0:02

DAVID KEITH: Welcome to what if I haven't lost count is lecture five, you haven't seen me since lecture one, and let me jump right in and kind of tell you how this fits in with the other lectures. So again, this slide you've hopefully seen in every lecture that should locate you. Last week you had Cael on carbon removal. Now you've got me on the first of the two lectures on sunlight reflection. And the division isn't perfect, but roughly, most of this lecture is really about how you might reflect sunlight if you wanted to. And the next lecture is more about what the uncertainties are what some of the consequences are, especially about the uncertainties in the climate response. So that's roughly how this, this lecture, the next lecture, are divided, or actually this lecture and the second to last lecture of the Shaw and Keith lecture, sorry.

0:55

Here's the way this lecture is set up. I’m going to start by resituating, reintroducing how sunlight reflection fits into other ways we might deal with the climate problem, and very quickly tell you what the methods are. Then I'm going to try and explain why the heck we talk about aerosols, why the stratosphere and why sulfur? Then I'll talk a little bit about some of the engineering aspects of doing this, then compare different methods for sunlight reflection, then look at climate response, and then just have a slide to raise some of the obvious and maybe less obvious concerns about these technologies.

1:35

So just the slide I started with last time to resituate you. The fundamental point is simply that climate change is, in some deep sense, a four dimensional problem, and this whole lecture series wants to frame that looking at these two pieces that we think of as climate engineering, carbon removal and sunlight reflection. This lecture takes you back to sunlight reflection, which at best weakens the link between the accumulated greenhouse gasses and the climate change.

2:10

So I'll start by trying to talk my way through a whole range of ways that humans could deliberately change the reflectivity of Earth. So I'm going to kind of do it from the top down. So from the top down, it's possible, it's physically possible, that one could build structures in outer space, either in low Earth orbit, which I think turns out to be kind of ridiculous for a range of reasons, or potentially at the, near the L1 point, quasi-stable point between the Earth and the Sun. It's actually sunward of the L1 point. One could, in principle, build large structures that would reflect some sunlight. There's actually been a fair number of papers and examinations of this going back for decades, but I think it's fair to say that it's there's no feasible way this gets done in the next half century at scale. But on the other hand, we're living in a time where access to space is getting dramatically easier, and this is a century or two century long problem. So I don't discount this at all. I think it's interesting and different from the other things, but it clearly is further away than any of the other things.

3:15

Next, again, kind of going down in altitude, is that we could put reflective materials in the stratosphere, most obviously sulfur. I'll get to, that'll be the main thing I'll focus on. I'll get to why it's most obviously sulfur and what those materials are in a second. So let me continue with the other ones.

3:32

The next one on the way down is that we could alter thin some kinds of high cirrus clouds that are not unlike contrails you see from airplanes. These are the high, wispy clouds that you see. They're mostly ice crystals, and they actually act in two, well, all clouds act in two different ways, but they act in two important ways. A low cloud, a cloud that's really near the surface, reflects sunlight, but its temperature is kind of the same as the surface, so it doesn't have any big infrared effect. A high cloud both reflects some sunlight, that's why you see it the white cloud, but it also acts as an infrared blanket, and so it traps some heat. It does both things, and that has important consequences, but it means that if you could, in many cases, reduce those clouds, you'll actually let more heat out, and that has the positive aspect that it is more directly and physically counteracting the problem that's been caused by the build up of greenhouse gasses like carbon dioxide. So at least in principle, doing something that lets more heat out for the middle of the atmosphere is a more perfect offset to the fact that the greenhouse gasses like CO2 are trapping more heat. But there's a whole bunch of uncertainties and problems we'll get to. But just to give you a little kind of tidbit of why this connects to other things that matter--if you fly, as I assume, many of you have, you have a choice of buying ticket. Some cases that might have you fly in the day or the night, and it's considerably more warming if you fly during the night than the day, because of the fact that, of course, these thin clouds and the contrails are basically the same as thin clouds in the night. There's no sunlight for them to reflect, so they have no cooling power, but they have that same infrared heating power.

5:20

Then going further down, there are ideas called marine cloud brightening for how we can make certain kinds of low lying marine clouds, like the kind you might see off the coast of Seattle or off other parts of the Western boundaries that you would see, make these clouds both whiter and more persistent, more reflective. Well, I will talk a little bit about that towards the end of the lecture.

5:42

And then finally, there are a bunch of ways that we might, in principle, make the surface brighter, by making crops that are more reflective or otherwise changing the surface.

5:50

So that's a big range of things that one could, in principle do to reflect sunlight. And there's some research on all of them, and I'm personally excited that we should do more research on a range of these things, but I think the following statement is fair, which is, only one of those, only sulfuric acid in the stratosphere, for only for that one is there a near term development pathway to deployment. That's not saying deployment is good or bad, but that's making a distinction between development and research. To me, development means that you're not doing any fundamental research. You understand what needs to be done. You could hand it off to engineers who could go and develop a system for deployment, again, not weighing in on whether that's good or bad, but I think that's a fact. We know enough about sulfur and stratosphere, and we'll come back to a bunch of that in details here, that there's a way in which we're confident, in a crude way, that it could be done, and the same cannot be said for any of those other technologies in the near term. But that's not a reason not to look at them, because first of all, research can unexpectedly show new things, and maybe some of those things that now look hard will turn out to be easy and have low environmental harms and be useful. So I absolutely am not saying that we should only look at salt from the stratosphere. Indeed, I've been excited myself looking at lots of other things, but I think it is important in this universe of things that get published and get out there in the media to realize there's really only one thing, if one wanted to do large scale changes to the temperature of the entire earth that is practically doable on the timescale of a few decades, which, again, may or may not be a good idea.

7:36

This should shock you a little bit, or sort of make you scratch your head. So the first person to propose deliberately putting sulfur in the stratosphere for reducing global warming was Mikhail Budyko, a Russian scientist, Russian clim-, famous Russian climate scientist. The first version of it I've seen is 1974, I think there may be some earlier versions in Russian, but basically, in the early 70s, Budyko suggested doing this. And ‘74 was, I looked this up, the same year that we had bell bottom jeans and Motorola's 8080, the first successful general purpose microprocessor. We've obviously seen a lot of innovation since 1974, so your reaction ought to be, why the heck am I still talking about the 1974 idea and not some much better or newer idea? And we'll get to that. I think there's actually lots of good reasons that these ideas have been stable, but that should be in the back of your head, I think, that this idea is old, roughly a little over 50 years old, and that there hasn't been, in some sense, any deep innovation. But as I'll come to the end, I think that's both a good and bad thing.

8:45

Now, now I want to deal with these three questions in a row in some detail. Why are we talking about aerosols? Why are we talking about the stratosphere? Why are we talking about sulfur?

8:55

So aerosols first. Aerosol is just a kind of fancy word for a particle that's small enough that doesn't sink very quickly, that is, that its settling tme is slow. So just think of as an aerosol as a particle could be a solid or liquid that's small enough that it is suspended in the air, not not forever, but for long enough that you can think of it as suspended. Aerosols are--can be, if they're about the same size as the wavelength of light--spectacularly efficient little scatterers or little mirrors. They're not like mirrors in the sense they don't reflect a single beam in a single direction. They scatter in a range of directions. So I'll get actually a little more detailed physics in a second, but imagine you've got, what did I lose here? Imagine you got some beam of incoming sunlight. It comes into some particle and gets scattered. And this, what this is showing is most of the scattering is scattering forward and the direction the light came from, but some the light is scattering backwards. And the message is that for particles that are about the wavelength of light, depends on a bunch of stuff you'll get to in the next slide--they can be stunningly efficient scatterers. And by stunningly efficient, I mean that if you compare them to mylar film, which we've all seen, which is very lightweight and amazingly, scatters a lot of sunlight, if you want, if I told you you had to make this area be reflective, mylar film will be one of the lightest weight things you could do--little these little particles can be 100 times more efficient at scattering light backwards per unit of mass than mylar film is. So that's something that's the underlying reason why there's so much kind of leverage or power in aerosols, and why aerosols keep coming up, both in climate engineering and in climate science itself.

10:42

And then finally, there's this last one, which is, of course, the main thing that scatters light in the, in the atmosphere is clouds. But clouds are made of little water droplets, and the size of those water droplets depend on the number of seeds from which the cloud grows. And all those water droplets essentially always grow from a little seed, which is an aerosol. So if you start with something that has air that has more aerosols, and the same amount of water condenses, it'll condense into more little droplets, and more little droplets means smaller droplets on average. And as we'll see, that means they reflect more effectively.

11:20

Now I'll kind of come to the most sort of physicsy thing I want to show. Sorry, I didn't have the mylar film up. This the mylar film. Let me actually give you a sense little bit more to give you some numbers behind what this is. So lots of things we've been talking about in this lecture are all little fuzzy or depend on really big models or complicated and so I want to just give you one thing that actually you can calculate with essentially perfect accuracy.

11:45

So for a spherical and homogeneous, that is, all the same all the way through, particle, there's this thing called Mie scattering, which means that you can perfectly calculate the way that light interacts with that thing, if you know just the index for a fraction that has a real and imaginary part. The imaginary part is how much its light is being absorbed, and a size parameter, which is just the ratio of the size of the particle to the wavelength of light. That's all you need to know.

And then I'll just tell you some key things. This is all what matters here is this K or Q. It's called different things in different literature, but it's the ratio of the geometric cross section, that is, how big the particle looks like, pi r squared, compared to the fraction of light going through that thing that is reflected or scattered, the scattering, dimensionless scattering cross section. And I just want to tell you two things. First of all, if the particle is really big, that is, if the radius is much bigger than the wavelength of light, then basically that k is two. So basically it scatters twice as much as the thing. But it turns out it scatters almost everything forward, so it doesn't really scatter back very much. And if the wavelength of light is really ti-, if the particle is really tiny compared to the wavelength of light, then the scattering is very small, and it grows sort of the fourth power of the of the radius or of the ratio. So basically, little particles, they grow bigger, scatter more and more efficiently. And then there's some, some peak in the middle.

13:17

And this should explain a lot of things. If I have a piece of glass, look through it. See through it pretty well. It doesn't scatter very much light. If I take that same glass and I crushed it up with a hammer into tiny little shards, it would be very efficient at scattering. That's the same physics. And likewise, all of you will have seen cases where you have blue sky and then a cloud appears. How the heck did that cloud look so bright and puffy when it has just the same amount of water in it as the air did before? How does it look so puffy? It's because when the water molecules are just moving around the air as water molecules, they're way too small, and they fall in this r much, much less than than lambda, that is, water molecules have sizes that are, you know, angstroms, and the wavelength of light is half a micron, so five, 500, and when the when those water molecules come together and make little water droplets, and the water droplets happen to be about the size of the wavelength of light, they typically get bigger, but if they're that size, then they're very efficient at reflecting sunlight.

14:26

So that's the kind of little bit of physics I want to show you. There's the underlying reason why aerosols keep coming up and keep being important. It's not just the size, it also is the composition. So I'll quickly now go through a few other things. This shows you some calculations we did specifically looking at different materials that might be used for sunlight reflection. So sulfur is the thing we know the best. I'll come back to all the reasons why that's true. But sulfur is not the only thing. We thought about putting diamonds in the stratosphere, or calcium carbonate or a range of different things. So this shows you a range of different compounds that have different indexes or fractions.

And what is shown here is the particle radius, the size of the particles, imagining that all the particles are the same size--which in practice, they're not going to be, this is just a simple calculation--and they're matching, they're all evenly distributed around the world. And this is showing you the amount of what we call watts per square meter of radiative forcing. This is something Tiffany talked about. It's basically how much we're pushing the Earth's climate. So I think you're going further down here, you're pushing the climate more. Doubling CO2 is about four watts per square meter. So going down here would be equivalent to about a quarter of doublings, offsetting the effect of about a quarter of doubling CO2. And this is for a given fixed amount of material, one teragram, 1 million tons of material. And you see, if you have, like silicon carbide, which turns out to be the very highest index, most scattering thing, you can get a watt per square meter out of that much material. And sulfur, so much here. And in each case, there's an optimal size. So that black is just the place where that number is biggest, and that's the optimal size. The optimal size varies a little bit, but it's around, for radius around point two or so, for some diameter around point four. So round numbers, call it half a micron. Just think about these particles being about half a micron.

16:15

KEITH: Quick. Yep?

AUDIENCE MEMBER: This is very dependent on the index of the fraction...

KEITH: Yes, that's why silicon carbide, which has a high index, is the big one. Yep, correct, yep.

16:28

So this gives you just a sense and all this stuff is pretty easy to calculate. We'll get to all the things that are really hard and not certain in a second, but this gives you a sense of the power of why we keep talking about aerosols for scattering sunlight. And the same computational codes, and these are part of the computational codes that really are correct. There are lots of other things about climate that are approximations, but radiant transfer, we know really well.

16:51

You can also from these same calculations, these same Mie scattering calculations, answer the question of how the sky would look different if there were materials in it. So here's an example where my student, Ansar Lemon, has looked at how the sky would appear different if it was if we were cooling it with aerosols, and we were using different kinds of aerosols in different amounts. There's a whole paper you can read, but I'd say the short answer, it's actually very subtle and complicated, because it turns out to involve lots about visual perception, but I'd say the short answer is, if you're cooling the

Earth no more than, say, half a degree or degree centigrade, and you did it in a reasonably sensible way with reasonable sized particles, a casual observer would not notice. A canny observer who was really looking at the sun behind a pole would notice, and you would also notice when the sun was below the horizon after sunlight, because then the stratosphere is illuminated and the lower atmosphere is not.

17:50

So that gives you some sense of why aerosols keep coming up in all these climate engineering schemes or sunlight reflection schemes. Next, this one's easier and shorter. Why the stratosphere? So the lower atmosphere where we live is called the troposphere. And troposphere is, means turning sphere, and the name of the and in the turning sphere, in the lower atmosphere, the whole thing is turned over roughly once a week. So roughly once a week, all the air is brought up in some big rain cloud, and then it slowly sinks back down. And so the whole lower atmosphere where we live is turned over roughly once a week, and air is cycled through. And that means aerosols don't last very long. Average, an aerosol pollutant that you know, comes from some truck in Mongolia or Kansas or wherever, some dust in the Sahara, on average, an aerosol particle, lasts for about a week in the lower atmosphere.

18:50

The stratosphere is really different. The stratosphere is stratified. It's stratified in the sense that in the lower atmosphere, temperatures are decreasing with height. In the stratosphere, temperatures increase with height, and that means that you have effectively air that is, where there's a density separation, so it really doesn't want to convect, and the air slides over itself, but it doesn't mix very much. So some of you who are older and they have memories of people smoking in smoke filled rooms, and thinking about the way smoke kind of moves around slowly in a room. That's how the stratosphere would look, if you could visualize it. And so the stratosphere really doesn't mix, and it moves very slowly. It doesn't mix much. It moves very slowly. And very roughly, things cycle through the stratosphere in about a year. I'm approximating a lot--there's some parts are less than a year, some parts are more than a year--but think of it as a year timescale for the air to move slowly through the stratosphere.

19:43

The stratosphere, in terms of altitude, is huge. This is altitude here in kilometers. A regular aircraft flies about here, so tens of kilometers up there. But in terms of mass, because the pressure is decreasing with altitude, roughly 90% of the atmosphere is the troposphere. The part we live in. The stratosphere and higher up is just 10% of the mass. But from this, you get this powerful thing, this ratio of about 100 to one. So if particles last in the stratosphere for 100 times longer they last in the troposphere, then if I want to reflect a given amount of sunlight, I've got to continuously renew particles. That's true for everything, because the particles all will eventually come eventually come out. So if I want to keep reflecting a fixed amount of sunlight, maybe 0.1% or 1% of the sunlight, if I put particles in the stratosphere, I need to put about 100 times less particles per year, per month, or whatever, than I would if I put them in the lower atmosphere. That's the reason that we keep coming back to talking about the stratosphere for these, these topics, or it's one of the reasons.

20:47

The other reason is that things mix in the stratosphere in a way that makes it comparatively easy. You can look at this, it's kind of, quickly we'll get political about what do you think is a good or bad thing, but it makes it comparatively easy to get a roughly even coverage of particles over the whole planet. So this is a illustration using real data from very high resolution winds in the stratosphere. And we're assuming that we have been for one month releasing particles. These are virtual particles modeled by a computer model. And this tells you a lot. You can start to see the jet or the tropical circulation here and the jets here, and you'll see that over just one well, it's one month of emissions, and then this simulation you're watching will run for two more months, which isn't very long, you'll see by the end of the simulation, you've got a reasonably even coverage. And more complicated simulations show that, if you would, just a few injection sites kind of averaged over a year, you pretty quickly get quite even coverage. And you actually can't avoid that very much. So the only knobs we have to change the distribution of stratospheric aerosols are really that we can do more of the poles or more of the equator, or we can do more than the northern hemisphere, more than the southern hemisphere, and that's about it. You can't make them sit just over one place, and you can look at that as a good or bad thing, depending how you think about it, but it's a fact of the physics that's important.

22:14

So why sulfur?

22:19

It must seem, I mean, I haven't said the obvious. It's got to seem pretty outrageous to say that it might make environmental sense to put sulfuric acid over our heads when we know that it causes acid rain and it's an air pollutant and so on. So you got to think, why do we keep going back to sulfur?

22:38

So first of all, it's the most common natural aerosol in a stratosphere. That's maybe the starting point. It's actually not that easy to think of other aerosols which so easily are stable in the stratosphere. One important thing to say is it's not the sulfur has some magic scattering property. A half micron droplet of pure water scatters only slightly less well than a half micron droplet of sulfuric acid. So water would do great scattering in the stratosphere. The problem is the stratosphere is extremely dry, and a half micron droplet would evaporate in minute, kind of timescales. So in some ways, the reason the sulfur is there is to keep the water in place. It's these strong acids kind of hold the water in place and make it stable. So in some ways, that's the point of the sulfur is to hold the water in the droplet there.

24:31

You're all, I'm sure have heard about volcanoes, and volcanoes are important. We'll get to them in a second. But I think there's a kind of more interesting and more important analog. So plankton in the ocean use sulfur. Well, we all use sulfur in our in our biochemistry, plants and animals. Sulfur is one of the most important elements of life and the grand biogeochemical cycles. But there are plankton that release a sulfur compound that's pretty stable in the lower atmosphere, so it makes it up through the lower atmosphere all the way the stratosphere. It's called dimethyl sulfide. And in the stratosphere, it's the main source of sulfur that forms these sulfate aerosols in the kind of background, quiescent stratosphere when there isn't a big volcano.

24:10

So then you can imagine, and especially if you're Jim Lovelock in the 1980s, you could imagine a kind of feedback, which he called a geophysiological feedback mechanism, part of his idea that the earth was somehow alive, like Gaia, which I think captures something real about the Earth, though I don't quite think it makes sense to call a living organism, and the feedback mechanism is what I show here, that if you imagine the earth was a little warmer, then the plankton are happier, and they make more of this dimethyl sulfate, and then these happier plankton making more dimethyl sulfate mean that there's more stratospheric aerosols, and that cools it down a little bit, and that's a thermostatic feedback mechanism helps to keep the earth's temperature what it is. And that is actually true. How important it is to long term climate control is debatable, but it is a real feedback mechanism. So you could argue that sulfate aerosols are what people like to market as a nature-based solution. They certainly are based on natural cycles. I think that's the kind of marketing ploy that doesn't mean that much, but it's a true statement.

25:08

I think the most important reason why, at least I think sulfur is the right place to start, if, or if one was ever going to start sunlight reflection and is really about unknown unknowns, because we've studied sulfur for so long, partly because it's a horrific pollutant of the lower atmosphere. There are literally of order 10,000 papers that have been written over the last century about sulfur, about 2500 papers about stratospheric aerosols, about 15,000 papers about aerosols in the lower atmosphere but not all of those are about sulfur. But that gives you a sense of the scale of scientific research. And what that means is that we know a lot about sulfur. In some sense, I think of it as the devil we know. It means that there are absolutely going to be harmful impacts of putting sulfur in a stratosphere, but it's unlikely there will be giant unknown unknowns, because we've studied it for so long and observed it for so long.

26:01

And this is where some numbers really matter. So many of you might have worried about acid rain, smarter things. So these numbers matter a lot. These are all in these units of a million tons sulfur a year. So when pollution of--in sulfur--peaked in the 19, about 1980, before air pollution laws around the world gradually began to, began to win and we began to reduce sulfur emissions, the peak was--round numbers, there's different data sets of different numbers, but round numbers--about 70 million tons a year of sulfur we were pumping in the lower atmosphere, which, to be clear, was killing over 5 million people a year from air pollution. Now, thanks to good environmental policy and other things, we're now down to some number about like 30. Again, there's actually significant uncertainty in these numbers, so a factor of two decrease, which is a huge thing to celebrate, and it's been going down fast now. So that's that scale.

26:50

Another thing to bear in mind is a particular volcano in the early 90s, Pinatubo, put in a single year--so it's not per year, but it's a one pulse--put about 8 million tons into the stratosphere, the amount needed to cool the Earth half a degree C, which I think of as a kind of important benchmark if we're going to slow down global warming over the next half century, the amount needed is of order, one and a half million tons a year, if you were clever about controlling the particle size. So that gives you this kind of important sense of comparison, I think, really deeply important. It allows you to see almost at a glance, that acid rain can't be a problem. It's true that all the sulfur you put in will eventually reach the surface, but it's tiny compared to this. And acid rain is a lot about concentration, whereas this is spread everywhere, whereas acid rain really was a problem near industrial emissions where it was high. So there's been papers that shows that it's pretty much a non--it is not pretty much--is a non issue. There are other problems, for sure, air pollution, we'll get to that.

27:45

It's also useful to note the industrial market for just moving sulfur around for sale in the world is around 85 million tons. So it gives you a sense of kind of how quantitatively small it would be to do a meaningful amount of cooling with sulfur, compared to other aspects of sulfur, which is, again, not claiming the risk is zero. That would be crazy to claim, but claiming we have a strong empirical basis to understand what the consequences are.

28:13

Okay, I want to talk about a little bit about engineering. In fact, the first couple slides here are kind of halfway between engineering and kind of science problems in the stratosphere, but they really are actually some of the cutting edge problems that we're we're dealing with.

28:26

So in general, in studying this, everybody's background idea is volcanoes, and the climate modeling community spent a lot of time modeling volcanoes because they're really important for climate. After big volcanoes, the climate cools down. And so the climate modeling world who cares about volcanoes and climate have tuned up and adjusted and learned the science of these climate model codes to try and reproduce the amount and size of the sulfur aerosols that are formed after a volcano. To be clear, volcano does not directly put sulfuric acid in the stratosphere, it puts SO2 in the stratosphere, and the SO2 oxidizes and turns into sulfuric acid.

29:07

So people tend to think about volcanoes, and the normal way people often talk about sunlight reflection is that it's kind of an analog to volcanoes. That's certainly true in some ways, but it's also turns out to be really different in some important ways, when you start to think about the practical the practicalities, because--we'll get there in a second--but almost for sure, if this is going to be done, the materials, whatever is the precursor, would be released from an airplane. Airplanes fly, as we all know, on long tracks. They would release material. And there'd be very high-density material in that track that would gradually move around.

29:40

So let's think a little bit about some of these analogs. So the first slide just tells you something about how important it is to have particles the right size. So this curve here is a scattering efficiency curve which is basically exactly related to the physics I showed you earlier. That's actually one of the things I, I calculated myself, which I like. Now, as a senior scientist, I don't get to do my own code enough. It's my own code running doing this Mie scattering and integrating over solar angles and stuff. And this is calculating these scattering efficiency as a function of the size. So basically, as they get too big, they're not very efficient, that's what I showed you; as they get too small, they're not very efficient. The other thing I plotted here is the fact that as particles get bigger, they fall faster. Duh, that's no big surprise. A cannonball falls very fast. So this is how much something settles in kilometers a year. So by the time a particle is as big as one micron, it's falling by kind of a falling by more like 10 kilometers a year, quite a lot. So the point is, you really want to keep these particles smaller more than the kind of half micron size that really matters. And if they get too big, they're really quite inefficient. They both fall out fast, and also they're not scattering very effectively.

30:51

So it turns out, if you just keep adding more SO_2 to the stratosphere, for reasons that I'm not going to go into the details of, most of the new sulfur you add ends up on existing particles. Either it directly condenses onto those, or it makes tiny little particles which themselves condense onto the big ones or agglomerate on the big ones by Brownian motion. So what you end up doing is when you pump more sulfur in, is you just make the existing particles bigger and bigger, which means they're less efficient scattering and they fall out. And so the net effect of this is you add more sulfur, you're not getting as much more reflection as you think.

31:26

So these are some early models that showed a saturation. This is sulfur injection going from zero to 20 million tons a year, which I think would be just a ludicrously large amount of sulfur to put in, although it's, in fact, what lots of the modelers in this business kind of assume. 20 million tons of sulfur a year is a lot, and this shows you how that this same watts per square meter I showed you before, where four watts per square meter is roughly offsetting double CO2. It shows you the saturation. This is an old paper that--different papers get different things. All these models are different. There's a lot of tuning. But the point is, you get this saturation effect, and that saturation effect is because of the fact you're just making the particles bigger, and you're not being efficient about scattering.

32:03

So when that first paper came out from our colleagues at ETH, Heckendorn et al and Tom Peter, we started talking and thinking a lot with them and others. And I think Peter Adams was the original person to think of this idea that maybe we could deliberately alter the aerosol distribution formed by a by an aircraft, by not just putting in SO2 or H2S but putting in some particles as seeds, again. This--those earlier things were assuming you were emitting a gas, or actually, it's a cold liquid that very quickly turns into a gas like SO2 or H2S. Those gasses themselves don't form particles. What happens is they react with the hydroxyl radical in the stratosphere, they're oxidized, and an oxidation chain that over some time scale that you can think of as a week or two, makes sulfuric acid that then very quickly condenses. And if you wait a week or two, and the thing spread out, you end up with this problem that most of this new material just ends up on existing particles. But if you could arrange that in the plume of the aircraft, you made more particles right away, then you'd end up depositing that sulfur on a larger number of particles, and so you keep the particle size smaller. And so one way you could do that is actually just by putting in a little SO3 which very quickly turns into sulfuric acid in the stratosphere, to make particles quickly when there's a high density. There's a bunch of other ideas that actually, Professor Mingyi Wang and some others are rapidly thinking of a range of different ideas of how to do this. So this is kind of an old slide that this point I would see as a flag for the fact that there are a lot of adjustable knobs that are really engineering about maybe adding some organics or different choices of materials that could affect that size distribution.

33:58

And one last important thing to say: this size distribution is crucial for predicting how much reflection you'd get for given amount of sulfur, but it's not necessarily that important to the overall uncertainty of sunlight reflection, because as soon as one started do this, even in a small level, you'd measure the size distribution. So we can't predict it very well from de novo, but we can measure it. So that's all I want to say about this topic. But this particular topic about what is the size distribution and how we might adjust the size distribution by choices about how we do deployment are, I'd say, a kind of cutting edge question. That's the practical side, kind of in between the kind of mainstream atmospheric science and kind of pure engineering.

34:41

Now I'll quickly show you stuff that gets closer to pure engin-, pure engineering, and I do this just two quick slides and then a longer one. This is from an old study now more than a decade that was the first study where we paid an engineering firm, Aurora Flight Sciences, to just go do a trade study of what it would cost to get material in the stratosphere using different kinds of craft. So they look both at aircraft and balloons and naval guns. These are all things that people had suggested before. And I'm not going to go into the study in detail, but this is assuming you're trying to put a million tons a year of something, they weren't studying what the thing was, into the--is a function of altitudes, is the altitude you're putting it in, in kilo feet in this case, so 20 kilometers is 60 some 1000 feet around here. And they're looking at cost in billion dollars here. But a billion dollars for a million tons is $1 a kilo, which is useful to put in your head. And that's kind of the scale of the cost to ship things across the Pacific by air freight today. And it's a log scale. So of course, you quickly get yourself up to $10 a kilo or more. And the some of these ideas, like these naval guns that came out in the 1990 or so National Academy report, I think, look pretty silly, but there's a bunch of choices of aircraft, and I won't go into details yet, except to say there's a big kind of argument between those of us working on this about how hard or easy it is to build aircraft that go to the stratosphere.

36:08

But I think what's clear is there's no question you can do it. After all, we have built aircraft that go to the stratosphere many, many, many decades ago, and now that we're beginning to really work with engineering firms to understand what it cost, I think it's fair to say that there are definitely both aircraft that one could modify that would get you to the lower stratosphere, outside the tropics, and that you can build aircraft with existing, commercially available engines that would get you to 60,000 feet, which would get you into the tropical stratosphere. So I think there's no question it's doable. Exactly what the cost trade off is, exactly what the trade off is against altitude, what the development cost is--those are things we don't know well enough.

36:52

I'm also just flagging the fact that this is really just to show, in a way, how little serious engineering work has been done on this topic. To give you a sense of a new study we're just in the middle of middle review right now that has looked at which compound you'd release. So typically, people have always assumed it would be SO2. But now that we've looked more carefully, and we hired a industrial sulfur safety consultant, and she has told us that, in fact, H2S and SO2 are kind of the same in terms of toxicity. They're both very toxic gasses, whether it be real risk to the aircraft crew and people managing the operations. On the other hand, there are gasses that are managed in huge quantities in industry today, and if you do it right, you can do it very safely. So there are industrial facilities near where I live in Alberta that manage million tons a year of sulfur, both either both sulfur dioxide and also H2S, and so we do know how to do this industrial world. We started to think a lot about the trade offs between these two and these other gasses. And I think all I want to say is that that that nobody has really looked at those trade offs very seriously. We're just kind of starting to do that now. And we think, in fact, H2S would be probably one of the compounds you'd carry the most because it's lighter weight.

38:06

Finally, I think I just want to flag on this engineering side, the idea of what, what I think of a subscale deployment, which is the idea of what, actually, any practical example of what could happen early on if some nations wanted to push towards doing this. Again, I think there's very good arguments to make about what's good or bad. I think it's also important to both understand the drivers of what people might want to do, what's good and bad, but you also have to understand what's possible, what's hard or easy. And this is an example that spells out in some detail from a study that Wake Smith and I did, what could be done with existing technology. And what this basically says as a bunch of details I've given you in American units here in pounds, but we're looking at a Gulfstream G6-50, which a particular business jet that's relatively large. And it turns out that 10 of those aircraft can, flying continuously from one air base move roughly a tenth of a million tons, 100,000 tons, a tenth of a million tons, to the stratosphere every year, not to the high stratosphere. They get a little over 15 kilometers, which gets you the stratosphere in the mid latitudes, but not in the tropics. But that's just ten aircraft. It's tiny in terms of an operation and what, what, what's a tenth of a million tons, this gives you, I think that's kind of important metric for what I think of as subscale deployment, and here's why. It's about the same as the background flux of sulfur into the normal stratosphere, where there's not a big volcano. So if people started doing this, 100,000 tons a year, we'd be roughly doubling the background flux in the stratosphere, which would teach you a lot about the way the stratosphere reacted, about what the aerosol size distribution was. You'd learn a lot about how good your stratospheric models were. But I think it's fair to say the risk would be objectively very small, because remember the numbers I showed you before. Pinatubo was eight million tons. This would be 80 times less than that. And it cools in a not insignificant amount. It cools to something like 0.2 C, which may seem very small, but that's the equivalent of delaying global warming by a year, which is not nothing, and you could ramp up from there. That gives you just a rough sense of what something that's doable, in principle, doable quite soon, if people wanted to, might look like.

40:24

Now I'm going to quickly go back to this question of comparing the different methods. So far, I've just, at the beginning, I told you that there were a bunch of different methods, then I spent most of the time on stratospheric aerosols, and particularly sulfate aerosols. Now I'm going to quickly just remind you there are a bunch of other methods and say about marine cloud brightening--say a little bit more. This is a table that compares the methods a little bit. I'm not going to talk to the table in detail, but I think it's fair to say that space-based, I said, have low physical uncertainties, but deep technological uncertainties. The cirrus thinning, which I haven't talked about much, these high clouds that are a bit like, bit analogous to contrails, cirrus thinning turns out to have maybe actually not such high technological uncertainty, because you need a very small amount of aerosol, but it has deep physical and science uncertainty. It's really easy to do that seeding wrong, so you actually end up having a warming effect rather than the cooling effect. There are ways that you could learn that pretty quickly, but the uncertainties are really big, I think it's fair to say. Marine cloud brightening, I think there's no question that in some places, if you add more aerosols, and what people talk about is sea salt aerosols, to marine clouds, it will get brighter. But how much and where is uncertain. We'll get to that. That's the part I'll say in more detail. And I've already talked about stratospheric aerosols.

41:45

So this idea of marine cloud brightening came from a paper in 1990 by John Latham, who's just now passed away, but a wonderful, unusual human, one of the more unusual humans I've been lucky enough to meet. And he published this short paper in Nature back in 1990 and really kind of helped to launch this whole field. Big efforts that have gone into trying to understand how you might do this marine cloud brightening. And I'll show you a little later a picture where people are actually trying this off the Reef of Australia. But the idea that he says simply is that if you add more of these cloud condensation nuclei, the seeds around which clouds grow, you'll make clouds whiter.

42:25

So how does that work? First of all, it does work. This is objectively just pictures of, these streaks you see are streaks of whiter clouds that are formed by ships, by ships that are driving freight, freighters driving the ocean, that are releasing some sulfur pollution. Those sulfur aerosols are making that, making their cloud seeds. That means the clouds are whiter, and I'll tell you the physics of why right now, but this is a visual evidence that there's no question it can happen, that you can add a small amount of extra aerosol and make clouds quite a bit whiter in particular parts of the ocean.

43:06

This all goes back to an even earlier paper, in ‘77 by Tumi--this thing is now called the Tumi effect--which just does the math that shows you that if you have more particles, the cloud gets whiter. And I'm not going to say much about the detail, but it's kind of one to show this original thing, except to show this key curve, which shows you the optical thickness, which is basically how reflective the cloud is. So up here means a cloud that's brighter versus the concentration, the initial concentration of these cloud condensation nuclei. These are the little aerosols onto which water molecules can condense and form the cloud. And it's worth looking at what that number is. These are, in the lower atmosphere, these are of order 100 or 1000 per cc. So every cc of air that might seem very clean air out in the ocean, that you might think of as fresh air, has hundreds of thousands of little tiny particles in the air, and those are the particles around which a cloud seed forms. And the fact is, you add, there's no question that you add more, add more cloud seeds, and you end up with a whiter cloud. That's the underlying idea.

44:15

People are actually trying versions of this. This is a recent experiments that have been done by Australian researchers in cooperation with the Australian Government and cooperation with local people that are actually trying to try this, to put sea salt spray in the lower atmosphere, with the idea that it would make clouds wider, with the idea that it would locally cool areas of the Great Barrier Reef to protect it from coral breaching. So people are working on this.

44:43

I think it's fair to say that there are deep uncertainties, both uncertainties in the physics of how it actually works. So it's clear that, all else equal, if you have a cloud and it has more seeds, it'll be whiter. But there's all sorts of other complexities about the way the clouds form and feedback loops. And what you can find is, in some cases, you add more particles and you end up actually making less clouds because you trigger rain, or you trigger circulations that trigger rain. So you can get both outcomes. You can end up making the overall scene brighter or darker. And I think it's hard to predict in advance exactly how that will work. Of course, you don't necessarily need to do that. You could use feedback to control use feedback to control it, but there are a big set of physical uncertainties. And it's also true that, despite some wonderful engineering work by a bunch of people now for 15 years, we don't know how to make a sprayer that will actually spray little, tiny sea salt droplets at the rate you'd need to do this practically. So it's still a research problem, I guess, no question it's solvable, but it hasn't been solved yet. So in that sense there is not a kind of direct deployment pathway to do this.

45:51

So I just want to give you a little more sense of this marine cloud brightening as one of the many different pathways that that that are not the one pathway that I'm saying we really do know enough that you could, in principle, start doing it essentially now, with no new research. Not to say you might not want more research, but there's not a fundamental need to do it to begin testing.

46:13

Now, I'm going to say just very quickly, a kind of teaser for the next lecture about what the climate response might be. So so far, this lecture has all been all about how we might make more reflectivity, how humans could reflect more sunlight. Now I want to give you some sense of what the climate response might be, and I think some context is really important. Early in the 19--around 1990 there was a big National Academy report that was one of the first reports to look really serious at this topic, and it concluded that that while there's no question that putting, making the Earth more reflective would cool our world, no doubt about that physics, the conclusion was that would inevitably be quite unequal, that even if, that you couldn't cool the world equally because the climate response would be unequal by season or by latitude. And in fact, I wrote a review paper, that's how I got into this field in the early 90s, published in 1992, where I said that, that it was going to be unequal, that you couldn't do this in equal way. And I think that kind of preconception is important. Then in the late 90s, ‘98 if I remember, right, there was a meeting in Aspen where there was a gentleman telling us about how beautifully this could work, how SRM would work fantastically, and it meant we didn't need to cut emissions. Obviously, I don't agree with that point of view, and myself and Ken Caldeira, another climate scientist, argued that, no, no, it would not work because it would be unequal. And to Ken's immense credit, he went back to his lab and with Bala Govindasamy, ran the first climate model experiment to look at what the actual response would be. And Ken's intent, I think, was to show that this wouldn't work very well. But the actual result was that it was pretty equal. And that paper was published in ‘99 or 2000 I can't remember.

48:00

It's now been 25 years on from that. And I think many people have had the assumption that these technologies really couldn't compensate for climate change very much. But I think that that the response from climate models is, shows that, in fact, they can compensate quite well. And I want to show you two examples of that, both of which from work I was involved with that I think really are the, to me, the biggest examples of why we should take this seriously, because they do show that doing this could reduce the big climate impacts in a surprisingly uniform way. So let me show you that.

48:35

This was done with colleagues at Geophysical Fluid Dynamics Lab--Gabe Vecchi and others--who used, in this case, a superhigh-resolution model that does a very good draw on tropical precipitation and tropical cyclones and so on. And the way we did this is we wanted, we did a couple things a little bit differently. We--we did--this model, first of all, doesn't actually use real aerosols. It just turns down the sun, which is actually about the same thing, but I'll show you a model that does use real aerosols in the model in a second.

49:04

For this thing, we thought a lot about what variables to look at, and we looked at four variables that we argue were some of the most important in determining climate impacts. That's annual average temperature, extreme temperature--so annual average is the most important overall driver of climate impacts, extreme temperature, which tends to drive, you know, heat waves and deaths and so on--precipitation minus evaporation, which tells you about the amount of water that's available, tells you about runoff, tells you about the amount of water available to crops, and then extreme precipitation, which in this case, we measured as the max amount over five days, which basically tells you flood risk. And you know, in IPCC and other kind of standard places that look at climate impacts, these are, I think it's fair to say, among the four physical variables that are most important in driving the human impacts of climate change.

49:54

So those are the four variables we looked at. And then we used regions that were standard regions that IPCC used. So these are these regions that are outlined here. So we weren't cherry picking. We did the statistics on each of those reason--regions, and then what we did is we color coded the things. So if, if, if it's black, so if it's blue, it means it's moderated. That means move back towards preindustrial so, so that means that the sunlit reflection is actually reversing climate change in the way you want. If it's red, it means it's moved away from preindustrial so it means that sunlight reflection is making things worse, or at least farther, it's exacerbating climate change. And if it's a lighter color, it's not statistically significant. So that was the way we did this.

50:40

And the big thing, and it feels, like, too good to be true. And each time I show this slide, it feels like kind of silly salesmanship, but it is a fact that we did this on a model, a state of the art model, and there's not even one red place. So none of the four variables at a locations is made statistically significantly exacerbated. Do I really believe this will necessarily be true in the real world? Not at all. I'm going to show you a going to show you a slide with exactly the same key and the next slide where at least a couple of them are. But the fundamental thing you get out of there is that in every region--first of all, temperature is significantly reduced everywhere. Extreme temperature, I believe, is everywhere, precipitation minus evaporation, the changes reduce most places. That's really stunning. It's really different than what many of us expected would be true, and I think it's the reason I, at least, it’s helped to change my attitude about these technologies and take them more seriously.

51:31

Just for record, this is, this next slide is uses exactly the same code, so I won't reexplain the codes. This is from a quite different model that does use stratospheric sulfates. And this case, you do see there are several places that are statistically significantly exacerbated, four of them, but interestingly enough, all these four are dry places that got wetter. And so I think if you just think of a kind of a ecocentric point of view, if you're a desert tortoise in the Atacama, I think you got to say wetter is bad, but, but if you're a human, not so clear. That may not be a robust fact everywhere, but it was what we found in this model, and some other models had found the same thing.

52:20

So I'm saying this, because a common thing that said is that sunlight reflection increases the risk of droughts or monsoon failures. We'll get to that in the lecture, it's not the next lecture, but the lecture after the next with Tiffany Shaw. But I think the answer is, there are certainly risks of that. But it turns out that it's quite hard to measure and detect this in the climate model simulations we have.

52:43

Finally, I want to just throw up a slide that gives you some sense of the concerns about this technology, mostly concerns that we'll talk about in the next lecture and the second next lecture and the final lecture, just to, just to, just to put them on the table so you you at least have them in your head. And I will just go through what I think of as a top layer and a kind of taxonomy of concerns, and there.

53:06

So there's physical risks of benevolent or well-intentioned deployment. The point is, if this is done in a way where--there's never going to be total agreement--but done in a way where there's reasonable stability, and some countries agree to do it, and they're generally trying to do it in a way that is has a broad public benefit--there will still be a whole lot of risks, as well as the possibility of accidents and failures. That's just normal in the way humans do things. Accidents, incompetence, exacerbation of climate changes; these are all things that could happen even with a well-intentioned deployment.

53:39

There's also different kinds of injustice. Again, we're going to get most of this in the most of this in the last lecture, but I just want to throw it up here. There's kind of political exploitation that's where fossil rich nations or fossil fuel companies might overstate how well sunlight reflection works and argue that that means they don't need to cut emissions. There's a kind of collective addiction process, which is just that all of us, like, sunlight reflection in the short term always looks good. In the long term, not so much. As I said in lecture one, in the long run, you cannot look at this as a total substitute for emissions cuts, because if you did, you just have more and more CO2 in the atmosphere, and you'd be in a more and more dangerous place. There's various just-, procedural and distributed justice issues that it's a procedural is who makes the decision about cooling, and the distributive is who's actually hurt or benefited. And there's possibility this, in different ways, triggers conflict.

54:29

I think the good news, very good news, is the only one of the technologies we really know how to do now, which is this putting stratospheric aerosols in, from that little movie video you showed, I showed you, you could see that it just spreads everywhere, and that means, in some deep ways, it's not very useful as a weapon, because you can't target it, and it kind of goes over two years. That's not true of all technologies. I mean, if you really had low altitude space based, you could do weather control and maybe have a weapon, but we can't do that now. And then there's complicated issues around humanity and nature, so I just wanted to throw that up there. We'll get to some of that in the discussion, the very last lecture. Thank you very much.