Climate Change Science
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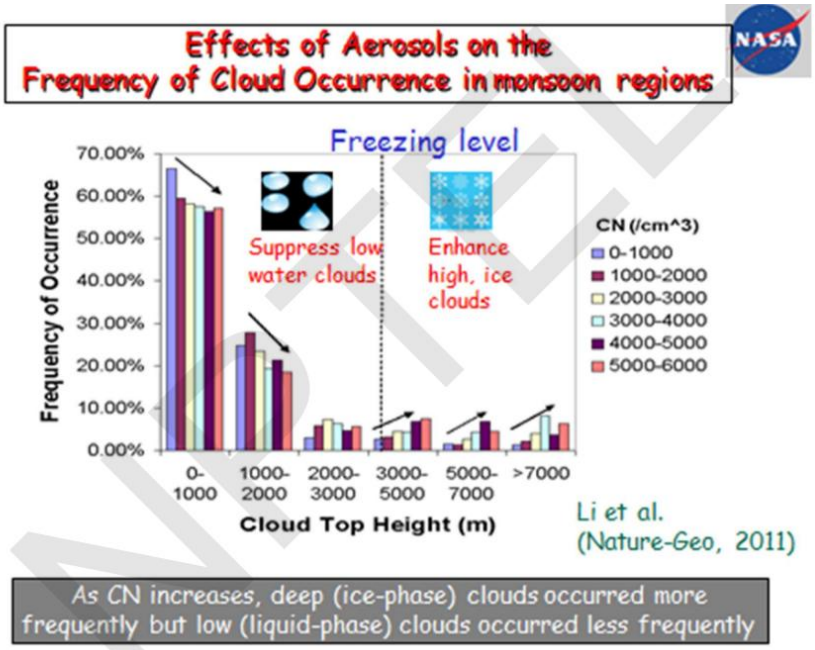
Lecture – 44
Relative roles of CO_2 and aerosols

In the last lecture, we began our discussion on aerosol and pointed out how complex the interaction is because of the different sizes of aerosol, different chemical properties, large spatial variation, and large temporal variation. Here we are discussing the effect of clouds, and you can see here how, as the number of aerosol particles increases, the cloud top height can change.



The low clouds can decrease, and the high clouds can increase. So, because clouds change the liquid droplets, they tend to reduce liquid water clouds and increase the ice clouds.

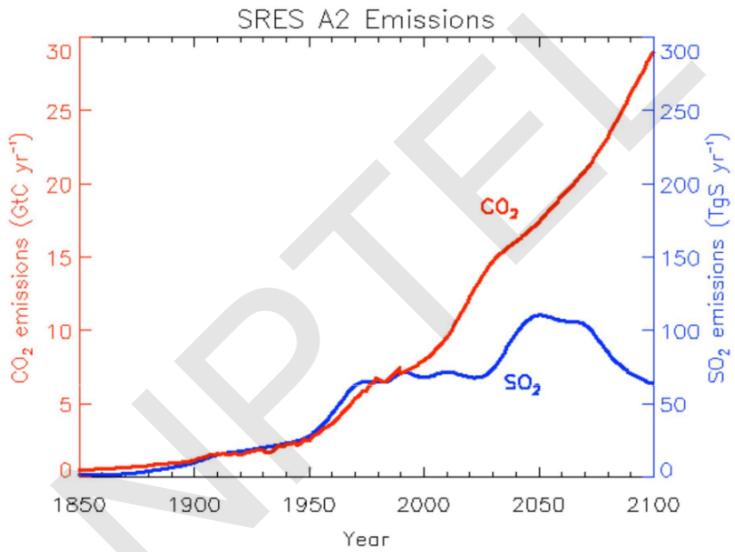
So, fundamentally, aerosols suppress the low water clouds and they enhance the high ice water clouds. Now, a long time ago, 30 years ago, Charlson and his collaborators showed that anthropogenic sulphate aerosol, which reflects solar radiation, has imposed a major forcing comparable to greenhouse gases, but opposite in sign. Greenhouse gases warm the Earth's surface. Sulphate aerosol cools the surface.

Climate Forcing by Anthropogenic Aerosols

R.J.Charlson et al., SCIENCE, January 1992

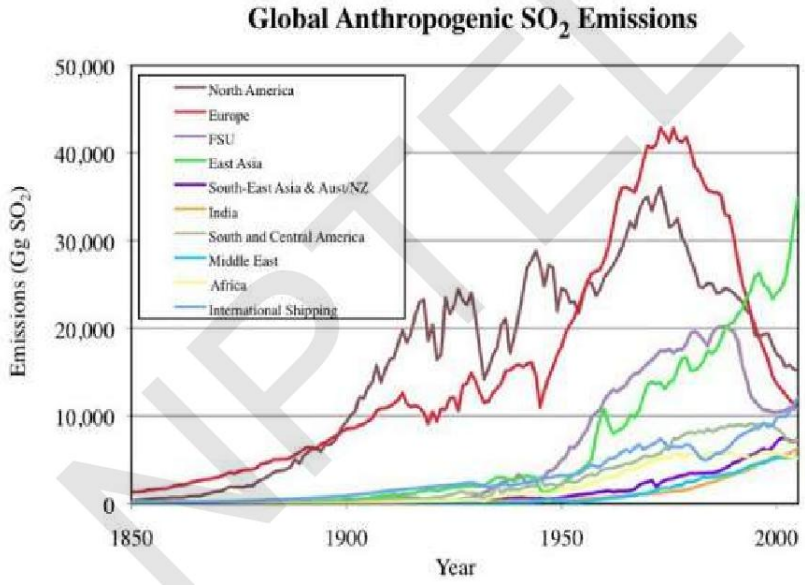
Anthropogenic sulfate aerosol has imposed a major forcing comparable to greenhouse gas forcing but of the opposite sign

And they claimed that the impact of sulphate aerosol was as large as the impact of greenhouse gases. Till that time, people did not realize the impact of aerosols on Earth's climate. Now, the challenge we face is that carbon dioxide is continuously increasing in the Earth's atmosphere on account of the burning of coal, oil, and gas. But sulphate aerosol, which was increasing along with carbon dioxide until recently, has started decreasing in some parts of the world but is increasing in Asia. Now, why is Sulphur dioxide emission decreasing? It is because of our concern with air pollution.



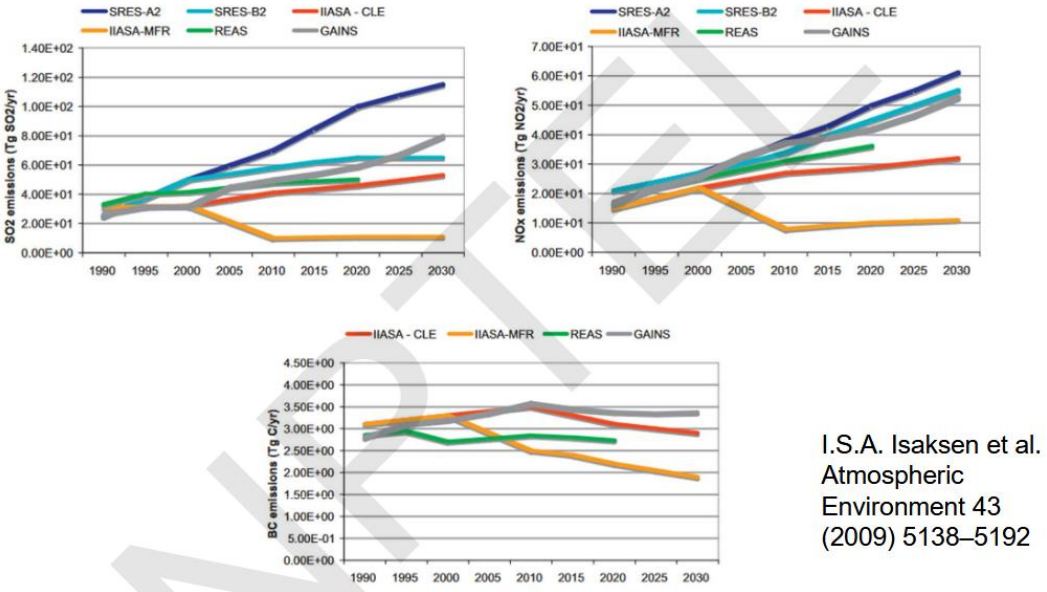
I told you that the biggest impact of aerosol is on our health, because we inhale these small particles, which go deep into the lungs and affect them substantially. It causes various allergic reactions and also various diseases. Because of that, in the developed countries, they have already cut down the emission of sulphate aerosol. This has not happened in China and India yet, but it is bound to happen because people are going to realize that the impact of aerosol on health is immediate, and we need to take action if we want to improve our health.

Now, here is an estimate by different groups of the amount of sulphur dioxide emission in gigagrams.



You can see there is a lot of variation. One shows that the sulphate emission peaked in Europe around 1970 and then started declining rapidly, and the same is true for North America. North America and Europe both enforced strict air pollution control laws around 1970, which reduced the amount of SO_2 emission. But in Asia, India, and other developing countries, it is continuing to increase because we have given lower priority to SO_2 emission than the developed world. We do not realize the serious consequences of emitting sulphate aerosol, and so we have delayed.

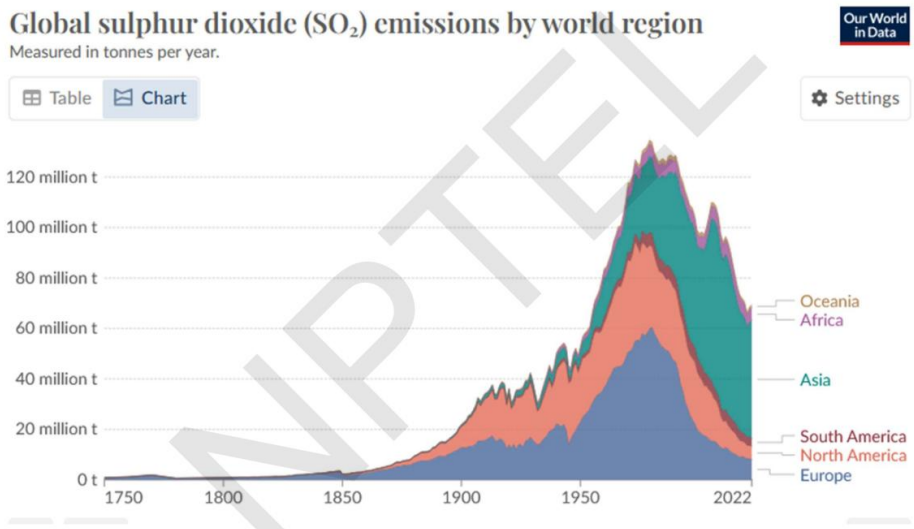
Here is another estimate made in 2009 of the emission of sulphur dioxide, nitrous oxide, and soot emissions.



I.S.A. Isaksen et al.
Atmospheric
Environment 43
(2009) 5138–5192

Fig. 6. Evolution of the emissions of SO_2 (left), NO_x (right) and BC (bottom) from different inventories for the 1990–2030 period; Source: SRES (Nakicenovic et al., 2000), IIASA (Cofala et al., 2007), REAS (Ohara et al, 2007), GAINS (Klimont et al., 2009).

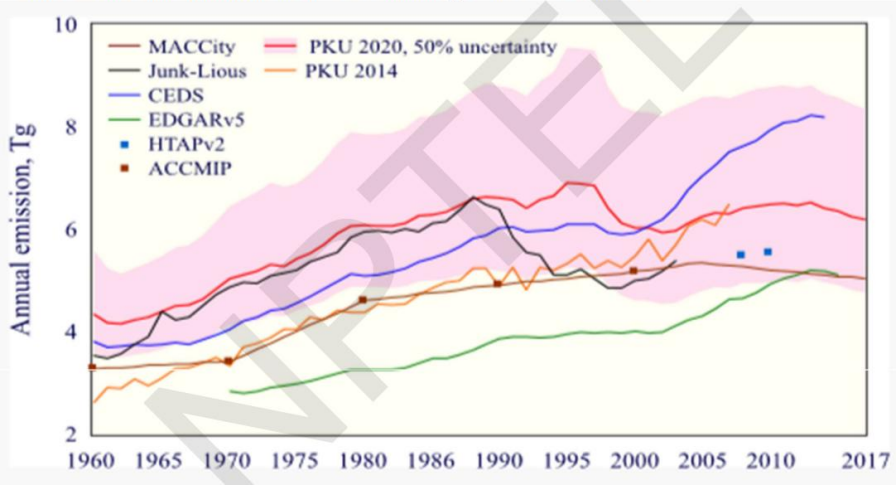
So, you can see that some of the more recent estimates claim that the soot emission is declining. As the people in the developing world recognize the consequences of aerosol on human health, we believe that a large decrease would occur everywhere. So, here is an estimate of aerosol emission as given by Our World in Data.



You see that the peak sulphate emission occurred around 1995. After that, it has slowed down, mainly because of a reduction in Africa and China. But aerosol is still increasing in India and China, although overall it is declining. This is good news, but India and China are still going up.

If you look at the black carbon emission—again I want to remind you—the sulphate emission is typically 100–120 million tons, while that of black carbon is much lower, about a tenth. So, the annual black carbon emission in teragrams is less than 10 teragrams, but there is a large variation you can see.

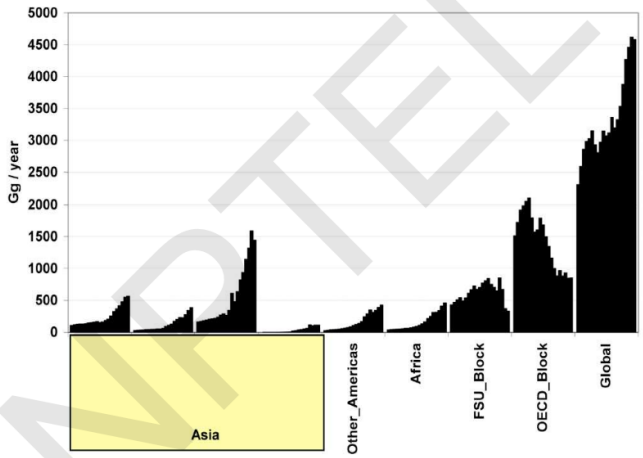
Updated Global Black Carbon Emissions from 1960 to 2017: Improvements, Trends, and Drivers
H.Xu et al., Environmental Science & Technology 55, 7869-7879,2021



Different groups are estimating the amount of emission of aerosols by sulphur combustion. It has a wide range. If you look at black carbon emissions, it is much lower than sulphate, but still, over Asia, the concern is that it is going up too rapidly. It is going up very rapidly in Asia, and so that is a concern—first for health, and then for climate.

Now, here is the annual emission of SO_2, black carbon, and organic carbon.

Figure 3: Black carbon emissions from 1900 - 2000 (Gg / year)



Source: Compiled from Bond et al. 2004 data

There are different models. I want you to notice that different models show different levels of concentration of sulphur dioxide, black carbon, and organic carbon. Now, here is the measurement of aerosol optical depth from satellite. What you see here is a seasonal cycle in different parts of the world.

Shown below are measurements from two NASA satellites, Aqua and Terra, sampling every 12 hours.

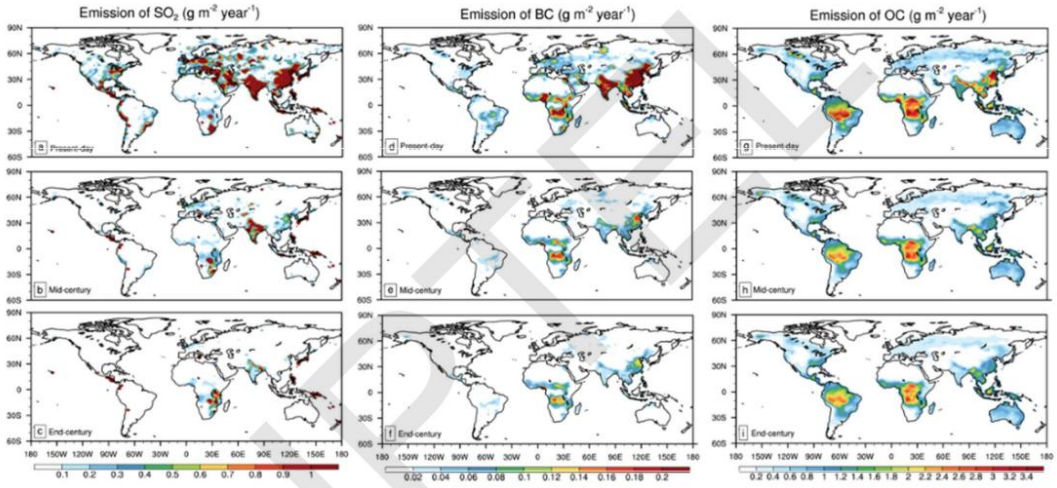


Figure S2 The annual mean emissions of SO_2 (a, b&c), BC (d, e&f) and OC (g, h&i) in 2020 (top), 2050 (middle) and 2100 (bottom). Unit: g m^{-2} a^{-1}.

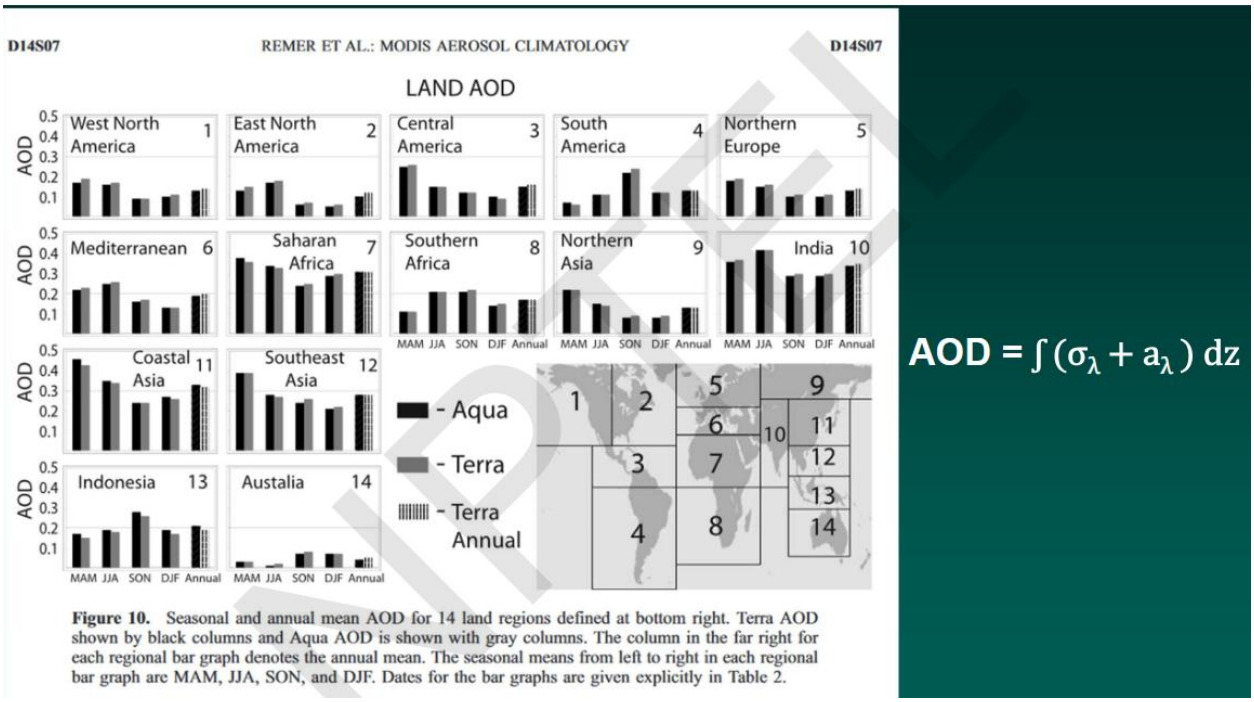
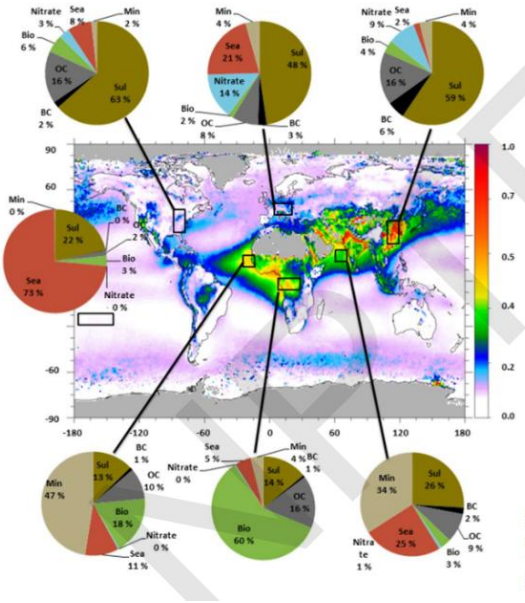


Figure 10. Seasonal and annual mean AOD for 14 land regions defined at bottom right. Terra AOD shown by black columns and Aqua AOD is shown with gray columns. The column in the far right for each regional bar graph denotes the annual mean. The seasonal means from left to right in each regional bar graph are MAM, JJA, SON, and DJF. Dates for the bar graphs are given explicitly in Table 2.

What I want you to remember in the above figure is that aerosol emission over India is very high throughout the year. In contrast, the aerosol emission in Australia is very small. Australia has very strict air pollution control laws, so they do not allow hazardous emissions. Now, the reason why aerosol optical depth is small over Australia is because the population density is very low. So, the industrial emissions are limited. While India and Southeast Asia have high aerosol optical depth because of high population density and a lot of industrial emissions. In the Sahara, the main reason is natural, coming from high winds over the desert, which kick up dust into the atmosphere to very high altitudes.

Now here is a picture showing the variations in the composition of aerosols around the world.



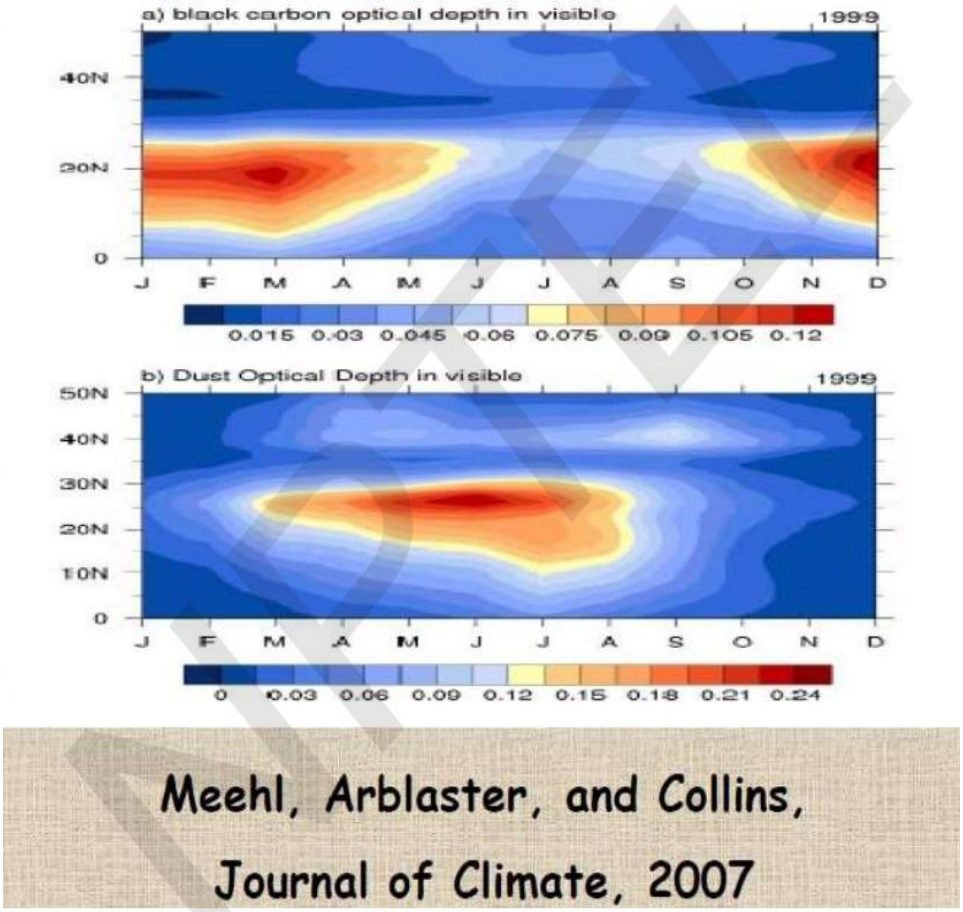
Large spatial variability of the composition of aerosols

https://www.nature.com/scitable/knowledge/library/aerosols-and-their-relation-to-global-climate-102215345/

There (in the picture above) is a sample from India, a sample from China, a sample from Europe, a sample from North America (eastern region and western region), and of course Africa.

So, at first glance, I want you to notice that there is a large variation in the composition around the world. Africa is mostly biological in origin because it is not heavily industrialized. You look at the Pacific Ocean—mainly sea salt aerosols. You look at Eastern North America—the major emission is sulphate from industries. Europe also mainly sulphate, and China also mainly sulphate.

India has minerals as well as sulphate, and both India and China have black carbon aerosols, which are not that prominent in the developed world. So, this is a problem when you want to model aerosols. We have to take into account the changes in the chemical composition, which varies with location. These observations began only around 20 years ago in India, so we do not have sufficient data for modelling.



Now, the other thing this data shows from models is that black carbon aerosol, which is very high from January to March, declines during the monsoon season and picks up again in winter. During the monsoon season, dust is dominant. So, in the pre-monsoon and post-monsoon, black carbon dominates. During the monsoon, the wind kicks up dust.

Here is an estimate made under the U.S. Climate Change Program of the global sources of sulphate, black carbon, particulate organic matter (POM), dust, and sea salt.

Estimated source strengths, lifetimes, mass loadings, and optical depths of major aerosol types. Statistics are based on results from 16 models examined by the Aerosol Comparisons between Observations and Models (AeroCom) project (Textor et al., 2006; Kinne et al., 2006). BC = black carbon; POM = particulate organic matter.

Aerosol Type	Total source[1] (Tg/yr[1])	Lifetime (day)	Mass loading[1] (Tg)	Optical depth @ 550 nm
	Median (Range)	Median (Range)	Median (Range)	Median (Range)
Sulfate[2]	190 (100-230)	4.1 (2.6-5.4)	2.0 (0.9-2.7)	0.034 (0.015-0.051)
BC	11 (8-20)	6.5 (5.3-15)	0.2 (0.05-0.5)	0.004 (0.002-0.009)
POM[2]	100 (50-140)	6.2 (4.3-11)	1.8 (0.5-2.6)	0.019 (0.006-0.030)
Dust	1600 (700-4000)	4.0 (1.3-7)	20 (5-30)	0.032 (0.012-0.054)
Sea salt	6000 (2000-120000)	0.4 (0.03-1.1)	6 (3-13)	0.030 (0.020-0.067)
Total				**0.13 (0.065-0.15)**

Synthesis and Assessment Product 2.3 Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, January 2009

And I want you to notice that the highest is sea salt—6000 teragrams per year; next is dust—1600 Tg/yr; next is sulphate—190 teragrams per year; then POM—100 teragrams per year; and finally black carbon, which is only 11 teragrams per year. So, remember that black carbon emission is about one-twentieth that of sulphate. I will point out why this is relevant a little later. In the atmosphere, for example, there is emission. In the atmosphere, there are 2 teragrams of sulphate and only 0.2 teragrams of black carbon—so one-tenth. The lifetime is around four to six days, not very different. And optical depth varies between 0.03—BC (Black carbon) is very small because the emission is small.

And here is the estimate in milligrams per square meter of sulphate and black carbon.

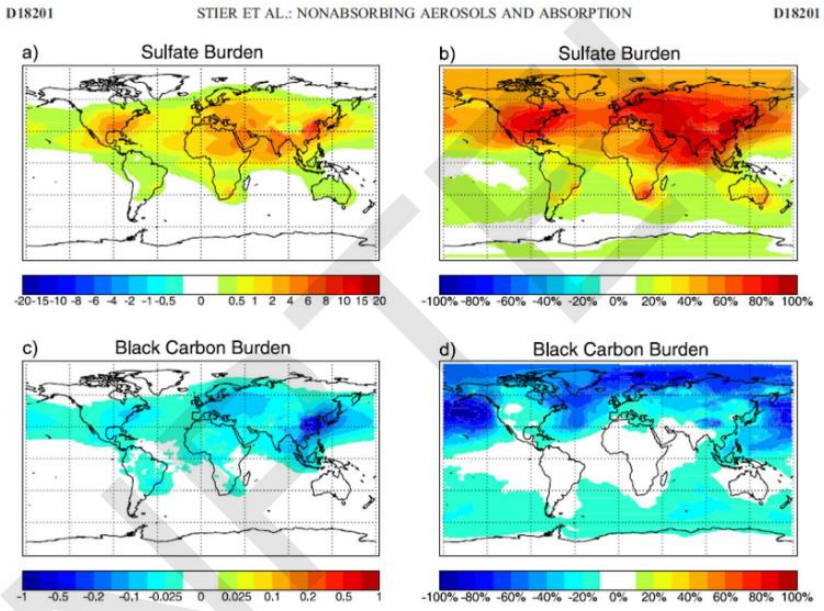


Figure 2. Annual mean aerosol column burden change of (a) sulfate (mg(S) m^{-2}), (b) sulfate (% with respect to year 2000), (c) black carbon (mg m^{-2}), and (d) black carbon (% with respect to year 2000) due to the addition of anthropogenic sulfate; derived as difference between a year 2000 simulation with all emissions and an identical simulation without SO_2 emissions from fossil fuel use, industry, and biofuels.

Sulphate is measured in milligrams per square meter. Here, it is a percentage contribution with respect to the year 2000. How much is the percentage contribution? You can see again that the sulphate burden is much larger than that of black carbon. The colors show up to 1 milligram per square meter, while black carbon is 0.1–0.2 milligrams per square meter.

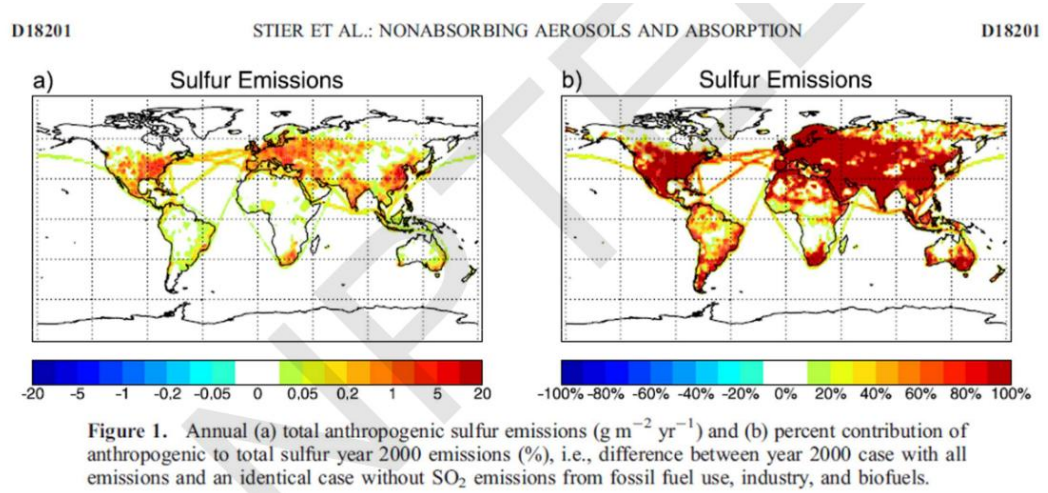
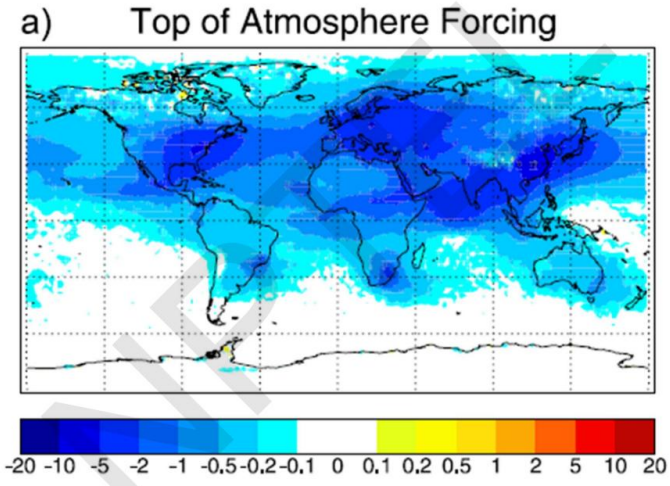


Figure 1. Annual (a) total anthropogenic sulfur emissions (g m^{-2} yr^{-1}) and (b) percent contribution of anthropogenic to total sulfur year 2000 emissions (%), i.e., difference between year 2000 case with all emissions and an identical case without SO_2 emissions from fossil fuel use, industry, and biofuels.

Now, if you look at the emission sources on the left—in grams per square meter per year—and on the right—percentage anthropogenic contribution—you can see that over most of the land, especially highly populated regions of Eastern North America, Europe, India, and China, most of the emission is anthropogenic, almost 100% human-made. While in areas with lower population density like Africa and South America, it is somewhat lower. So, for places like the Amazon, the major source is natural, not man-made. Because of this aerosol, more radiation is reflected by the aerosol into space.



So, there is a negative atmospheric forcing in W/m^2 and the value is around -0.5 W/m^2, indicating reflection of solar radiation. Now, aerosols affect climate in two ways. Salt and sulphate reflect solar radiation, so they cool the atmosphere and the surface. While dust and soot heat the atmosphere because they are absorbing, but cool the surface.

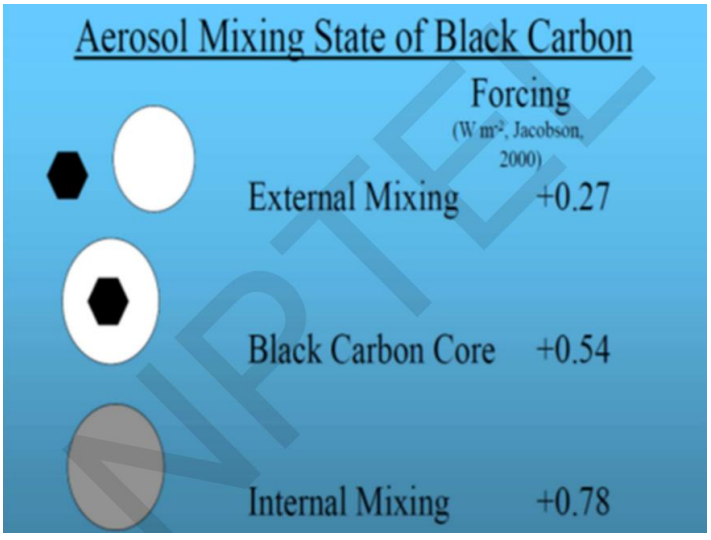
AEROSOLS AND CLIMATE

- **SALT AND SULFATE**
  cool the atmosphere
- **DUST AND SOOT**
  heat the atmosphere

So, this diversity affects the impact of aerosols on Earth's climate. Aerosol properties depend on the mixing state, because aerosols are released individually—as soot, sulphate, or salt—but when they enter the atmosphere, they start mixing. So, the mixing state is very important.

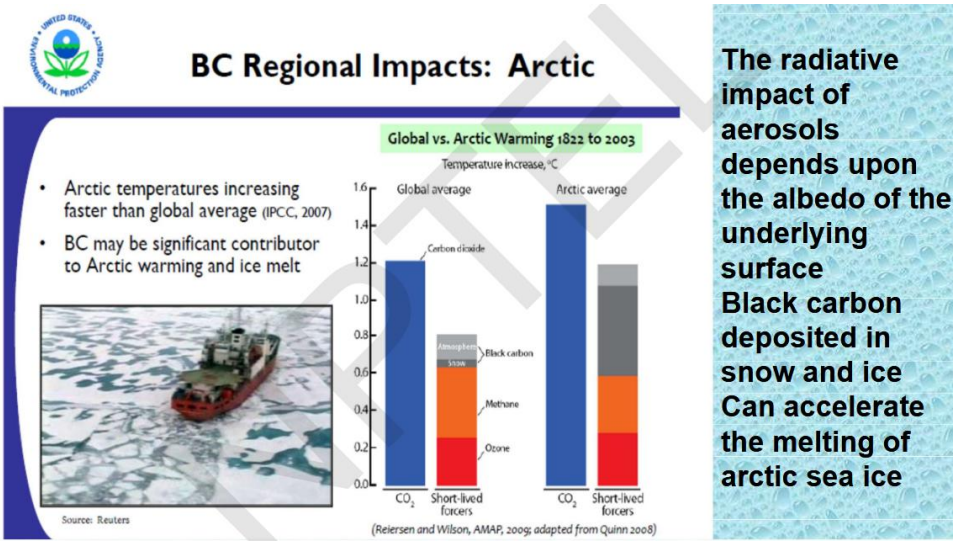
The radiative properties of an aerosol population depend on the aerosol mixing state, that is the degree to which the chemical components occur as independent particles (external mixing) as compared to a component mixture in each individual particle (internal mixing)
The effect of atmospheric absorption on the top-of atmosphere(TOA) aerosol radiative forcing, i.e. net change in the radiative fluxes at TOA introduced by the aerosol, depends crucially on the effective albedo of the underlying surface (e.g. Haywood and Shine, 1995; Myhre et al.,2004). The aerosol single scattering albedo (SSA), i.e. the ratio of the extinction due to scattering to the total extinction due to scattering and absorption, decreases with increasing aerosol absorption.

Imagine a dust aerosol surrounded by salt—then its absorption will not be seen. On the other hand, if soot coats sulphate or salt aerosol, it will fundamentally alter the properties of that aerosol. So, this is one of the toughest challenges we face. We have very little data on the mixing state of aerosols because it is very difficult to actually go there, grab the aerosol, and look at the mixing state. It is a very tough situation. Here is a cartoon showing what is called external mixing. Firstly we can see that the black carbon and sulphate or salt are separated.



(Please refer to the cartoon shown above) In another case, black carbon is inside, coated by sulphate, and here it is completely mixed. Internal mixing means they are all uniformly mixed, so it gets a grey color. Where the sulphate looks white, this is distinct—they do not mix. Here, salt or sulphate coats black carbon, so it looks white. In the uniformly mixed case, they look grey. So, there is the difference in the forcing in watts per square meter due to the mixing of aerosol.

Recently, there was concern about how aerosols will affect the Arctic Sea ice. It is melting rapidly. We talked about it. The rate of melting of Arctic Sea ice depends upon both global warming by carbon dioxide and the deposition of soot on the sea ice.



This has been a major concern—that in the Arctic, black carbon on snow will have a huge impact compared to the global average. So, this black carbon released from Canada and America will blow into the Arctic Ocean, which has sea ice on it, and it will deposit directly on the ice. So, it will melt very rapidly. Much of the Arctic warming, as Shindell and Faluvegi tell us, is an unintended consequence of clean air policies that have greatly decreased sulphate aerosol.

See, if sulphate deposits on ice, it does not have too much effect. It is either reflecting, or the ice is reflecting. But if you remove all the sulphate by strict air quality standards, then black carbon and carbon dioxide will cause the melting of Arctic Sea ice. So, that is the point—we are making

that sometimes air pollution control can have a different impact on Earth's climate because it removes the regulating aerosols. Now, when you come to India, here is a photograph of the Gangotri Glacier, one of the biggest glaciers in the Himalayas.

Behind it is the Bhagirathi peak, and this glacier you would think would be white in color because of ice and snow. But no—it is covered with rock and dust from the surrounding mountains. So, it appears brown in color. So, if black carbon or other absorbing aerosols fall on the Gangotri Glacier, it will not alter the albedo too much because it is already dark. But Arctic ice is different.

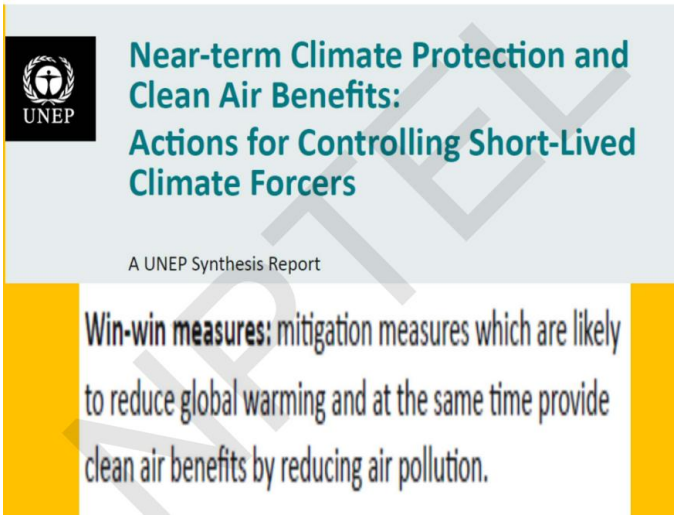
Arctic ice is extremely white in color. So, the impact there is dramatic. Here, the impact will be limited. People have studied the impact of greenhouse gases, volcanic forcing, and black carbon. They are saying that although people are concerned about the effect of black carbon, they do not see much effect on temperature when compared to greenhouse gas and volcanic forcing. So, regarding black carbon, there is a lot of controversy, and I will talk about it a little later.

Although the effects of greenhouse gases and volcanic forcing are robust across model specifications, we cannot detect any effect of black carbon on temperature.....

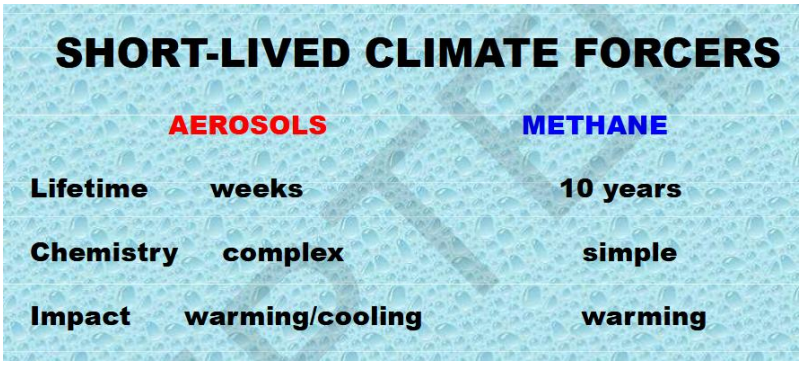
Anthropogenic and natural causes of climate change
Stern and Kaufmann
Climatic Change, 122, 257-269,2014

UNEP (United Nations Environment Programme) put out a document saying that by controlling air quality, we can control both air pollution and global warming. But this turned out to be wrong, because if you control air pollution—especially sulphate aerosol, which is reflecting—it will increase the impact of greenhouse gases. Right now, global warming is somewhat lower than it should have been due to carbon dioxide, because sulphate aerosols are reflecting Sun's radiation.

If you remove all the sulphate aerosols, you will get much higher warming. So, there was confusion caused by IPCC about 10 years ago by calling aerosols and methane "short-lived climate forcers."

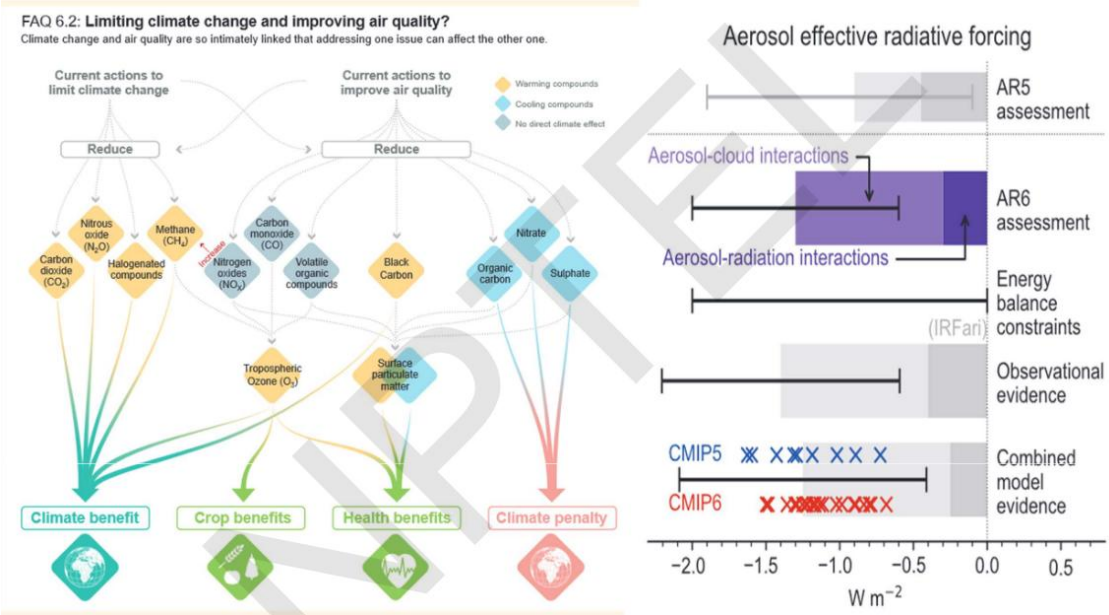


This was done because both these things have a much shorter lifetime than carbon dioxide. But methane and aerosols are very different. Aerosols have a lifetime of weeks; methane has a lifetime of 10 years.



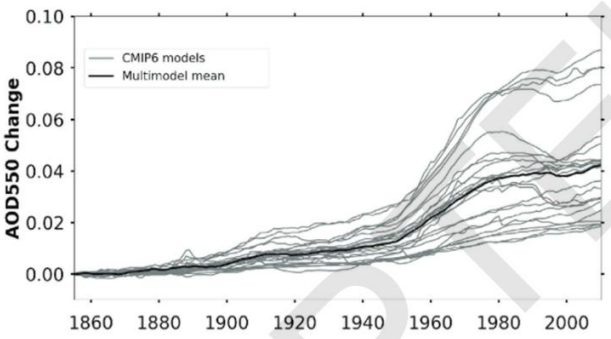
Methane aerosol chemistry is simple—it converts from methane to carbon dioxide—while the chemistry of aerosols is complicated. It depends on whether it is sulphate, black carbon, or something else, or organic carbon. Aerosols can cause warming or cooling depending on the composition, while methane causes only warming. So, it was not a good idea to combine these two, but it was done for a certain political reason, which I will talk about a little later. Now, the recent IPCC report—the Sixth Assessment—which came out recently, has clearly shown the difference in what happens with greenhouse gases. If you reduce them, you get a benefit.

If you reduce black carbon, warming will come down. The health benefit also goes up. Same thing with ozone at the surface. All three, if you reduce. But if you reduce sulphate or organic carbon, which reflects radiation, it will warm Earth's atmosphere but improve air quality. So, sulphate is one thing which, if you reduce, you improve air quality but cause global warming. This is a point now of great concern.



Now, on the right, I have shown how this assessment shows that the major impact of aerosol is not the direct impact through absorption and scattering, but indirect—through clouds. It is much larger than the direct effect and, unfortunately, it has a large level of uncertainty. So, this is a major issue we have to deal with—that aerosol-cloud interaction is very complicated. Different models do not agree on the magnitude of the impact. So, the large uncertainty, as I have shown right here, ranges from -0.5 to -2 W/m^2.

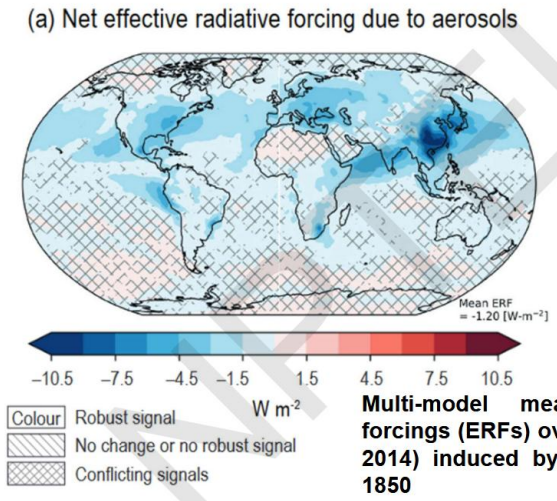
Now, here is an example of how aerosol optical depth has changed according to different CMIP6 models used by IPCC.



From Chapter 6
Short-lived Climate Forcers
IPCC AR6

Figure 6.8 | Time evolution of changes in global mean aerosol optical depth (AOD) at 550 nm. The year of reference is 1850. Data are shown from individual Coupled Model Intercomparison Project Phase 6 (CMIP6) historical simulations. Each time series corresponds to the ensemble mean of realizations done by each model. Simulation results from years including major volcanic eruptions (e.g., Novarupta, 1912; Pinatubo, 1991), are excluded from the analysis for models encompassing the contribution of stratospheric volcanic aerosols to total AOD. Further details on data sources and processing are available in the chapter data table (Table 6.SM.3).

So, you can see a whole range—from 0.02 optical depth to 0.08, a factor of four—with a mean value around 0.04. So, this is a huge issue. The range is so large that it causes large uncertainty in predicting the impact on climate. The net effect, of course, is cooling—that we all know.



Multi-model mean effective radiative forcings (ERFs) over the recent-past (1995-2014) induced by aerosol changes since 1850

So, black carbon is not having the kind of impact people thought 20 years ago it might have. It is mostly cooling in most of the areas, especially where aerosols are large—like China, India, and North America.

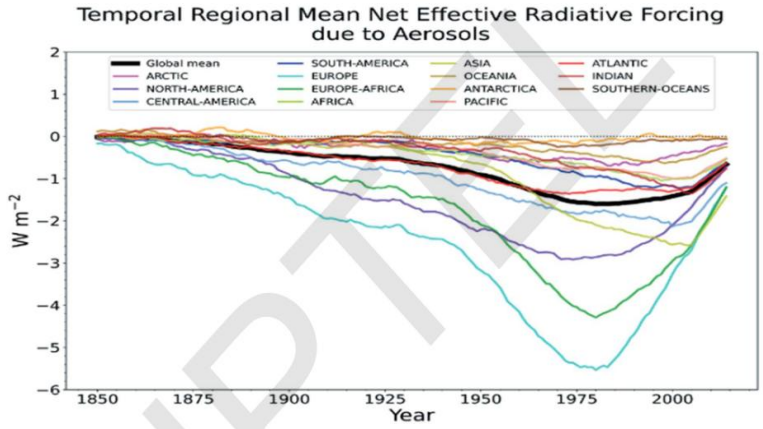


Figure 6.11 | Time evolution of 20-year multi-model mean averages of the annual area-weighted mean regional net effective radiative forcings (ERFs) due to aerosols for each of the 14 major regions in the Atlas, and global mean, using the models and model experiments as in Figure 6.10. Further details on data sources and processing are available in the chapter data table (Table 6.SM.3).

Now, you can see that the total aerosol impact is here—global mean, black line. It increased with the sulphate increase, but in the last 20 years, sulphate aerosol has declined, and so the impact of sulphate aerosol is reducing. So, very soon, the impact of aerosol may be close to zero. So far, aerosols were causing cooling, CO_2 was causing warming, and the combination somewhat mitigated global warming. But that will not happen in the future. You can see surface temperature decreasing in most parts of the world due to aerosols.

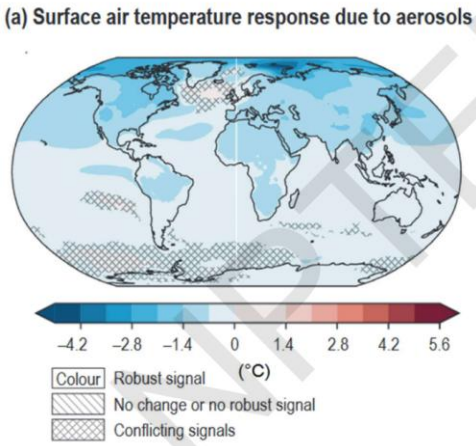
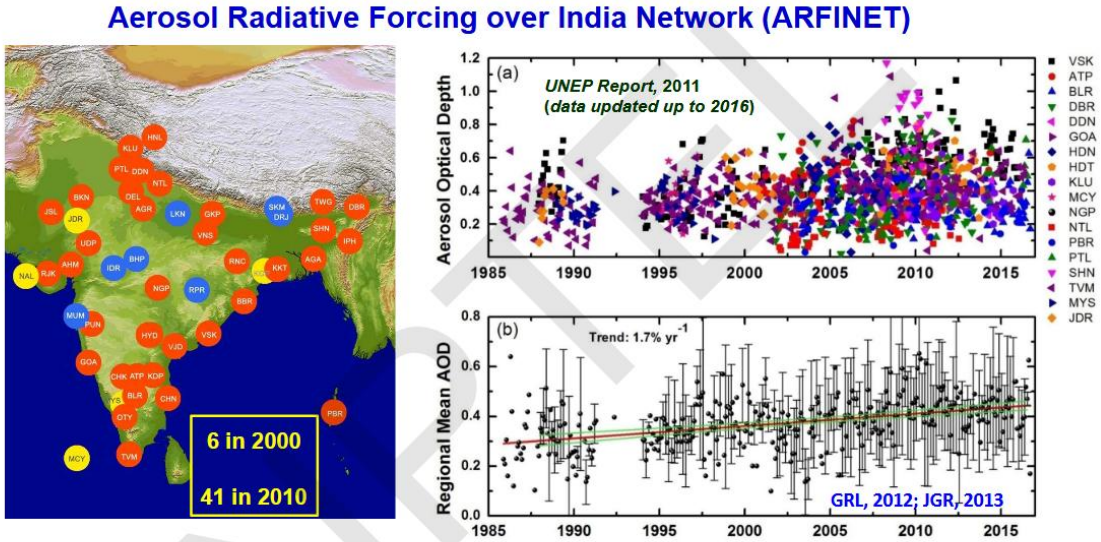


Figure 6.13 | Multi-model mean surface air temperature response over the recent past (1995–2014) induced by aerosol changes since 1850. Calculation is based on the difference between CMIP6 'historical' and AerChemMIP 'hist-piAer' experiments averaged over 1995–2014

Now, the recent report also shows that it also has an impact on the ocean because it causes a change in temperature within the ocean. The southern Indian Ocean, where there is not much land, is showing below-thermocline changes due to aerosol-induced heating.

The late twentieth century sub-thermocline cooling of the southern Indian Ocean was primarily driven by increasing anthropogenic aerosols and greenhouse gases. The models simulate a slow-down in the sub-thermocline cooling followed by a rapid warming towards the mid twenty-first century. The simulated evolution of the Indian Ocean temperature trend is linked with the peak in aerosols and their subsequent decline in the twenty-first century, reinforcing the hypothesis that aerosols influence ocean circulation trends.

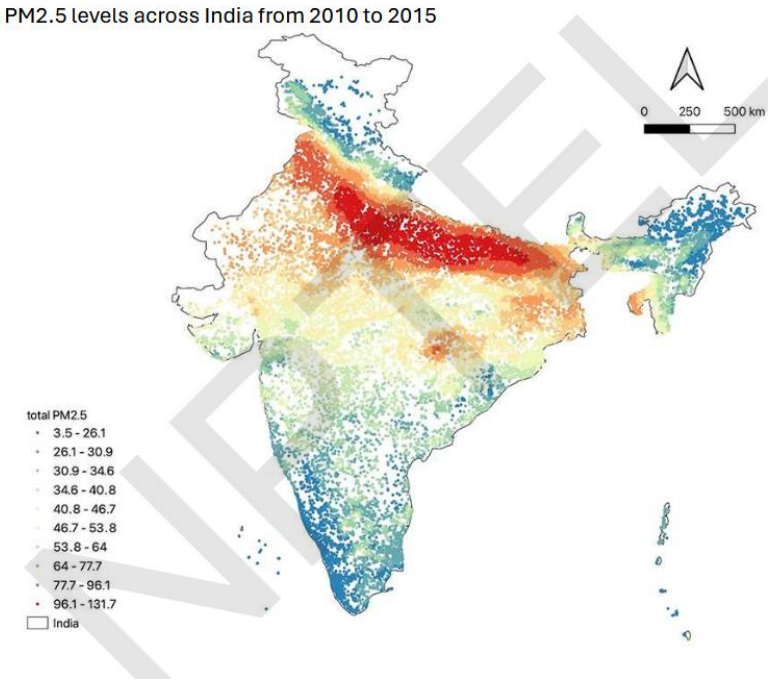
Now, here are a few examples from India.



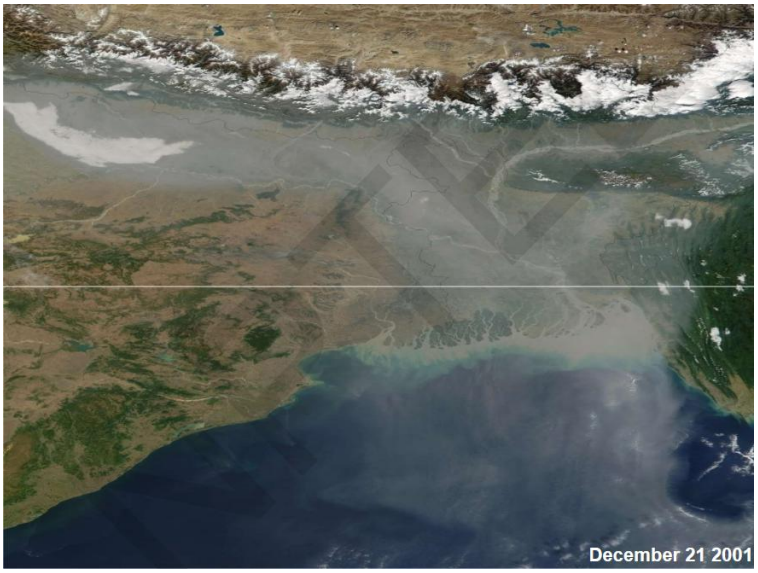
Data: 1984 - 2016; Trend until late 1990s: 1.7% per year;

Trend from 2000 to present: 2.3% per year

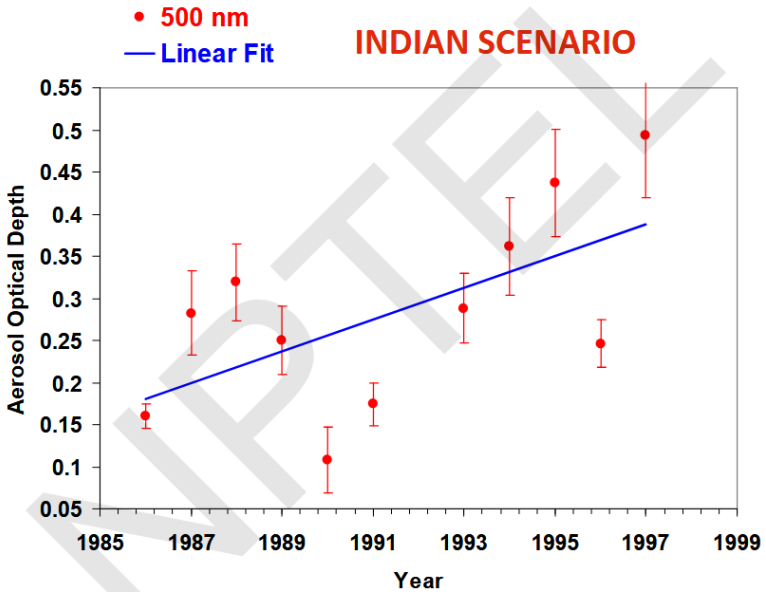
In India, a lot of work has been done on aerosols because of concerns about both air pollution and climate. There is a steady increase—around 2 percent per year—from 1985 for about 30 years.



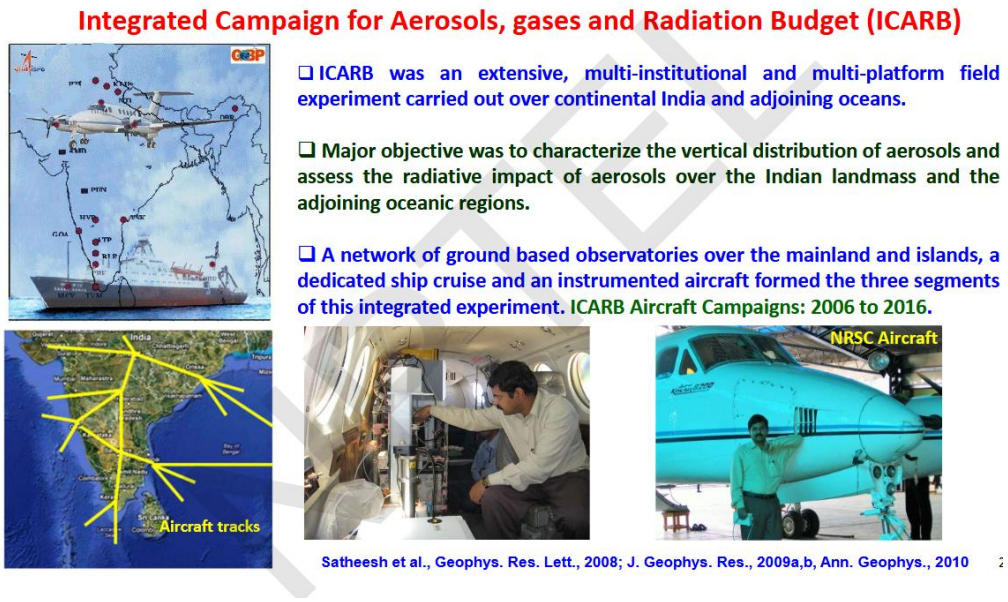
Data show increases at various stations all over India. The highest levels, of course, are over the Indo-Gangetic plains. That is shown by satellite data, indicating huge aerosol loading coming into the Bay of Bengal.



Here is another example of the increase in aerosol optical depth.

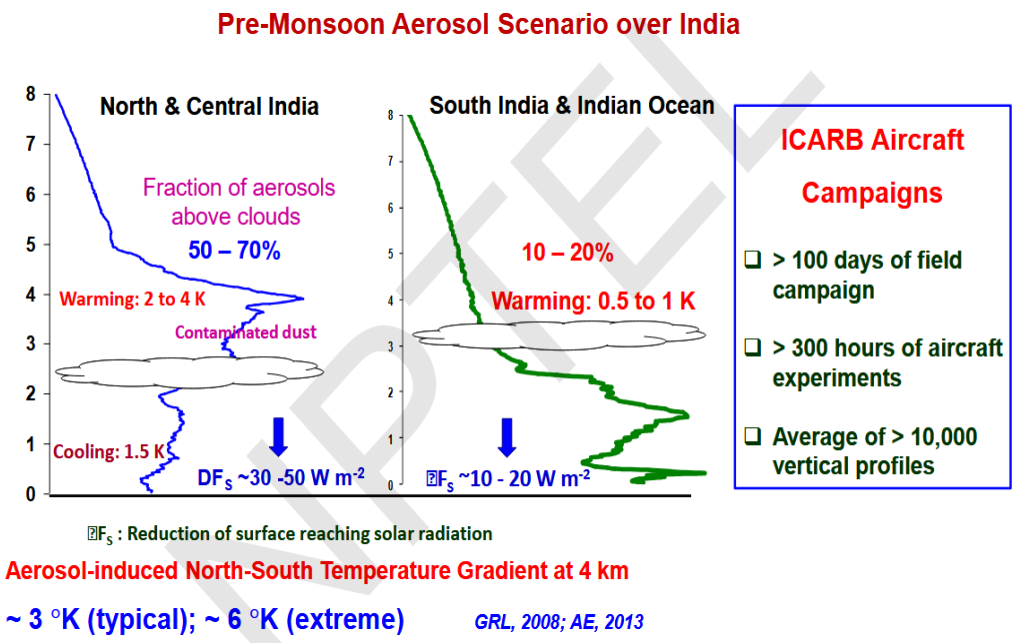


Measurements were made of aerosols' vertical variation, which is important for simulating their impact. It was found that the maximum amount of aerosol is not at the surface but at about 4 kilometers in height. So, this was a great surprise, and the exact reason for this is not clear, although aviation may be playing a role.

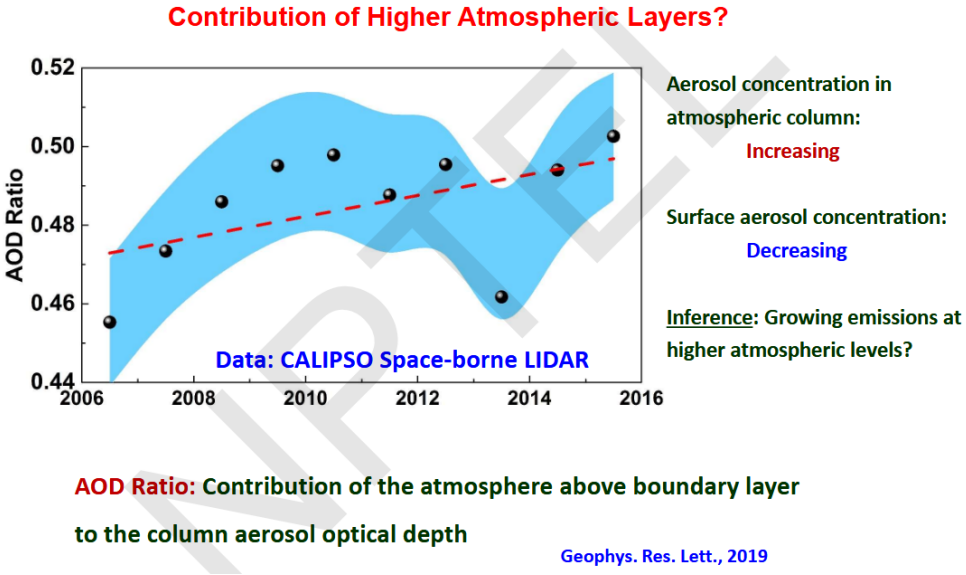


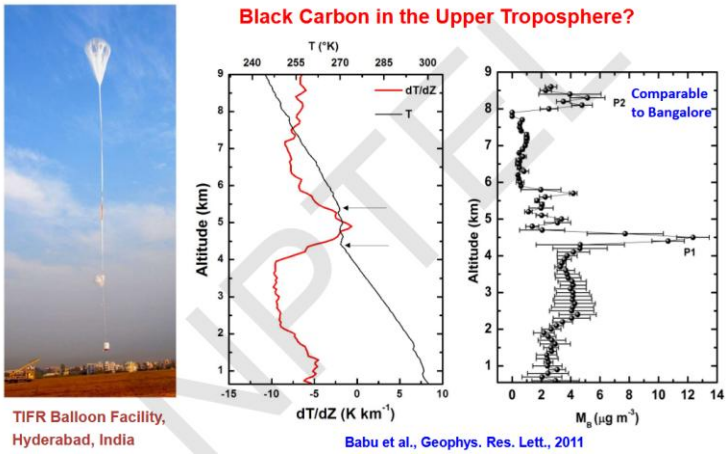
This is a concern that has emerged recently regarding the role of aircraft in Earth's climate.

Here is an example (shown below) from a balloon launch from Hyderabad showing that the temperature gradient in the atmosphere has been altered where there is a lot of aerosols.

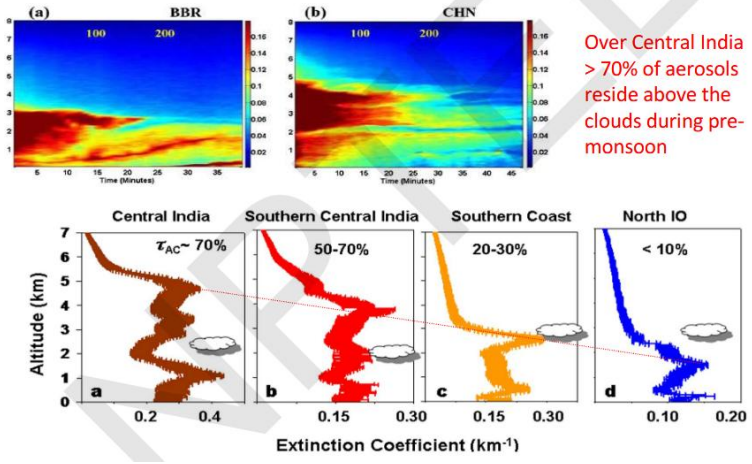


This is a new result that has to be looked at very closely. These are called elevated aerosol layers, which impact temperature variation with altitude.





Elevated aerosol layers



But still, if you look at the emission inventory of India, sulphate emission is still much larger than black carbon.

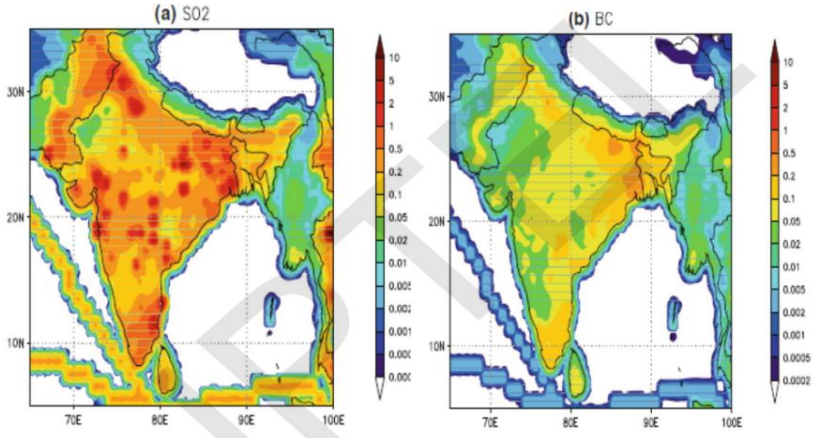
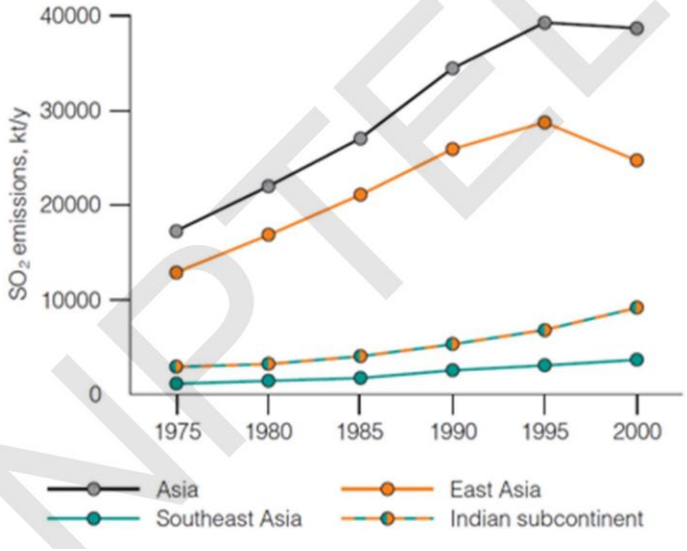


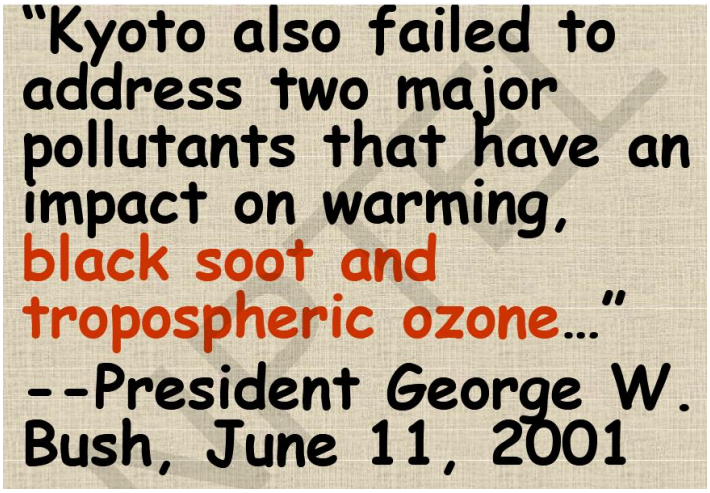
Fig. 2 Emission inventory in South Asia (units: 10^{-10} kg m^{-2} s^{-1}): a SO_2; b BC; c OC

Zhenming Ji et al., Climate dynamics, 2011



So, black carbon emission is large in India, but still smaller than sulphate. You can see that in the developed world, both East Asia and India, the aerosols were increasing, but in the last couple of years, they started decreasing. SO_2 has decreased, but black carbon is still increasing.

I will stop here with a mention about why aerosol became controversial—because in 2001, America decided to withdraw from the Kyoto Protocol on greenhouse gases, saying that black soot contributes to more warming.



We know today that this was a false statement. Today, we know that black soot's impact is very limited, and this particular excuse given by the United States was not valid. We will discuss this more in the next lecture.