | **551** Citations | **18** Altmetric | [Metrics](#)

What happens when you put something black in the atmosphere?

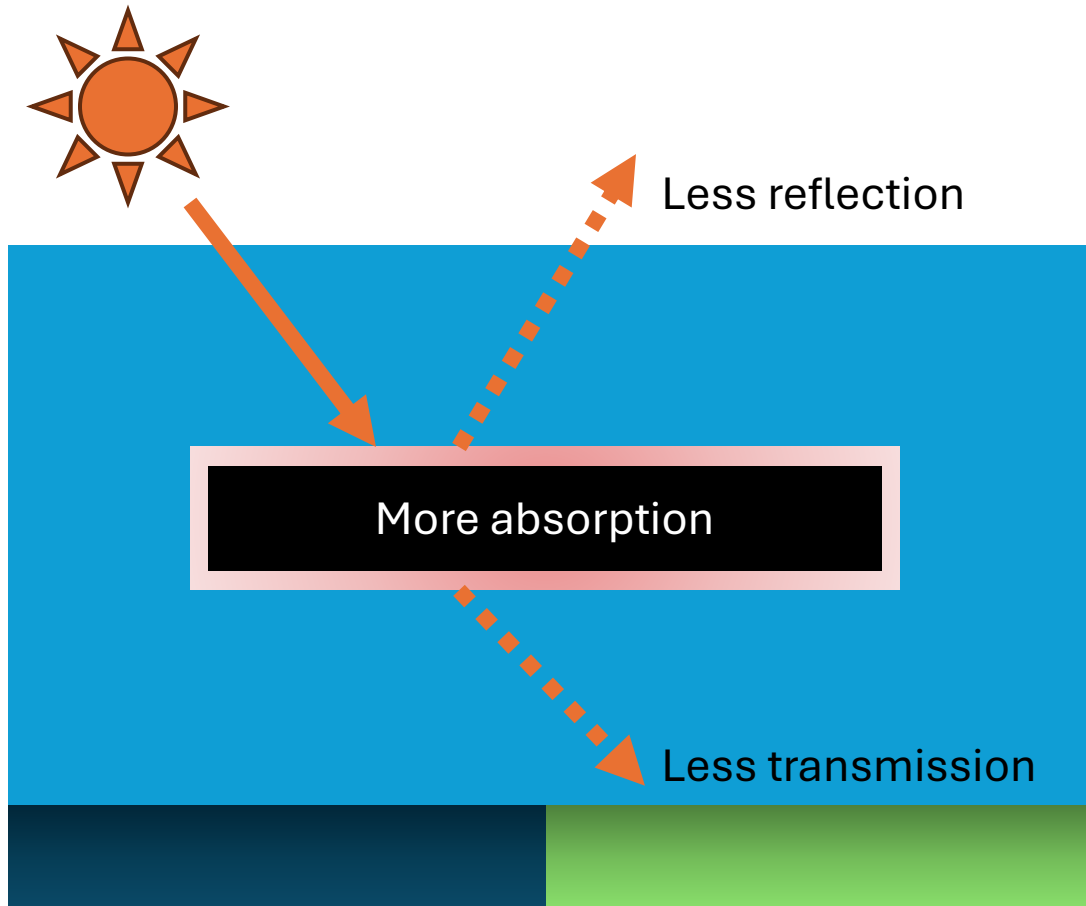


What happens when you put something black in the atmosphere?



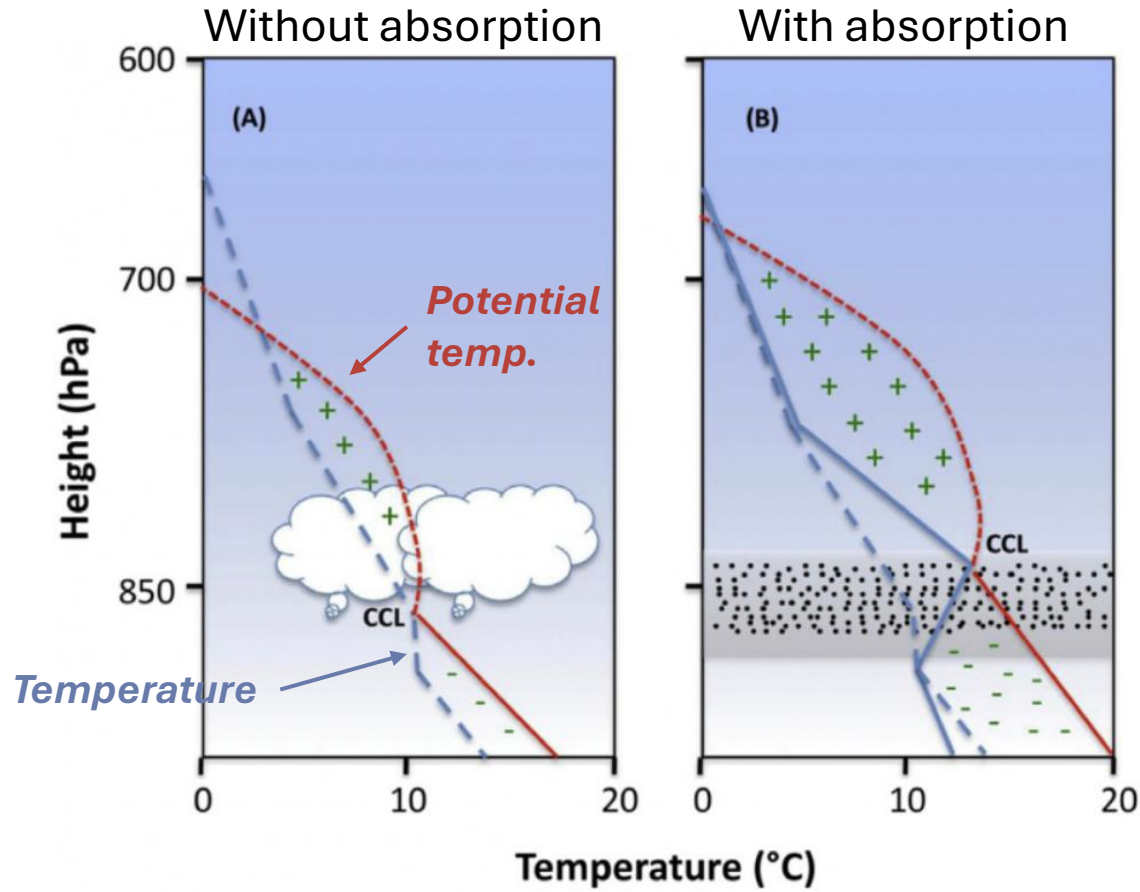
- Increased absorption of solar radiation
 - Less solar radiation reaches the surface
 - Less solar radiation is reflected to space

What happens when you put something black in the atmosphere?

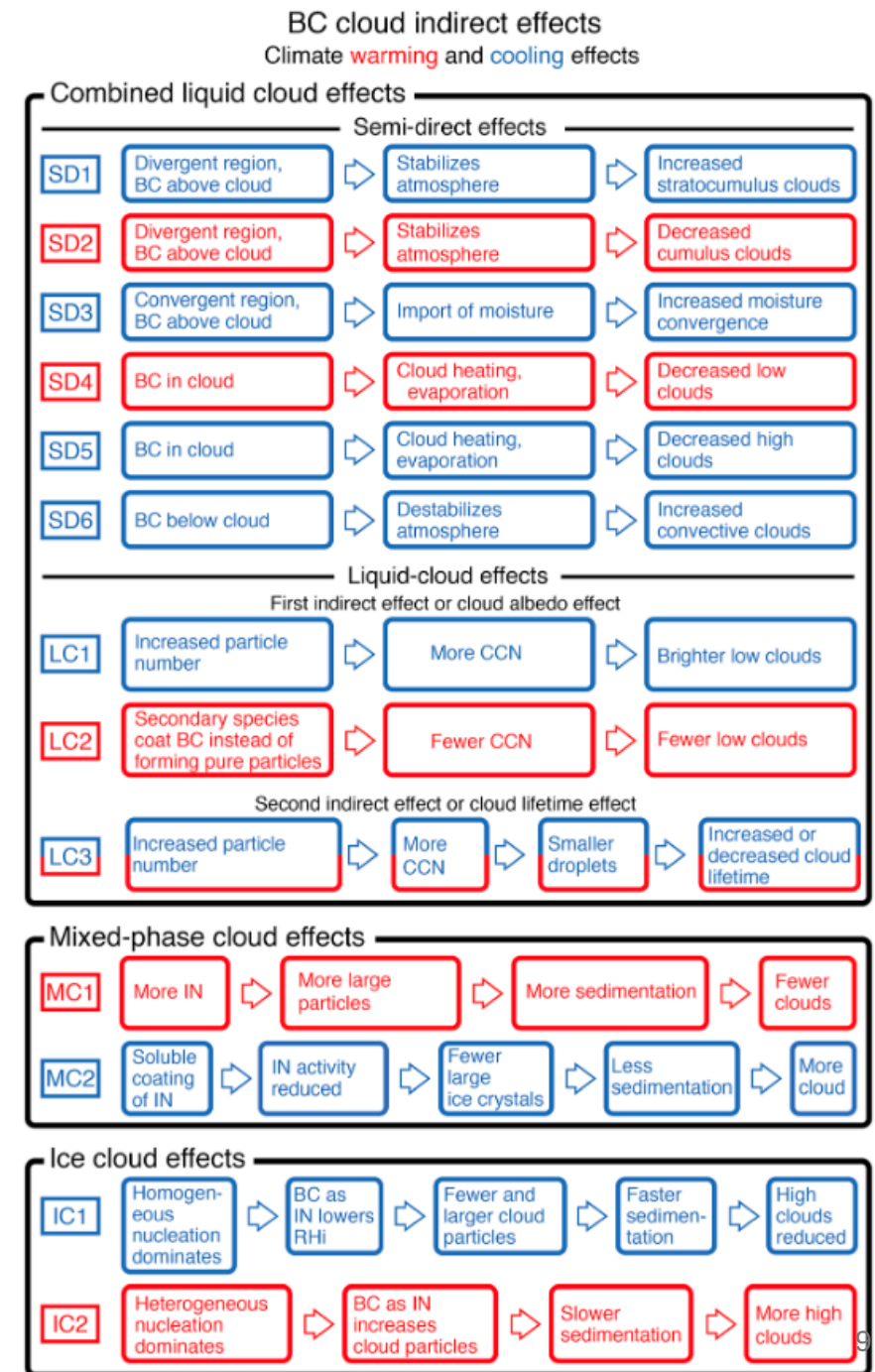


- Increased absorption of solar radiation
 - Less solar radiation reaches the surface
 - Less solar radiation is reflected to space
- Additional, local heating
 - Decreased atmospheric lapse rate
 - Change in atmospheric stability

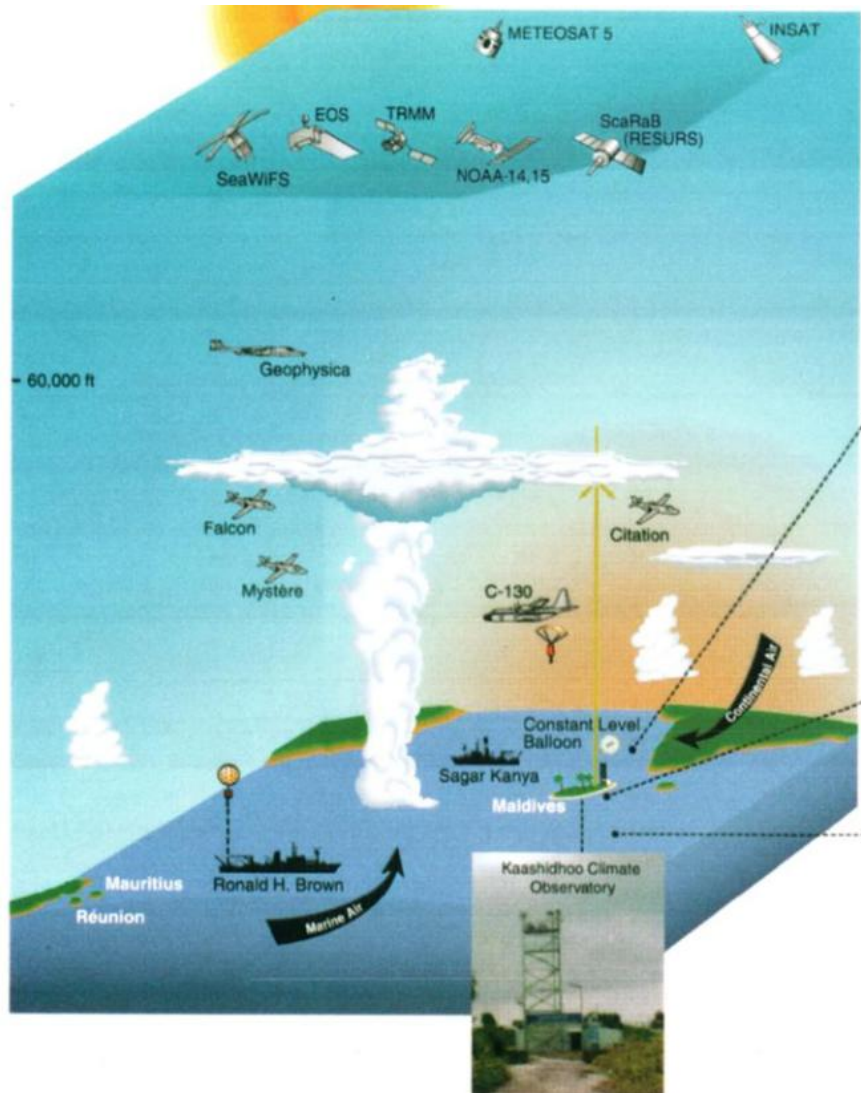
Absorption modifies cloud formation



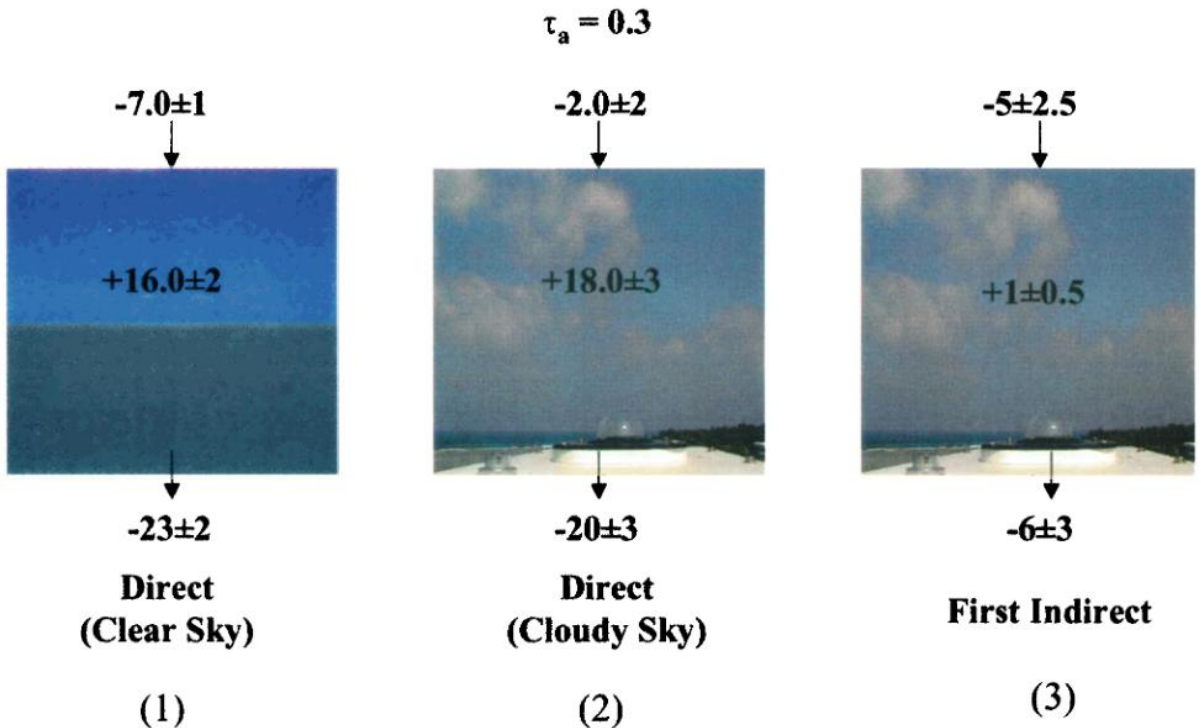
Source: Wang et al. (2013) <https://doi.org/10.1016/j.atmosenv.2013.09.034>
 Bond et al. (2013) <https://doi.org/10.1002/jgrd.50171>



Indian Ocean Experiment (INDOEX)

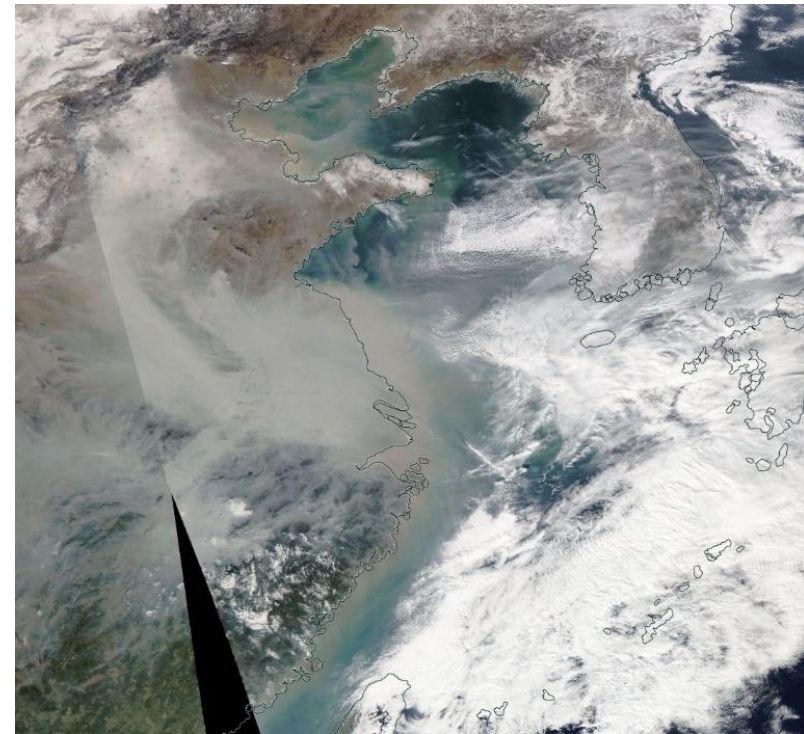


**Aerosol Radiative Forcing (W m^{-2}): North Indian Ocean
(Jan - March, 1999; $0 - 20^\circ\text{N}$)**

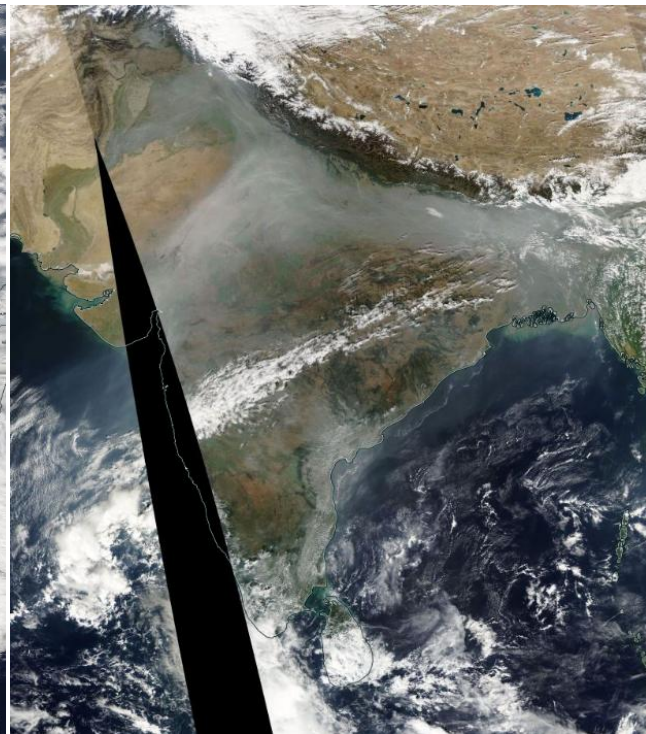


Source: Ramanathan et al. (2001) <https://doi.org/10.1029/2001JD900133>

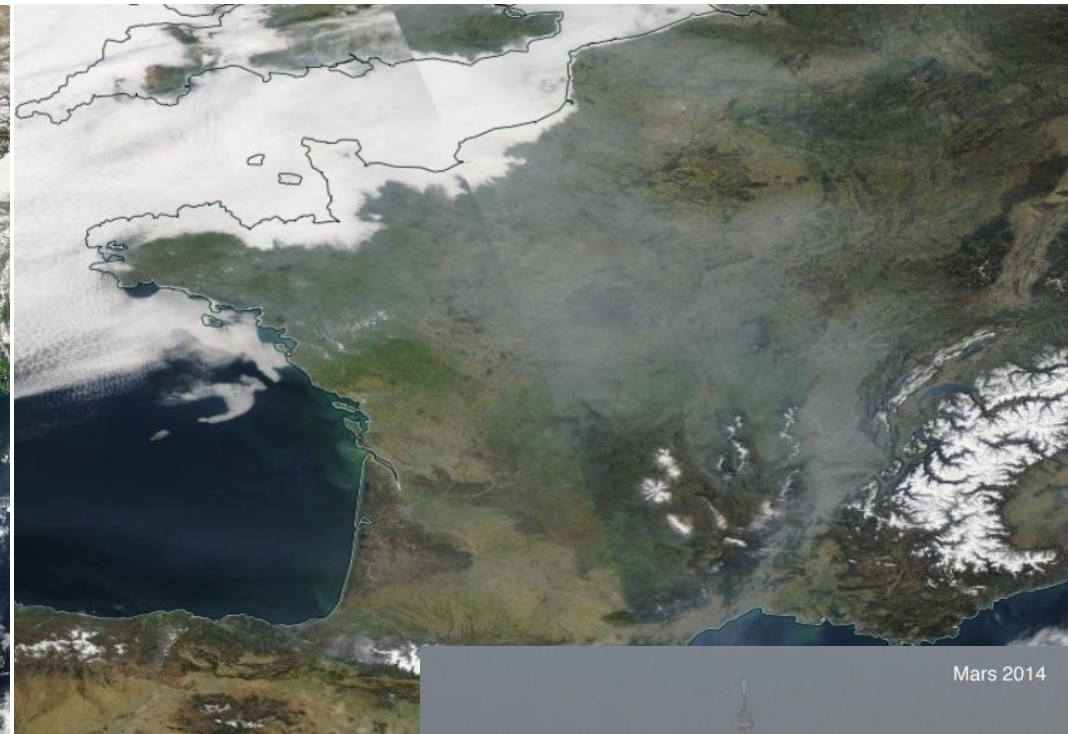
The large scale: Atmospheric brown clouds



10 Jan 2003



11 Dec 2008



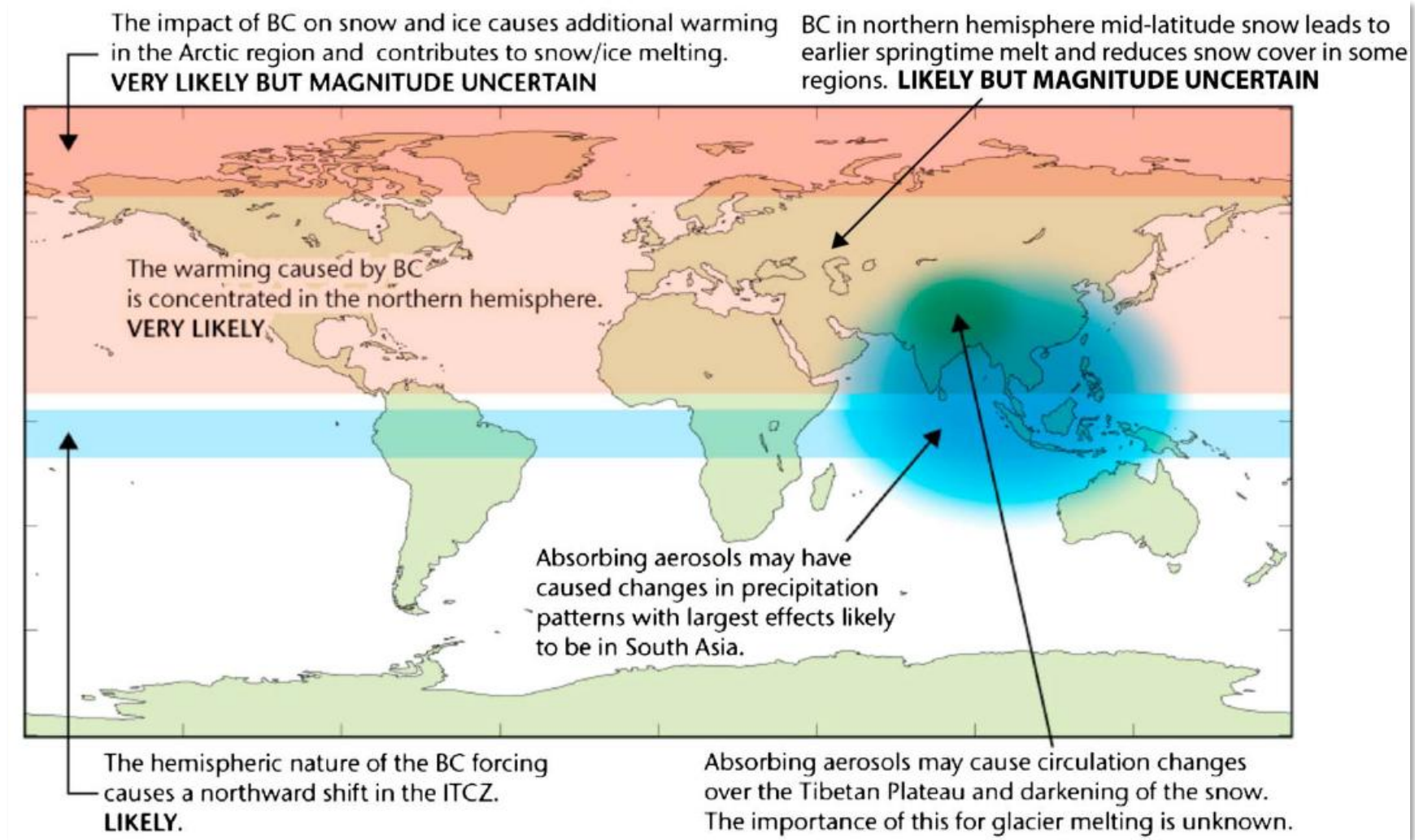
14 Mar 2014



Mars 2014

Source: Satellite imagery, MODIS/Aqua instrument, <https://worldview.earthdata.nasa.gov>

Climate impacts of soot emissions



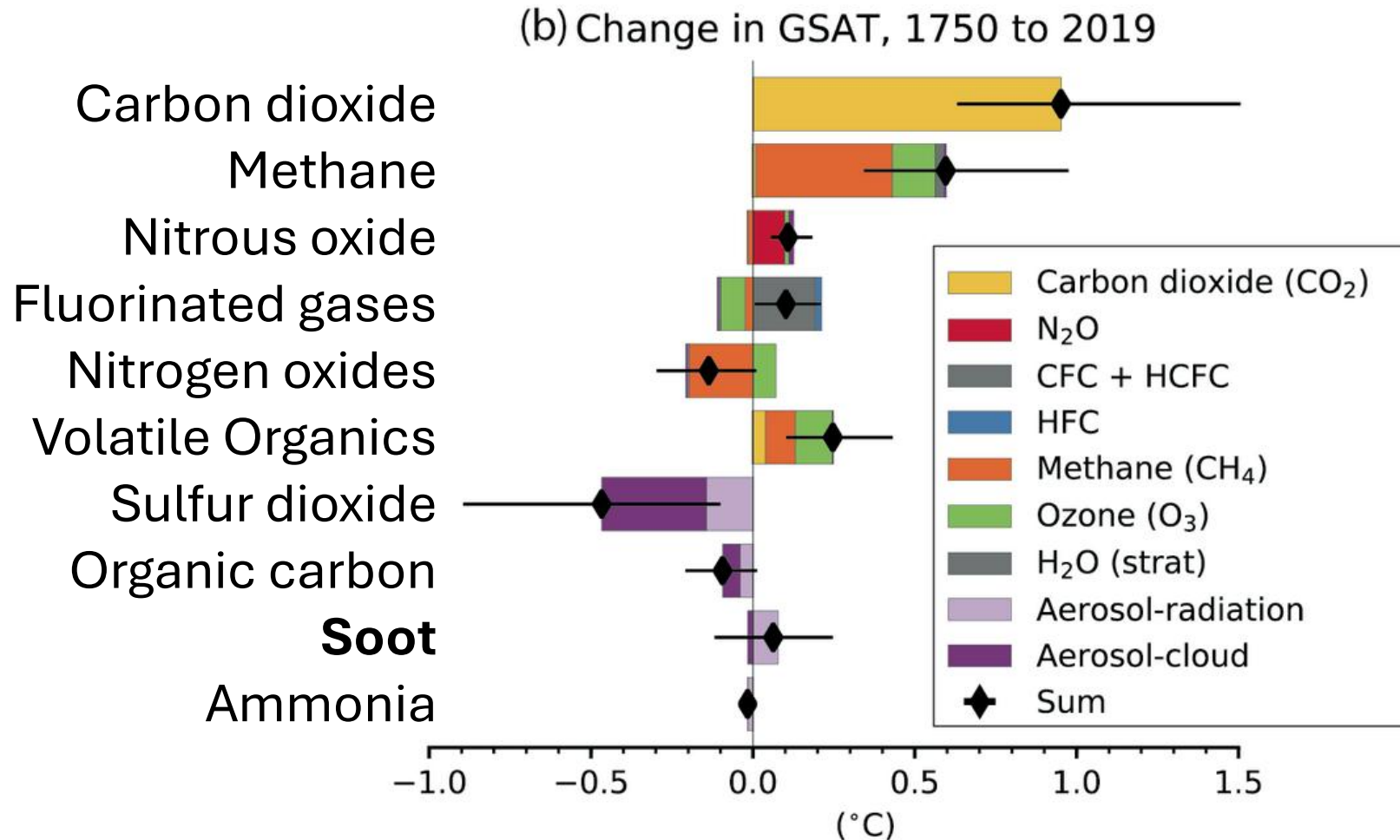
Soot and the South Asian monsoon



Effect	Mechanism	Outcome
Elevated heat pump	Build up of soot over northern India causes warming aloft	Earlier monsoon onset in northern India Weaker rainfall over central and southern India
Cloud microphysics modification	Increased pollutions leads to clouds with more, smaller droplets	Rainfall suppression
Large-scale circulation changes	Northward shift of intertropical convergence zone	Regional redistribution of rainfall
Snowmelt	Darkening of snow and ice by deposited soot	Hydrological cycle feedback

Source: Section 8.3.2.4.1 and Box 8.1 of the 6th Assessment Report of the IPCC <https://doi.org/10.1017/9781009157896.010>

Soot and climate warming

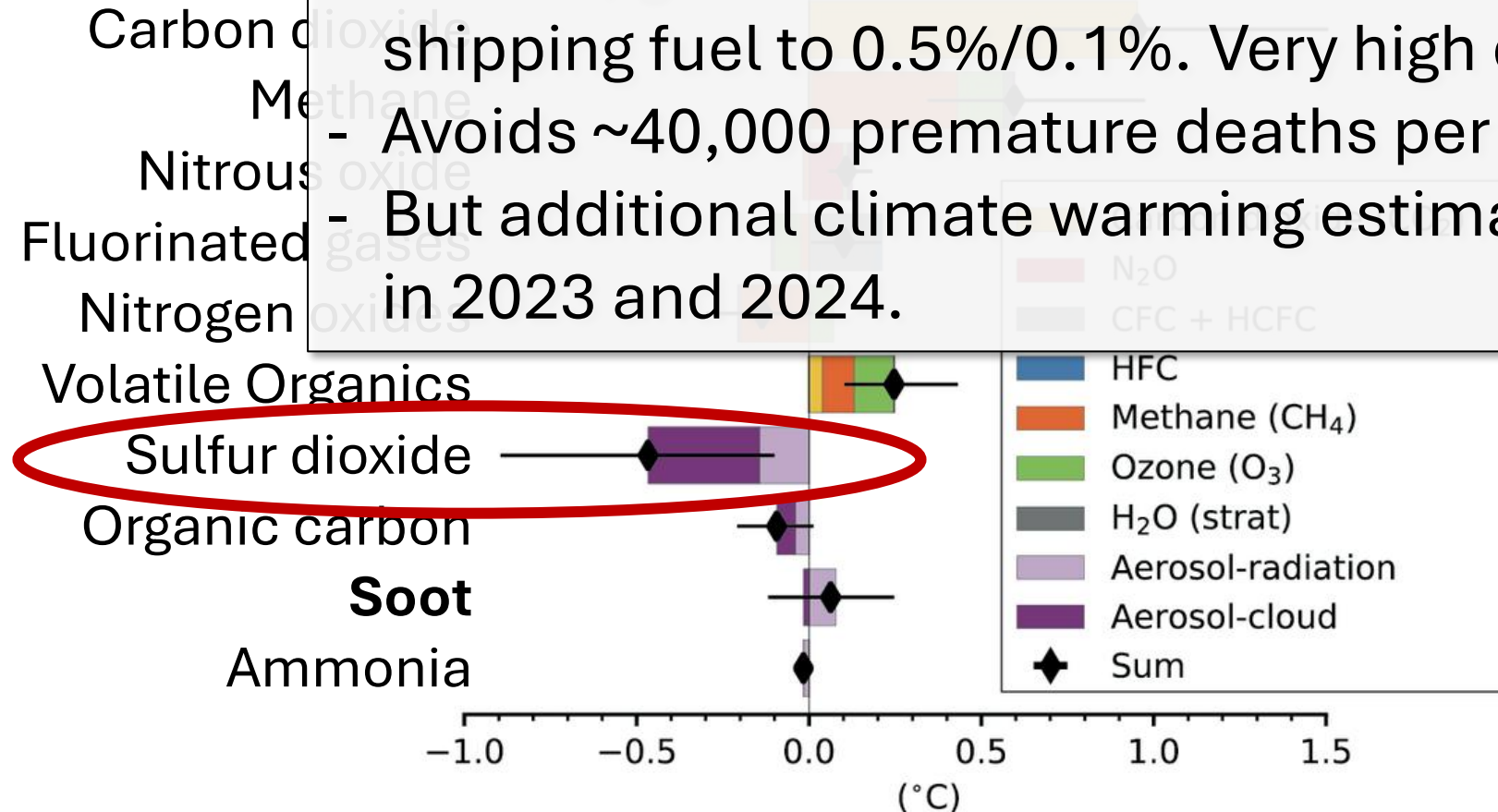


- Soot is the 5th strongest climate warmer
- Reducing soot emissions is also attractive because of their impacts on regional water cycles, and because of potential future increase in wildfire frequency and severity
- Reducing soot emissions benefits both climate and air quality

Soot and climate warming

Win-win for soot mitigation is in stark contrast to SO₂ mitigation:

- In 2020, global decrease in sulfur content of maritime shipping fuel to 0.5%/0.1%. Very high economic cost.
- Avoids ~40,000 premature deaths per year.
- But additional climate warming estimated at 0.03°C to 0.08°C in 2023 and 2024.



because of potential future increase in wildfire frequency and severity

- **Reducing soot emissions benefits both climate and air quality**

In summary

- V Ramanathan's research led to the recognition of soot as highly relevant to climate change, in addition to local air quality
- Soot has distinctive climate impacts compared to other particulate emissions by human activities
- Soot climate mitigation has large benefits on human health
 - Soot concentrations are decreasing in many regions of the world, including India