

Climate Change Science
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Lecture – 45
Kyoto Protocol

In the last lecture, we began a discussion on the impact of aerosols on climate. We mentioned that, in comparison to carbon dioxide, the impact of aerosols is not so easy to model. This is because aerosols are not uniformly present everywhere on Earth. Aerosols released by human activities are confined to land, mostly urban areas. In contrast, the carbon dioxide released by human activities over land mixes uniformly all over the world, because it is a gas that does not react and has a long lifetime. So, it has time to spread all over the world, all the way to the poles.

So, the amount of carbon dioxide, in parts per million, is almost the same everywhere. Aerosols are very different. They are not gases; they are particles. Their lifetime in the atmosphere is on the order of days to weeks. And so, they are very high only in the regions where they are released. Then they decay very quickly. So, the first problem is, to estimate the impact of aerosols on Earth's climate, you need to know the complete data on aerosol concentrations all over the world, both over land and ocean. Then you have to average all that and calculate the impact of those aerosols on the solar radiation absorbed or reflected. For a long time, we did not have good data.

After people realized the importance of aerosols and climate, most countries have taken up detailed measurement of aerosols in various cities and other areas over the last 20 years. We have good data now, which we discussed. We showed the number of stations in India that measure aerosols. The second problem is that aerosols are not of one chemical composition. Carbon dioxide is CO₂; it does not react, it does not change, it remains the same as long as it is in the atmosphere.

But aerosols come in a variety of forms—ones released by human activities include sulphate aerosols from sulphur dioxide, black carbon aerosols from incomplete combustion (what we call soot), organic carbon, and a couple of other types. So, you need to know the amount of aerosols in a given region and the various types. Is it sulphate, or is it black carbon? For example, at present, in the developed world, black carbon emission is very small; it is mostly sulphate, and even that is coming down. On the other hand, in developing regions like India and China, there is a lot of black carbon emission due to incomplete combustion while cooking. When you use firewood or coal, you release a lot of soot into the atmosphere. So, you need to know the relative amounts of sulphate and black carbon in different parts of the world. They are not the same. This has made an accurate estimate of the impact of aerosols on global climate very difficult, because sulphate aerosols reflect solar radiation and thus cool the Earth—partly compensating for the warming caused by carbon dioxide via the greenhouse effect. But black carbon heats the atmosphere by absorbing solar radiation and hence adds on to the warming caused by carbon dioxide.

While these issues are being debated, when the Kyoto Protocol was signed—if you remember, it was signed in 1997, almost 27 years ago—this Protocol was signed by almost all the countries in the world except a few.

Kyoto Protocol (1997)

Legally binding treaty through 2012 (when ratified by states) intended to enact resolutions from the **United Nations' Framework Convention on Climate Change (1992)** to achieve “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system”

Green =
signed & ratified

Red =
signed, but not
ratified

Grey =
non-signatory



Image from Wikipedia (see “Kyoto Protocol”)

The United States signed the Protocol and was involved in the negotiations, but after that, the government changed in the United States, and the new administration decided not to ratify the Kyoto Protocol. They signed it, but they did not ratify it, because a few countries did not even sign. Those are very small countries. So, this became a major issue. What reason did the United States give for not signing or ratifying the Kyoto Protocol? President George W. Bush, who took office in January 2001, said the Kyoto Protocol failed to address two major pollutants: one is soot and the other is ozone. He was completely wrong. This was an excuse not to ratify the Kyoto Protocol. Because of this, for a long time an impression was given that the global warming caused by black carbon is as high as that caused by carbon dioxide. This is not true at all.

All the work done in the last 25 years has shown that the warming caused by carbon dioxide dominates the global mean temperature. Black carbon has a very minor role to play, but this was an excuse used by the United States not to ratify the Kyoto Protocol, and it led to a lot of confusion. I mentioned in the last lecture that they decided to put methane and black carbon under the so-called “short-lived climate forcers.” Those are emissions that cause warming in the short term, but not in the long term, because CO₂ has an impact on the very long term—100 years, 200 years, and so on—while methane and aerosols have a very short-term impact. But methane and aerosols are not similar. Methane has a lifetime of 10 to 20 years, while black carbon and sulphate aerosols have lifetimes of weeks. You cannot compare aerosols to methane, but they were put together in one category, which is completely scientifically inappropriate.

Now, with the United States not ratifying the Kyoto Protocol, all kinds of data were given to indicate that by reducing black carbon, we might rapidly curb global warming. Two examples are given here from papers published in 2009 (one in *Nature Geoscience*, a well-known journal) claiming that a drastic reduction of black carbon could provide near-immediate relief.

**Reducing Black Carbon May Be the
Fastest Strategy for Slowing
Climate Change**

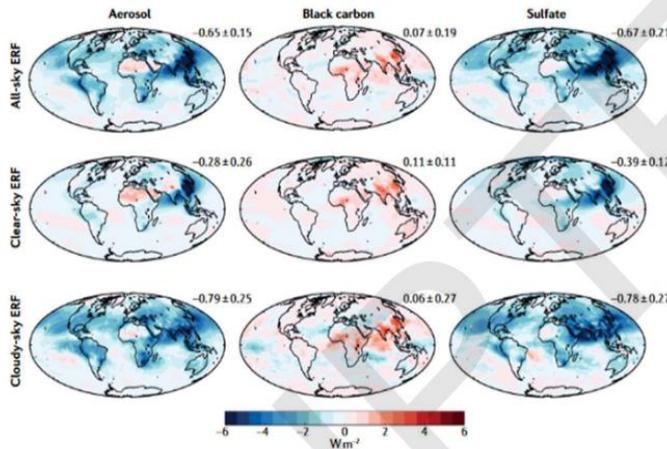
**IGSD/INECE Climate Briefing Note
June 2009**

**A drastic reduction of black-carbon
emissions could provide near-
immediate relief**

**Grieshop et al., Nature Geoscience,
August 2009**

This is completely wrong. There is no basis for it. All the work done subsequently in the next 15 years shows that the role of black carbon is very minor. Here are some papers, and the reason is very simple. If you look at satellite-measured aerosol radiative forcing—i.e., the impact aerosols have at the top of the atmosphere, in watts per square meter—you can compare it to carbon dioxide. Focus on clear sky, where our understanding is very good; cloudy sky is more complicated.

Aerosol Radiative Forcing is defined as the change in Radiative flux due to the presence of aerosols.



The impact of sulphate aerosols is almost 10 times larger than black carbon. The global mean effect of aerosols is to cool the earth but the uncertainty is large

Fig. 3 | Effective radiative forcings for all aerosols, black carbon and sulfate over 1850–2014. Top row: all-sky effective radiative forcing (ERF) for all aerosols (left), black carbon aerosols (middle) and sulfate aerosols (right). ERF is calculated by averaging the results of 14 Coupled Model Intercomparison Project Phase 6 models as the difference in the net top of the atmosphere radiative flux between the aerosol forcing run for the year 2014 and the pre-industrial control run. The numbers at the top right represent the multi-model mean and standard deviation. Middle row: as in the top row but for clear-sky ERF. Bottom row: as in the top row but for cloudy-sky ERF. The climate forcings of scattering (sulfate) and absorbing (black carbon) aerosols are opposite over most regions, and that of absorbing aerosols is highly uncertain.

**Nature Reviews | Earth & Environment
volume 3 | June 2022 |**

In clear sky, aerosols cause a cooling of -0.28 W/m^2 , while black carbon causes a warming of $+0.11 \text{ W/m}^2$. I will first look at sulphate: sulphate causes a cooling of -0.39 W/m^2 ; black carbon

causes a warming of $+0.11 \text{ W/m}^2$ (about one-third). If you combine those two, you get a total of -0.28 W/m^2 .

So, cooling by sulphate still dominates over warming by black carbon, and black carbon's impact is much smaller than that of sulphate. It is very clear, based on various coupled models (about 14 of them) and satellite data, that the warming due to black carbon is much smaller than the cooling by sulphate.

Remember that in many industrial processes, incomplete combustion releases both sulphate and black carbon aerosols. So, when you reduce aerosol emissions, you reduce both—except for cooking with firewood, which is a separate case.

So, the point to remember is that when you look at cloudy sky, the effect is even more dramatic. The warming caused by black carbon is $+0.06 \text{ W/m}^2$, while that caused by sulphate is -0.78 W/m^2 —almost 13 times larger cooling by sulphate. Quite clearly, the impression given by the U.S. government that black carbon emission is very important was not valid.

These aerosols, which have been released over the last 50 years, cause a reduction in radiation reaching the surface—that is why they cause cooling.

The dimming varies greatly over the planet:

- 10% over the USA (*Nature*, 2002)
- 30% in parts of the former Soviet Union (*Science*, 2005)
- 16% in parts of the British Isles (*Science*, 2005)
- 27% over China (*J. Climate*, 2001)
- 33% over India

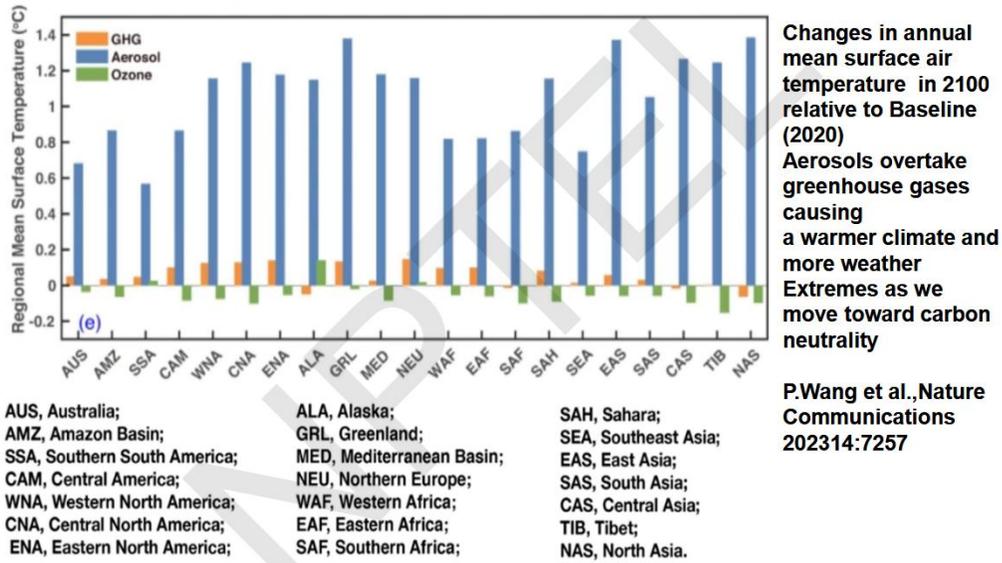
The local impact of aerosols is much greater than global impact

The reduction in radiation (called “dimming”) is over 10 percent in the United States, where there are strict air pollution control laws, but much higher over Russia (the former Soviet Union), China, and India. In those countries, air pollution control did not occur between 1991 and 2001; hence, there is much more dimming. Remember that the impact of aerosols is highly local. The reduction in radiation over the U.S. is only 10 percent, whereas in India it is 33 percent. When you look at aerosols, the global mean is not as relevant as local conditions.

What will happen in the next 50 years as we try to reduce the greenhouse gases as per the agreement in Paris? What will happen is, as the greenhouse gases are reduced, the warming caused by the greenhouse gases will come down. So will the cooling caused by sulphate aerosol.

The cooling caused by sulphate aerosol will have an immediate impact because its lifetime is only weeks. While the warming caused by carbon dioxide, its impact will not be seen for 30, 40, 50 years.

That is why here in this result, they are comparing the surface air temperature at 2100 relative to 2020.



On account of the reduction of greenhouse gas emission, you find that the warming due to aerosol dominates, the blue curve, all over the world. Every part of the world is covered here.

In all of them, the warming caused by aerosol— aerosol is causing warming because the greenhouse gases were removed and the major aerosol is sulphate, which used to cause cooling—and the impact of sulphate is seen immediately, very next week. You remove sulphate today, next week you will see a warming. While the greenhouse gas impact will be seen after 50 years. That is why paper by Wang in *Nature Communications* in 2023 clearly points out that in all parts of the world, we will see a warming of the order of 1 to 1.5 degrees because of the reduction in greenhouse gases. Both greenhouse gases and sulphate aerosols are going to reduce. The impact of sulphate is immediate and the impact of greenhouse gases is more of a long term. So, aerosols overtake greenhouse gases to cause warming and also extreme weather.

Another paper published 10 years ago said, although the effects of greenhouse gases and volcanic forces are robust across model specifications, we cannot detect the effect of black carbon. So, the bogey of black carbon that was created by the United States has been shown to be completely irrelevant.

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

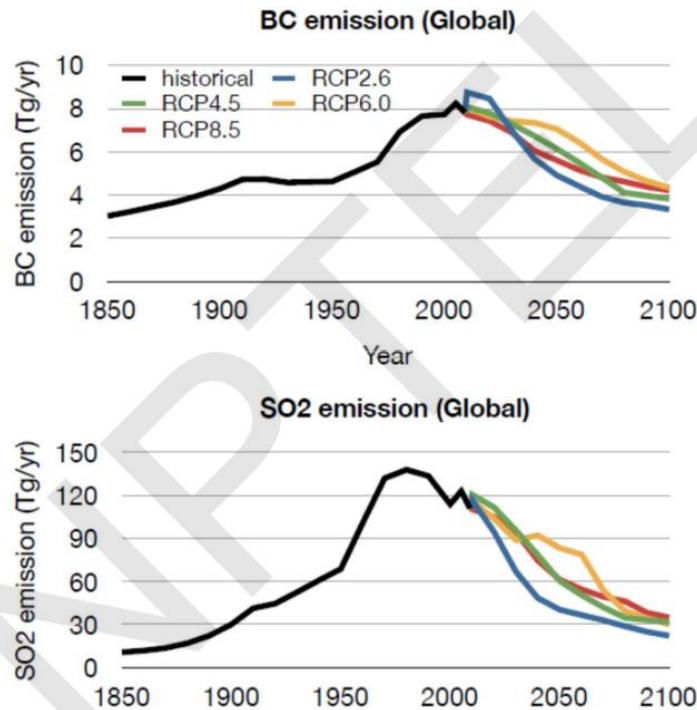
Stern and Kaufmann Climatic Change, 122, 257-269,2014

It has hardly seen any impact in this one. Another paper says that we find that the maximum 21st century warming is largely unaffected by additional black carbon-related measures because the key emission sources are already phased out during CO₂ mitigation scenarios.

We find that maximum 21st-century warming in 2 °C-consistent scenarios is largely unaffected by additional black-carbon-related measures because key emission sources are already phased-out through CO₂ mitigation.

J. Rogelj et.al., Proceeding of National Academy of Sciences, 111, November, 2014

When you mitigate CO₂, you also mitigate black carbon and reduce it. So, its impact is not seen as much as CO₂ because CO₂ is the dominant factor in global warming. So, the results of course depend on how rapidly black carbon is reduced compared to sulphur dioxide. Sulphur dioxide causes cooling, carbon dioxide causes warming, but I want you to see the difference.



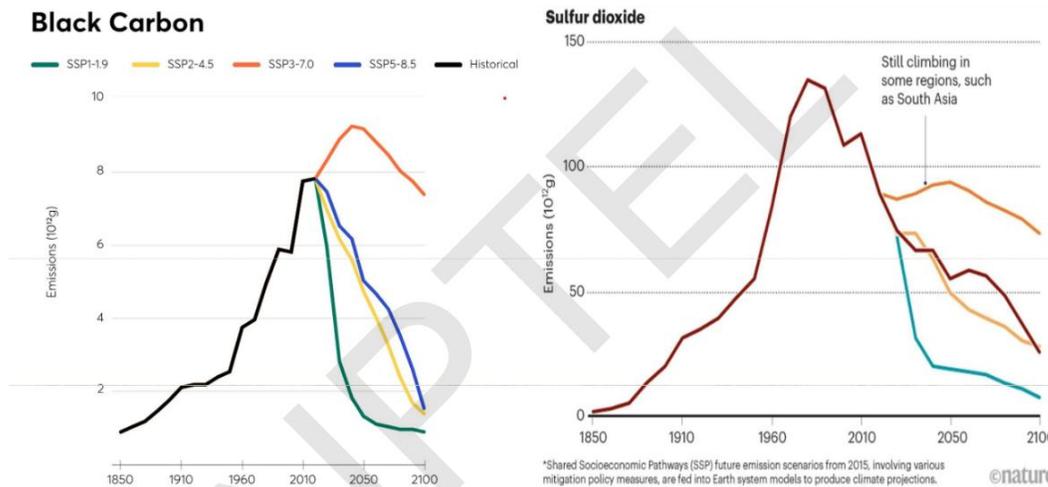
The peak in black carbon emission is around 8 teragrams per year. While the peak in sulphate is 140 teragrams per year. So, sulphate dominates over black carbon by a factor of 10 or more. So, the reduction in sulphate will see much more impact than the reduction in black carbon. That is why when you remove sulphate and it is already going on, the cooling due to sulphate is gone.

And so, you will see a lot of warming caused by greenhouse gases. So, that is why even in 2009, a paper published in *Science* said clean the air and heat the planet. If you clean the air, it reduces air pollution—which we must do because it causes about 1 million deaths in India on account of inhaling these aerosols. If you do that, air pollution control will accelerate global warming.

Clean the Air, Heat the Planet?
 Arneth et al., *SCIENCE*, 30 October 2009

Studies available to date mostly suggest that air pollution control will accelerate global warming in the coming decades.

But there is not much choice. In most countries, air pollution control will happen because it has immediate improvement on our health, but it will cause a long-term warming, which is unavoidable unless we bring down the carbon dioxide emission more rapidly. So, this is in the coming decades. As you go further, it may not be as bad. So, this point is also made in a recent paper in *Nature* by Persad in November 2022, showing that both black carbon and sulphur dioxide are being reduced.

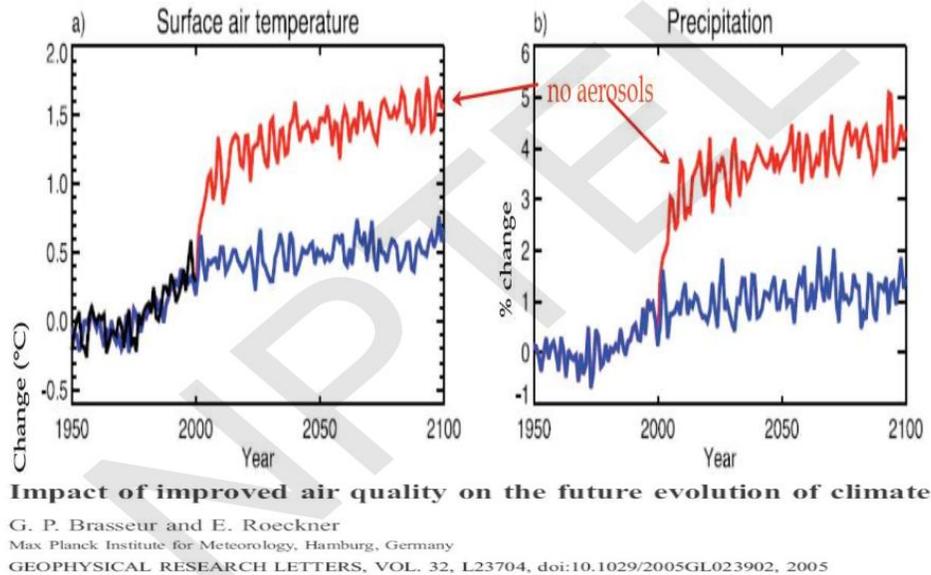


Estimates of aerosol emissions in the past and projections of how they might change in the future need to be refined. Policymakers must recognize that changing regional aerosol emissions are transforming the landscape of climate risk and should demand projections that account for that. G.G.Persad, et al., *Nature*, 611, 24 November 2022

But, sulphur dioxide reduction started in the 1970s because of strict air pollution control laws in Europe and United States. So, they have already come down rapidly by a factor of 2 in 50 years, while in the case of black carbon, which is primarily released by the developing world, the reduction is still pretty slow and in some cases it may even increase. So, there is a big difference between sulphate aerosol and black carbon aerosol in terms of air pollution control laws. Because in rich countries, the major emission was sulphate and they enforced strict laws to bring it down.

In the developing world like China and India, black carbon was a dominant emission and that has not yet been completely controlled.

It will take another 30–40 years. So, the impact of sulphate will be seen first, the impact of black carbon may be seen somewhat later. This is brought out by the paper by Brasseur and Roeckner published almost 20 years ago.

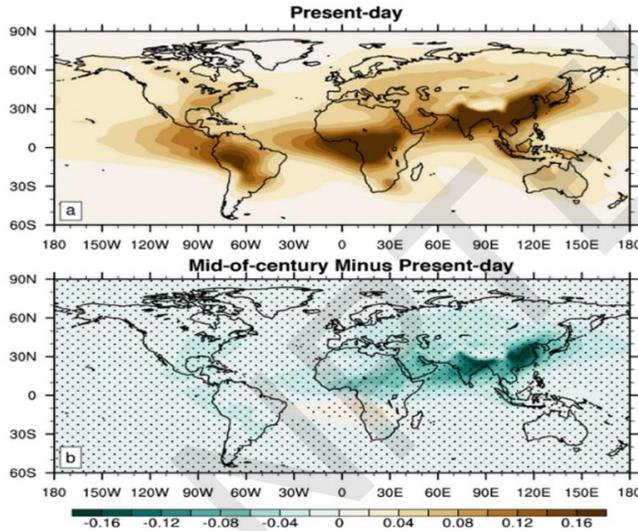


They show that if you improve air quality, the global mean temperature will rise by almost 1 degree centigrade between now and 2050. And so will the global mean rainfall. When the temperature goes up, the humidity goes up and that increases rainfall.

But, our concern should be this rapid warming will occur in the next few decades because of measures related to air quality. So, this is an unavoidable consequence because of the different lifetimes of aerosol versus CO₂. Aerosol has a lifetime of weeks and CO₂ has a lifetime of hundreds of years. The impact of two will occur on two different timescales. So if we reduce CO₂ from today, we will see the benefit 50 to 100 years later.

If we reduce sulphur dioxide emissions today, we will see the impact in terms of warming immediately. That is the point I want you to understand.

Now, this is again shown by a recent paper in *Nature Communications* published last year (please refer to the graph shown below) that the present-day aerosol optical depth— a measure of total aerosol in the column as measured by satellites— is quite high in India, China, Africa, and South America. By 2050, these countries will start reducing the sulphur dioxide emissions. So, the aerosol optical depth will come down substantially and hence global warming will accelerate.



The spatial distributions of aerosol optical depth (AOD) (at 500 nm) in 2020, and its changes in 2050

**P. Wang et al.,
Nat Commun 14,
7257 (2023).**

That is the point Wang has made. So, this is the point which has to be dealt with, which is rather complicated—that we want the global warming to be mitigated in the next 20 years. It will not happen because of sulphate aerosol.

In addition, remember that there are so many other chemicals we are releasing into the atmosphere over the last 40 years. Most of them are greenhouse gases, they have an impact and they have a long lifetime like carbon dioxide.

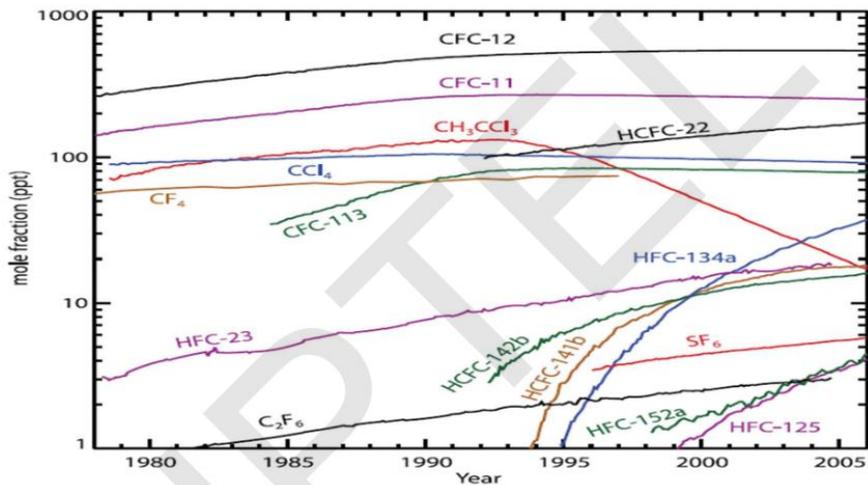


Figure 2.6. Temporal evolution of the global average dry-air mole fractions (ppt) of the major halogen-containing LLGHGs. These are derived mainly using monthly mean measurements from the AGAGE and NOAA/GMD networks. For clarity, the two network values are averaged with equal weight when both are available. While differences exist, these network measurements agree reasonably well with each other (except for CCl_4 (differences of 2 – 4% between networks) and HCFC-142b (differences of 3 – 6% between networks)), and with other measurements where available (see text for references for each gas).

So, they will also have some impact which is unavoidable. Now, as you go to aerosol, even now there is no agreement on the indirect impact of aerosols. That is the impact due to the way aerosol alters clouds.

Tosca et al 2010

The **absence of an interactive cloud microphysical response to aerosols** in CAM3 introduces several limitations to our analysis.

Several studies show a **reduction in precipitation in response to aerosol indirect effects** (Rosenfeld, 1999, 2000; Khain et al., 2001)

Lin et al. (2006) and Rosenfeld et al. (2008) provide evidence, however, that for deep convection aerosol indirect effects may **instead invigorate updrafts and therefore increase precipitation**.

For example, in a paper published by Tosca and others, they say the absence of an interactive cloud microphysical response— that is, the response of liquid droplets on ice— introduces limitations to analysis. Most studies show that there is a reduction in rainfall because of the aerosol indirect effect— that is, aerosol affecting clouds. Another paper says deep convection aerosol indirect effect will invigorate updrafts— that is, make it more vigorous— and increase rainfall. That is only for deep convection, that is, clouds which go from surface to about 10 kilometers. The other studies were related to shallow clouds, which change in a different way than the deep clouds.

Now, let us look at the aerosol effective radiative forcing as documented in the IPCC report published in 2007, in comparison to the more recent one. The IPCC calculated up to 2005 because they released the report in 2007. While the most recent one, AR6, calculated the forcing up to 2019.

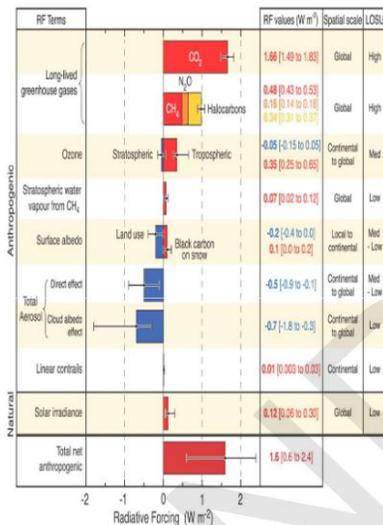
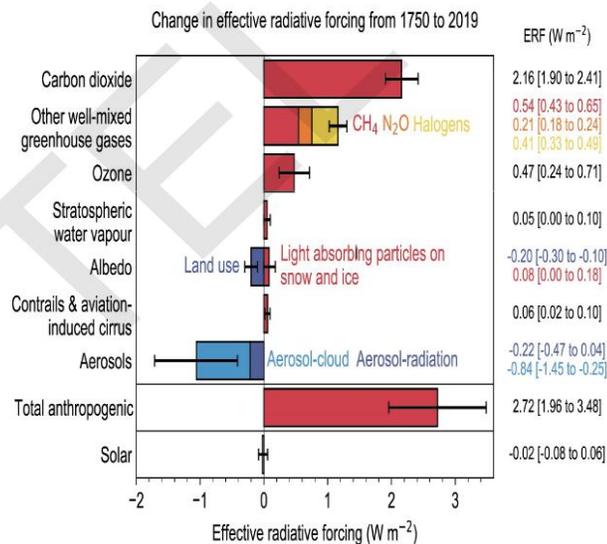


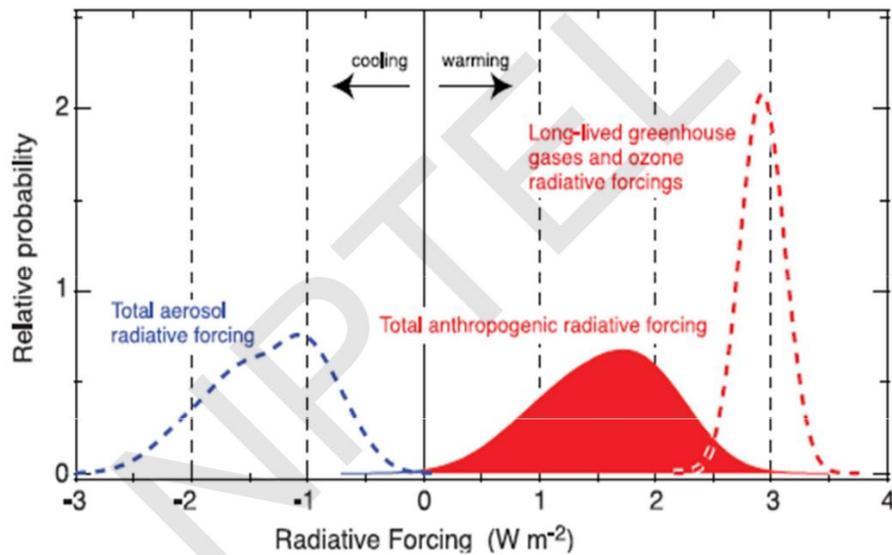
Figure 4. A comparison of the difference in radiative forcings from 1750 to 2005. LOSU, level of scientific understanding [from IPCC, 2007, Figure SPM.2].



Therefore, you can see CO₂ forcing has gone up in those 14 years. Aerosol effect is not that different. So, the net forcing by human activities was 1.6 in 2005, it is now 2.7. So, this increase of 1.1 is mainly due to carbon dioxide and methane. So, notice that the total aerosol effect is shown

here. This is little higher than here because there is much more time to be accounted for. But the main thing is that the net anthropogenic forcing has gone from 1.6 to 2.7 and the uncertainty in that forcing—the large variation in our estimate—here is about 1.5 W/m^2 , while here also it was around the same value, little more actually. So, we still have to deal with 2.7 W/m^2 of human-induced forcing, even after accounting for the cooling by sulphate aerosol.

Now, this is where the problem comes in. You see that we have fairly accurate estimates of the radiative forcing by greenhouse gases. There is a very small spread here due to CO_2 , ozone, and other gases. While aerosol has a huge spread, all the way from minus 3 to all the way to 0.

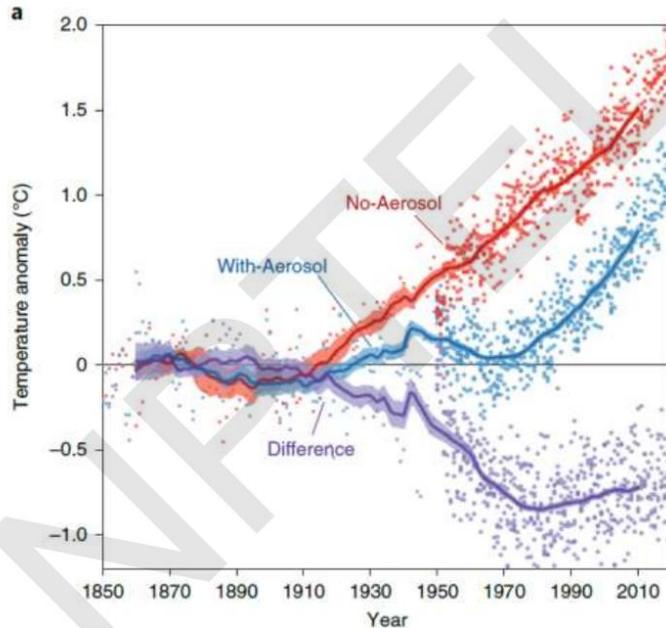


So, you have to combine these two—aerosol and greenhouse gases. So, the net anthropogenic radiative forcing now is highly uncertain compared to only greenhouse gases.

Notice that it is skewed to one side. On this side, there is more than on this side because of the aerosol uncertainty. This is what causes large uncertainty in our ability to predict how much global warming occurred. Notice that this ultimately is less than this. This is around minus 1 and this is 3. But, because we do not know if it is minus 1 or minus 2, there is a large uncertainty in the future warming.

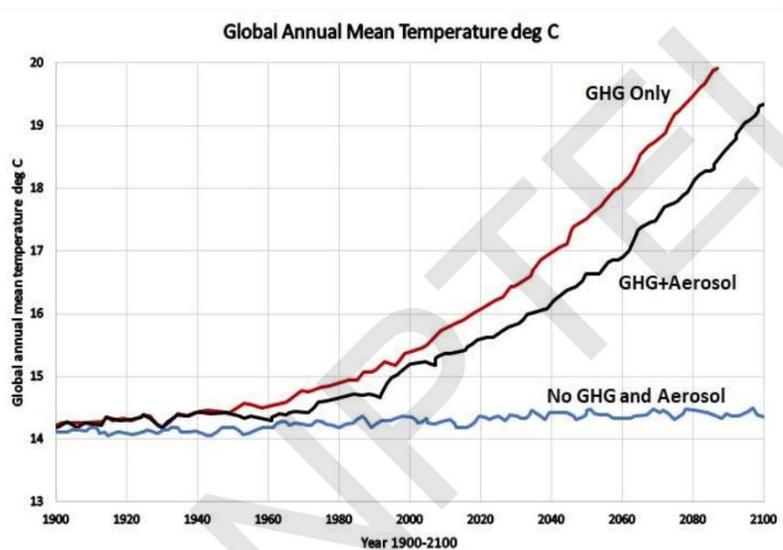
On top of that, when we reduce the air pollution, this aerosol forcing will go out. Then, the warming will go up much higher and our ability to predict the warming also will become very high.

To highlight this, I am showing from various models what is the global warming over the last 160 years. If you do not include aerosol, and if you include aerosol, you can see the huge difference here (the graph is shown below).



Without aerosol, we would have got by now around 2°C warming. We are only around 1.5 °C now. So, we are lucky because of the cooling caused by aerosol, which is of the order of 0.75 watts per meter squared.

There is one more such graph in the Sixth Assessment, the latest one.



Aerosol air pollution has made the planet about 0.4 °C cooler than it otherwise would be, according to the IPCC 6th assessment report

So, if you look at around 2020, they are saying that without aerosol you would have 2 degrees warming from 14 °C to 16 °C, but because of that, we have 1.5 °C warming, which we saw last year. 2023 had a warming of 1.5 °C, and that is what, when you combine greenhouse gas and aerosol, that is what you get. If we did not have these emissions by human beings, you would have had almost no change.

This is due to natural processes only. So, you can see clearly that the 1.5 degrees warming we have seen today around 2023 is mainly on account of greenhouse gases, partly mitigated by sulphate aerosol. But, in a regional scenario, things are quite different.

In India, if you look at the winter maximum temperature between 1951 and 2010, which is a 60-year period, you see that most of South India, there is warming of the order of 0.02 degrees per year or 2 degrees in 100 years, which is what we expect due to greenhouse gases.

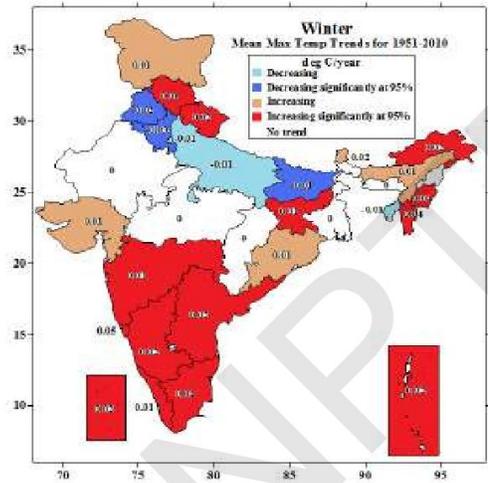
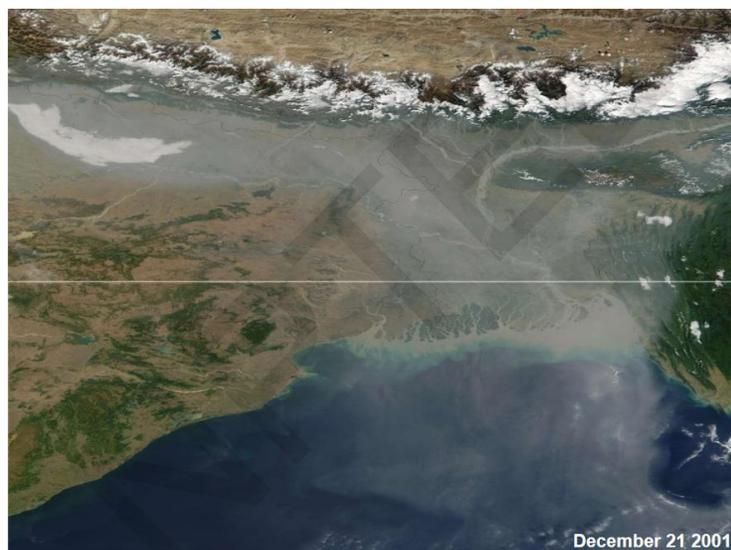


Figure 8: State level mean maximum temperature trends for winter season.

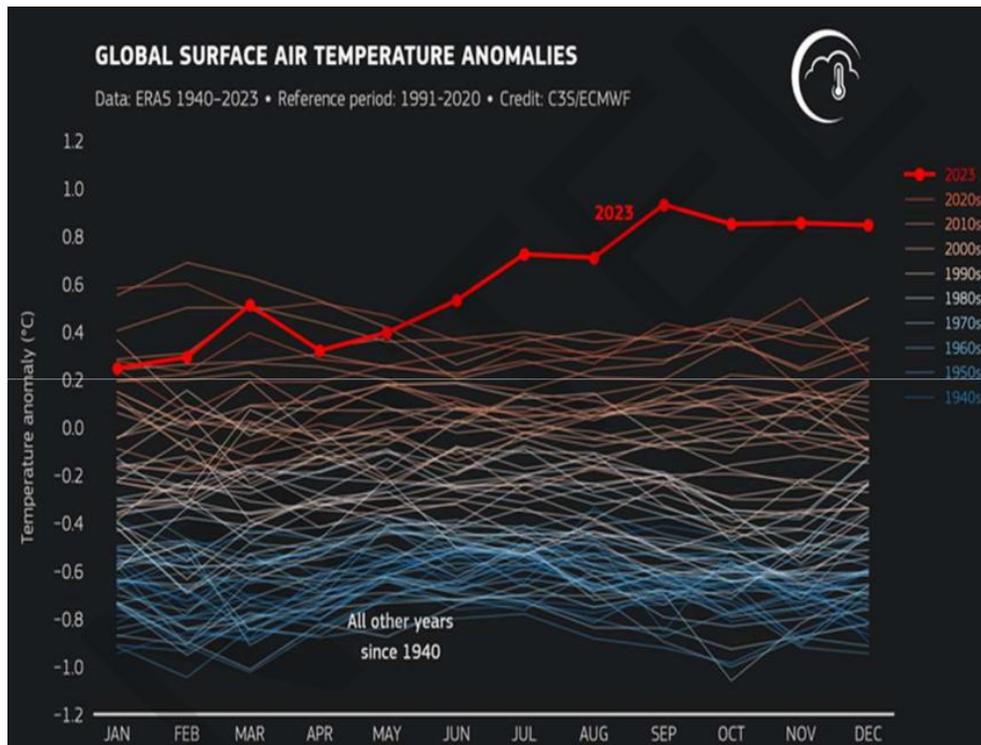
The impact of aerosols on the decrease in maximum temperature in winter is evident in the Indo-Gangetic plains

But, over the Indo-Gangetic plain, which is highly polluted in winter—all of you know that—you see a cooling of 1 degree in 100 years. So, I want you to see the huge impact of aerosol—that is, there is a difference between South India and the Indo-Gangetic plain because air pollution in the Indo-Gangetic plain in winter is very high. And that is clearly shown by the satellite data showing a huge layer of pollutants on top of the cloud. This pollutant reduces warming due to greenhouse gases.



So, India is a place where we clearly see locally there is a change in sign. South India, there is warming; North India, there is cooling.

Now, last year we had a world record of 1.5°C warming of the temperature. Of course, this is here showing compared to 1991 to 2020, which is only 1°C, but if you compare it to the 19th century, it was 1.5°C warming.

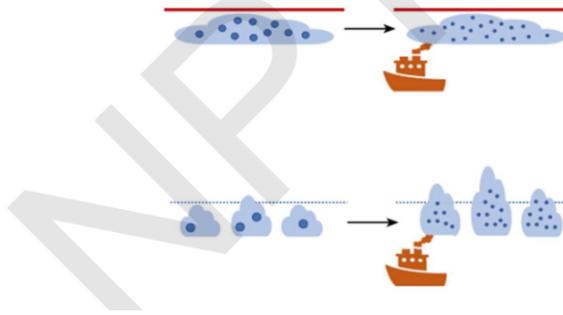


The year 2023 was the warmest year on record, with climate change adding an extra month of abnormally high temperatures for the average person. This May, countries from India to the United States to Mexico have all experienced dangerous heat waves. Scientists estimate that more than 5 billion people will be exposed to these types of deadly heat conditions by 2050

The major question was: why was it so high, that warming last year? There are various reasons, and many parts of the world saw this huge warming, which caused heat waves, and the United Nations warned about this problem. One of the interesting reasons is due to the fact that clouds have changed in 2023. That is because the body which controls emission by ships globally—it cannot be controlled in various countries—it is a maritime shipping authority which has passed a law in 2020 to cut down the emission of soot and sulphate by these ships.

**‘We’re changing the clouds.’ An unforeseen test of geoengineering is fueling record ocean warmth. Pollution cuts have diminished “ship track” clouds, adding to global warming
Science, 2 August,2023**

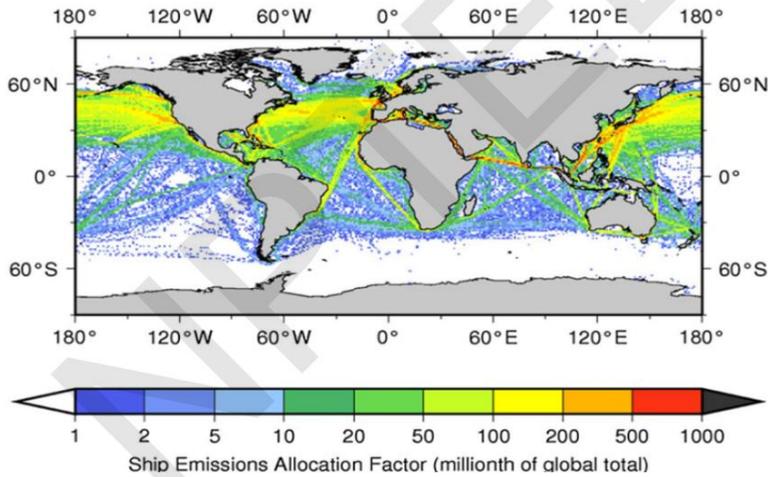
**Global reduction in ship-tracks from sulfur regulations for shipping fuel
T. Yuan et al., Sci. Adv. 8, eabn7988 (2022) 10.1126/sciadv.abn7988**



It was enforced in the last few years, and the impact of that is seen. These ships mainly are transporting goods to the developed world from China. That is a major path.

Regulations imposed in 2020 by the United Nations’s International Maritime Organization (IMO) have cut ships’ sulfur pollution by more than 80% and improved air quality worldwide.

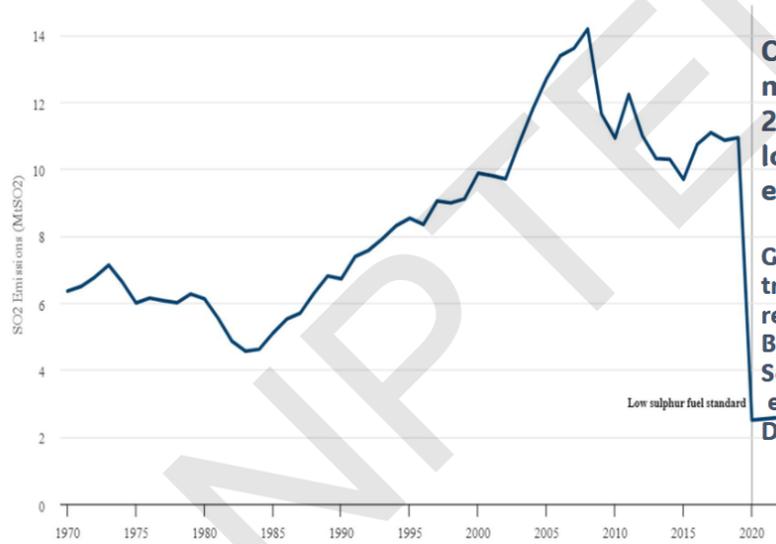
ICOADS



When the International Maritime Organization enforces law, the sulphate emission suddenly dropped around 2020 onwards from around 12 megatons 10 years ago to almost 2 megatons. So, this paper showed that had an impact on global mean temperature.

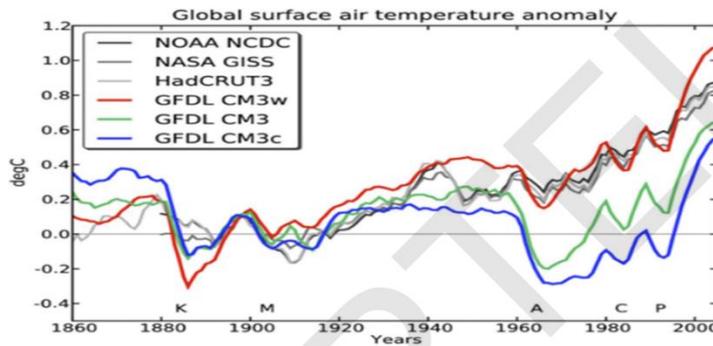
Declining sulphur emissions from international shipping

In millions of tonnes of sulphur dioxide (MtSO₂) per year



Could the high global mean temperature in 2023 be on account of lower sulphate emissions from ships?

Global reduction in ship-tracks from sulfur regulations for shipping fuel
By T.Yuan et al., Science Advances eabn7988 (2022)
DOI:10.1126/sciadv.abn7988



Seinfeld et al., PNAS . May 24, 2016
10.1073/pnas.1514043113

Fig. 1. Sensitivity of predicted global temperature evolution to three versions of the aerosol–cloud submodel in the GFDL climate model: CM3w, CM3, and CM3c (8). In the simulations, emissions of sulfate precursors, organic and black carbon, and GHG concentrations were held constant at their 1990 values. For CM3w, increased cloudiness (the lifetime effect) owing to reduced autoconversion of cloud droplets to rain is partially offset by increased cloud erosion. For CM3c, the increased cloudiness that results from less efficient autoconversion of cloud droplets to precipitation is offset by reducing the lower bound on the vertical velocity variance for CCN activation. The net warming predicted by the three different submodels is: CM3w, 0.57 °C; CM3, 0.22 °C; and CM3c, –0.01 °C. By comparison, predictions of three other GCMs are: NOAA NDC, 0.59 °C; NASA GISS, 0.53 °C; and HadCRUT3, 0.56 °C.

We will conclude the lecture today, and I will continue this discussion in the next lecture talking about the impact of aerosols. Thank you.

