0:03

TIFFANY SHAW: Thank you for coming on this beautiful day, probably one of the last we'll have. It's my pleasure to be here today to continue this series, the Compton Lecture Series, on the introduction to climate systems engineering. My name is Tiffany Shaw, and I'm a professor in the Department of Geophysical Sciences, and I'm going to tell you a story today about climate models, which, as you well know from our schedule here will give you a scientific basis for predicting, our scientific basis as a climate science community, the basis for understanding what happens when you increase greenhouse gas concentrations in the atmosphere, what happens when you have industrial pollution that increases sulfate aerosols in the atmosphere.

0:48

And it's really a physical science story, and I'm a climate physicist by training. I started my ventures into science as a Math and Earth Science undergrad at the University of British Columbia and Canada, and then I completed a PhD in atmospheric physics at the University of Toronto. They have a great physics program, atmospheric physics program there. Recently, I was nominated as a coordinating lead author for the Seventh Assessment Report of the Intergovernmental Panel on Climate Change, where we assess the climate science state of the knowledge, including observations and models, which is a key component of my research lately. I'm really interested in understanding the physical processes that drive the climate system. Why are things happening? When will they happen? And knowing that will allow us to have more confidence in what's coming, and we need to know that if we want to intervene and have responses that we expect and not unintended catastrophic consequences. Some of my recent work is listed here. I won't go through it in detail, but I would be happy to discuss any of this with you after my lecture, during the lecture, please feel free to ask questions in my department. That's sort of standard protocol for our seminars, so I'm very, very used to it.

2:08

All right, let's get started. Before I dive into my specific story, today, I want to highlight this wonderful article that came out of quantum magazine that I was a part of. It was led by the science journalist Zack Savitsky, and he tells a story here about how climate scientists saw the future before it arrived. I really encourage you to take a look at this if you're interested in this material. And it's part of a very nice series of papers, series of articles that were under the title, you know, how we came to know the Earth. And so if you're if you're if you're interested, highly recommended. And I really like this image that he included on the website. This is really how you should think about climate models, sort of a discretized, coarse grained version of our of our Earth, a fake version of our Earth built on the laws of physics in as much as you know we know them as they apply to the climate system.

3:04

So if we're trying to predict the future as changes in emissions evolve, and we want to go from 2025 to 2090, as we'll see, the story today is that we need to rely on physics and our application of physical laws to the climate system. And so this really matters. As we look at the global mean temperature evolution since 1950 observed in the white line, what these models have told us, and I will tell you today, is that the decisions that we make will determine how much more global warming the earth will have by the end of the century, or any time in the future. If we substantially cut emissions, we should expect to be able to bend the curve, and if we don't, then we should expect to continue to see an increase of this global warming signal.

3:53

But it's not just about the future. Our application of physical laws to the climate system began in the 1960s as I'll tell you in much detail. And when we look back at those early predictions, which are all shown in different colored lines, relative to the observations in the black line, the difference between those early predictions and the observations shown on this bottom graph have been remarkably successful.

4:20

And so that's going to be where I start my story today. And I'm really going to leverage it off of this success, which was awarded part of the Nobel Prize in Physics in 2021. This was a prize that was awarded to two climate scientists, Syukuro Manabe, who is from Princeton University, in the Geophysical Fluid Dynamics Laboratory, which is funded by the National Oceanic and Atmospheric Administration, and Klaus Hasselmann, who is a scientist at the Max Planck Institute for Meteorology in Hamburg, Germany. Their contribution was awarded for the following quotation, “the physical modeling of Earth's climate, quantifying variability and reliably predicting global warming.” And so that's the story I want to tell you today. How--what was it? What approach did they take to have such a reliable prediction? And I'm really going to focus in on the contributions of Syukuro Manabe, who really laid out an approach to predicting the global warming response to a very complex physical system.

5:27

So let's start where Manabe started. The Earth's climate is very complicated, and as with most physicists, it's easier to start with a simpler system, the so called spherical cloud approach. So what Manabe did was he decided to average over the complexity of land versus ocean and longitude and the tropics versus the pole and latitude, and just consider the globally averaged temperature varying with altitude.

5:56

And so this nice schematic from the Nobel Committee highlights that when you consider the atmosphere in this way, and you can apply the physical law of energy conservation, there's really only two types of energy transfer that you need to be considering. The first is radiation, electromagnetic wave radiation. The really important thing about this energy transfer is it doesn't require direct contract. So we can get energy in the form of UV, invisible all the way from the sun, that can interact with your surface, warm it up. And then, of course, the Earth is also a physical body, and it radiates energy, but more in the infrared. And so it emits energy that interacts with the atmospheric gasses, as we'll talk about, leading to emission both downward and upward.

6:44

So radiation was pretty easy. I think the issue for Manabe was a lot to do with how he needed to represent convection. So convection is another fundamental heat transfer, but it involves turbulence, the bulk movement of fluid in the vertical and so what Manabe had to do was, was, was, was relate these two energy transfers to the physics that we know. So radiation, as I said, was easy. He could rely on quantum mechanics, the Planck, Planck function, blackbody radiation, all of that beautiful theory that tells us, for example, from the Stefan-Boltzmann Law, that the emission of any body in the universe is proportional to the temperature to the fourth, okay, but it's not a perfect black body, so we consider it with an emissivity, and then that emissivity should be related to its absorptivity, and that is Kirchhoff’s Law. So all of that can be brought to bear on the atmospheric gasses, the greenhouse gasses, ozone, that interact with the sunlight and the infrared Earth light. And so that was pretty good, pretty good to go for him. That was standard physics, and it all depended on temperature, so very small-scale quantum mechanical interactions could be all represented in a thermodynamic equilibrium approach dependent on large scale temperature. That was crucial.

8:00

The next thing he had to do was figure out how to relate convection to temperature, large scale temperature. Now, what convection really does, of course, is it moves the fluid around. And if you think about what its ultimate goal is, it’s to go from an unstable situation where there's too much warm and light air near the surface to mixing that around to have a more stable configuration. And so the process of doing that is really just an energy redistribution, so that the temperature as you change it from moving the air up and it expanding and doing work on the environment and cooling, some of that cooling will then be partly offset by the fact that the air has water vapor in it that releases some latent heat, and so there's a predicted temperature profile when that reaches equilibrium, called the moist adiabat. So the offset between the work done and the latent heat added can be used to predict a moist, adiabatic temperature. Every other process that drives temperature changes would then be diabatic.

9:01

So what he did was he said, Okay, let's just represent convection as a relaxation toward that moist adiabatic temperature. And so what he ultimately showed was that, if we could just take the physical law represented here in a simple form, proportional to temperature, this is the energy equation, because internal energy for the atmosphere, which is an ideal gas, is proportional to temperature. He was dealing with a vertical column. So all he needed to consider were these terms, how radiation would impact the temperature, how convection would impact the temperature. And here is a schematic from his paper with Weatherald, where they had the physical I'm highlighting here the things that we know really well. You know, the equation itself, the way that water vapor depends on temperature, and then these so called terms that we're making assumption about how those small scale convection and radiation processes depend on temperature. Because what we needed, what he needed, what they needed, was one equation and one unknown. So everything needed to be proportional to temperature.

10:05

So they succeeded in doing that. They integrated this equation forward in time. It's a time dependent system, and they did many things in this paper, but the thing I want to highlight right now is what the predicted temperature looked like for three different concentrations of carbon dioxide, which are greenhouse gas is greenhouse gas and Earth's atmosphere.

10:27

So here they are, 150 parts per million by volume, 200--300 parts per million by volume, 600 parts per million by volume. Now you can't really see the different lines. What I'm highlighting for you in the colors is what is the emergent behavior? What is the emergent temperature response? As you dial up CO_2 under this physical constraint of energy conservation, with these assumptions about radiation and convection, the strat- the upper levels of the atmosphere, the so called stratosphere, cool, and the lower level, lower layers of the atmosphere, the so called troposphere, warm. And it was very well understood in this model why this was happening. It was not a very complicated climate model. This signal of cooling in the upper layers was really just a consequence of radiation. CO_2 is a greenhouse gas. You dial it up, the emissivity increases, you're radiating to space, and the amount of radiation coming from below is not enough to compensate for that. So you get radiative cooling. In the troposphere, what you have is the CO_2 also increasing the emissivity, and then you're trapping more of that Earth light, which is coming from the Earth's radiation toward space, leading to then a re-radiation back to where the atmosphere is. The atmosphere traps it and reradiates it back to the surface. So at a fundamental level, this is really just a radiative response. But convection also does adjust and partly shape the warming structure. There's no convection in the upper layers, so there's no connection to convection there.

11:58

So what they also did beyond just looking at what the temperature prediction was, was they tried to understand the sensitivities or the uncertainties. Why was this happening based on some of the assumptions that they had to make, some of which were probably not, they were probably not very comfortable with some of the assumptions. So let's talk about those.

12:19

The first assumption they had to choose was, how was water vapor going to change? So water vapor is humidity. It's the amount of water vapor in the in the air. And in this table of their paper, they distinguish between two cases, one when they fixed absolute humidity, so the water vapor was not increasing, which actually violates a physical law we know from the Clausius-Clapeyron, the Clausius-Clapeyron, which I've just oh, there we go, that it should go up with warming. But you can do these things in models. That's the beauty of physical models. You can start to turn on and off physical processes. 1.33 degrees of warming if we don't allow humidity to go up, and we have average cloudiness.

13:04

But what happens in the case where we allow humidity to increase? So this is so called fixed relative humidity. Fixed relative humidity. Relative humidity is a ratio between the humidity in the air relative to the saturation value. So that's like the maximum 100% relative humidity means you have the maximum amount of humidity in the air before, you know, you start to sweat, before it starts to condense out. What they found in that case is that when water vapor could increase because of the saturation value increasing, that the warming was a lot larger. So there was a feedback between how CO_2 would increase, and water vapor would then amplify the warming. In this case, it was a degree larger. Yeah.

13:46

AUDIENCE MEMBER: Is there a model of the air in the model?

SHAW: So the increase of humidity in the atmosphere is a nonlinear function of temperature.

AUDIENCE MEMEBER: That complicates...

SHAW: Oh, yeah. I mean, it's a given equation that you can measure in the laboratory. Yeah, so this is the Clausius-Clapeyron relation. So that's what's being shown here. And then the difference between the average cloudiness and the clear sky, where they just took the clouds out of their model together, was also quite important. They saw, you know, here 0.6 degrees warming difference because of clouds. Now, the clouds were very, very simple in this model. They weren't allowed to change at all that they were either there or they weren't there. And even today, this continues to be a major source of uncertainty in climate modeling, that clouds are very complicated and they're very small scale, very multi scale, and so we're continually challenged to do better at representing them.

14:44

SHAW: So this paper was amazing for many reasons. I'll highlight one more reason, which foreshadows some of the application of these models to the topic of climate systems engineering, which is that they also consider what would happen to this physics based climate model based on energy conservation, if you dialed down the sun, okay, which, of course, you can do many things in a model. So here's another example of a figure in their paper where they just changed the solar constant, which is a constant value in their model, and they just turn it down. And what they saw in their model was that there was cooling at all vertical levels. And so we'll learn more about later how this kind of foreshadowed ideas, also based on this very clear physical prediction about how we might think about potentially intervening.

15:29

So I've, I think, shown a lot on this axis of physical complexity, and this is how I'm going to tell the story today. I've started here on the left, so the most simple setup the spherical cloud starting approach, but now we're going to move on, as they did, and we're going to move on to add a dimension. And the dimension here is latitude.

15:48

Okay, so why you choose to add latitude is because there's another conservation law, another symmetry that you bring in to the problem, which is that the Earth is, you know, rotating around an axis, and there is a symmetry about that axis which leads to angular momentum conservation. So they add a dimension here. It's latitude, a very, still very, very simple model, no longitudinal differences. They have some land and some motion. So now they have an equation for the energy, and now they have an equation for the momentum. But as you add latitude, you have to account for the fact that the air moves. It's really what I focus on in my research. And you know, storm systems that you've probably heard about, weather systems, they're really moving things around in the in latitude. They're moving warm and more moist air poleward, and cold and dry air equatorwards. So this accounts for a term in the equation that we call advection. It's very complementary to convection. Convection is mixing things vertically. Advection is mixing things horizontally. So you add that when you add latitude, for the energy conservation and then for momentum, we have it there too, along with the Coriolis parameter, Coriolis force, because we are in a non-inertial reference frame. The Earth is rotating. We have a pressure gradient force and then some turbulence, along with wave induced momentum. These are small scale processes. So everything on the right hand side has to be closed in the usual way of turbulence. We know the large scale things on the left, so we need to make the small scale things related to those large scale variables. This is a classic closure problem for mean field theory, and we deal with this in climate just as we deal with it in other branches of physics, and we do our best. It's not an easy problem.

17:34

So here's what they have in their model. Now there's the different boxes for thermodynamics of this atmosphere, the momentum for this atmosphere, the water vapor, we have to account now for its full conservation. And then all of the red is meant to show you where we're making these assumptions about small scale processes, radiation, convection, evaporation, now off of the half of the ocean, half of the globe is the ocean here. The other thing they had to contend with because we have latitude, there's not a lot of sunlight. Half of the year over the arc over the poles, there's no sunlight. Temperatures will get low enough to form ice and snow, and this fundamentally changes the surface. A surface covered in ice and snow will reflect a lot of sunlight incident on it. It has a so-called high albedo. Albedo is the ratio of the amount of reflected sunlight to what comes in. High albedo is a property of ice and snow, and low albedo is the property of land. So this was really important, as their surface now had land, ocean, and also very cool temperatures. So they put all of that new physics in, they made the same equilibrium calculation. What they did was two values. They took the 300 parts per million by volume in this model, they integrated it to equilibrium, and then they took another version, where they dialed up the concentration to 600 parts per million by volume, and they ran it to equilibrium, and then they took the difference. And so what's shown here is a figure from their paper the difference now showing altitude and latitude the pole on the left.

19:13

So what jumps out? Well, there's definitely some interesting structure here, but let's start in the upper layers. Nothing really new there. It's cooling just as it was before, and what we can then distill from that is all this complicated new physics that we added is not really essential for understanding that cooling response. So now let's move into the lower part of the atmosphere. Let's start at the surface. And it's quite striking that while there's global warming, every latitude is warming. Where the warming is maximized is over the pole. It's not over the equator, and it's quite a lot of warming there in particular. And so what they ultimately realized, but this was a consequence of the physics they added, the first ingredient being the atmosphere moves, moves energy and momentum around. Specifically, it's moving energy poleward, because warmer air holds more moisture. That moisture is being moved poleward, and when it cools and condenses, it releases heat. Okay, so that's partly what drives this polar amplified warming. But the other really crucial ingredient was the fact that over the poles, before you dialed up the CO_2, you have ice and snow. As you warm that polar region, some of the ice and snow melts, revealing a darker land surface underneath, which will then absorb sunlight and warm more, melt more, warm more, and so this is a positive feedback that we call the snow and ice albedo feedback. So it was very clear that the new physics that they added was leading to the emergent temperature response that they found. And that's, I think, really a clear testament to the fact that they understood what this model was predicting. Yeah.

20:58

AUDIENCE MEMBER: With longitude, assuming symmetry,

SHAW: Yeah.

AUDIENCE MEMBER: So it goes with the latitude angle, with the radius...

SHAW: So this is the equator and this is the pole. Sorry, yeah, yeah. We always assume these things. You have to choose, you know, where you start your latitude from, 480 degrees. Yeah. So this is the equator, this is the pole, this is altitude.

21:19

So the next step, which will be the last step for the summary of this nice work, would be to then, to then do the full calculation, including longitude, so the full complexity of altitude, latitude, longitude. And in this case, you have to deal with the fact that the ocean is covered 70%, sorry, the globe is covered by 70% ocean. So you have to now deal with the physics of the ocean, but you take the same approach, right? You take the energy conservation of the ocean, the momentum conservation of the ocean, and that's exactly what they did. Now, the tricky part about the ocean, interesting, but tricky, is that it's very slow, very, very slow compared to the atmosphere. So I don't know if you've heard about the ocean conveyor belt, but it takes, like, 1000 years for if you imagine an ocean parcel post, parcel of ocean that's at the contact with the surface as it goes through this conveyor belt, it takes a long, long time. That wasn't good news for their modeling, because at the time, the amount of computational power these are all, I should say, numerical predictions, was not going to be sufficient for them to make equilibrium calculations. They had to move to a transient calculation. And what they chose to do was to increase the carbon dioxide 1% per year. Okay? And then look at the time in the future of this scenario, when the carbon dioxide was doubled compared to where they started. So it's still the same doubling of carbon dioxide, but now not in equilibrium.

22:51

So let's look at the spatial sorry. Let's look at the model ingredients again, as I just articulated the very simple ideas were applied with the atmosphere and the ocean, and then making assumptions about how they interact through turbulence closures, very simplified, linearized, even bulk, aerodynamic formula, Yeah.

23:11

AUDIENCE MEMBER: I'm sorry, could you explain what is that that takes 1000 years, one, one revolution of the conveyor belt?

SHAW: I mean, it's 1000s, yeah, for the ocean.

AUDIENCE MEMBER: So one, so one whole...

SHAW: The conveyor belt, yeah, the conveyor belt has different places where the water sinks, but yeah, if you imagine starting wherever it sinks, in one location, then coming back to that point, yeah.

AUDIENCE MEMBER: If you're running a time sequence of it, how long does it take? Can you time sequence to an equilibrium to saturation, do you ever get to equilibrium, or do you just look at the transients?

23:51

SHAW: So these two earlier models were run to equilibrium, where the time, the time tendency, the partial derivative of temperature with respect to time was negligible, you know, to numerical precision, right. Now, as I said, the challenge of this last case, this last result, was that they weren't going to be able to reach that case, the ocean. Timescales of the ocean is too or too long, and they didn't have enough compute power. We're doing much better today, but at the time, it was just not possible.

24:27

So here's what they found in that calculation, again, for a doubling of carbon dioxide concentration, but not in full equilibrium. So this is transient. We're getting a snap snapshot of the evolution. And what you can clearly see, let's just orient you in the axes. So North Pole, equator, South Pole, so latitude and then longitude. You can very--you can see these very, very coarse outlines of the continents. This is how numerically resolved they were, but you can identify them. Here's North America, South America, Africa, Europe and so on.

25:03

AUDIENCE MEMBER: Is that the surface?

SHAW: Oh, this is the surface. Yes, excuse me, yeah, this is the surface. And so what I've highlighted, once again, are the isolines. Let's start with the red one, which is highlighting the close contour of the warmest part of the response, which is over the Arctic. And not unlike what we saw here, those, this wasn't necessarily the Arctic, it was too idealized. The other thing that you can clearly see is that the continents, the land, is warming more than the ocean. And then finally, something they had never seen before, there was transient cooling in you know, when you take the spatial average of this, it's global warming, but over the Southern Ocean, it's cooling transiently. Okay. And they, what they could, of course, understand, is this had to be a consequence of the ocean physics that they added that had not been added in the previous cases. Okay.

25:52

So there's two things that's--that are important about the Southern Ocean that they argued was why they were seeing this transient cooling. One is that we shouldn't expect much warming there to begin with, because the Southern Hemisphere, the Southern Ocean, is ocean, its high its heat capacity will be higher than the Northern Hemisphere, which has mostly land, and therefore a lower heat capacity. So we should expect a delay in the warming of the Southern Hemisphere, but really this cooling that they argued was not necessarily a consequence of that, but more about the fact that they were seeing more precipitation, that as you have more water being transported toward the high latitudes, that was adding a freshwater signal in their model. I think we have other reasons to think that that could be due to Antarctica today, melting and so on. But let's suffice it today, they well understood why it was happening in their model.

26:46

Now, what's amazing about this is these were worlds we could never we had not seen. They had not seen, you know, starting in 1989 or even 1967, okay. So in the intervening years, what has emerged these? All of these signals have then emerged. We're talking about Arctic warming the most, four times the global mean, land warming more than the ocean, and the Southern Ocean transiently cooling. Okay, so you know, this is why you get a Nobel Prize, or at least in our field. I don't know if we would have ever expected to get one in the first place in physics, but we were very, very grateful that our colleagues were recognized for this really amazing out of sample prediction, following an approach that was fundamentally built on the laws of physics, but of course, needed to make assumptions, and therefore all of our predictions have uncertainty.

27:40

So where have we gone in the intervening years? I love this quote from my colleague Dave Randall, that, you know, 60 or so years later, we've basically gotten better at pretty much doing the same thing, you know. So we'll see that's good. It has some good aspects to it, and maybe it's time for a change. So here's a nice figure from a National Academy of Science report that shows the world of climate models evolving from the 1970s to the present. And also on the side here, showing how the numerical resolution, the discretization of these models has been, you know, the grid scale has been getting smaller and smaller, so higher resolution. So it's always built on the same approach large scale. Large scales are being represented by physical laws, and then we have these closures for smaller scale physics that can sometimes be, you know, the best that we can do, but maybe, you know, still quite empirical.

28:37

So at the beginning, we just had the convection and the radiation, and we had simplified clouds, and we made clouds time dependent, and then we just, you know, ran with it from there. We added more things in the atmosphere, like aerosols, which are, you know, natural, both natural due to volcanic but also associated with industrial emissions. We talked--we added land surface, we added chemistry, you know, important questions about air quality. So there's a lot of stuff in these models, but what Manabe has always shown us is that there are powerful tools for being able to also disentangle processes by adding and removing things. I think his hierarchy approach is how, for example, I continue to use these models, not just using the most complex ones, but also taking things out of the models or adding them in.

29:27

We also do this as a community across dozens of modeling centers. So this is actually an old figure, but many, many places, they are developing climate—physics-based climate models following Manabe’s approach--nd then using these models given boundary conditions, as I'll highlight, to make predictions of the future. So what do they need to make their predictions? It's not an initial value problem, it's a prediction that depends on the boundary conditions. So as Manabe showed, the CO2 can, you know has can tell us about what, how climate will change. That's a boundary condition. It's an external parameter in our models.

30:11

So here are some of those boundary conditions. Lots of lines, but I'll walk you through it. So here's, for example, CO_2 emissions observed in the black and then a bunch of socioeconomic scenarios for how carbon dioxide will evolve in the future. Okay, so many different choices, as I highlighted at the beginning, of how things could go. So what the models do is they get given these values, and then they, you know, run the prediction when it's observed. We can compare it to observations. And then for these scenarios, we have to wait for the system to evolve, for our choices to be made, and then to the observations to then account for what ultimately happened. There's also boundary conditions due to sulfate, sulfur dioxide. This comes back to what I was talking about aerosols, so particles in the air. You can think of these in the natural form as being associated with volcanic eruptions, but also industrial emissions. There's a human influence here, and so those get, are provided often to the models. And then there's natural sources, or natural changes, like total solar irradiance. You know, the sun doesn't always give us the same flux all the time, and so you can, you know, account for that in these models.

31:31

So I want to illustrate for you what they're good for. So for example, let's start with this two degrees Fahrenheit warming that we've observed since preindustrial times, 1850 most aggressively warming, really, in the satellite era since 1980 stands out quite clearly. Now, using observations alone, you can't really fully disentangle what's driving this. Okay, you know, I love observations, extremely important. But the value of these physics-based climate models, then is to use them in counterfactual type of scenarios or worlds to say, what if?

32:09

So, if the model can reproduce this evolution, which many of them can, you can say, okay, well, what if we only give the model all of the natural changes, so volcanic eruptions, changes in the solar flux and so on. What would happen then? And this is the blue line, and all of these lines have shading, okay, because there's uncertainty in all of these predictions. So you can think of this as the mean of the of all these different models around the world and that they ran, they have different assumptions about small scale processes like clouds and convection. They have, we have noise in the climate system, so we try to sample that. But given all of that, you know, what this is telling us is that we cannot in this world where there's no change, there's only natural changes, no changes from human influence, we cannot account for the especially the aggressive warming that has happened since the 1980s so it's only when we combine both the natural changes in the human influence that we can with these models, which are not perfect, they have uncertainty, but can we, can we really identify the human contribution, and this was the other part of the Nobel Prize associated with Klaus Hasselmann, that we can fingerprint and attribute that humans have been driving--human influence, human emissions of greenhouse gasses have been driving this global mean warming.

33:28

Okay, so this is all still part of a very, potentially well known story. I think what is now really coming online is this idea that we can really start to test these models and their predictions beyond the global mean temperature, beyond the temperature pattern, because there's a whole host of other changes that we want to make sure that the models are giving us the right information, and just as a physicist that you know, are the assumptions we are making correct? Do we--how well do we really understand the system? And this--for this, we had to wait. We had to wait as the signal grows larger, as emissions are not being cut, as the warming proceeds.

34:10

And so climate science finds itself--science finds itself in a very interesting time for very many reasons, but from a scientific perspective, we're at a really crucial time in terms of being able to test our predictions against other signals beyond just the Manabe success. And it really is a nice story to put in the context of earth system predictability.

34:34

So if we look at the prediction, time scale on the x axis and spatial scale on the y axis, there's really two sides of this diagram. There's the diagram of weather prediction, which I'm sure you're all familiar with, because I'm pretty sure you probably many of you at least have an app on your phone, and you can look at two hopefully no more than two weeks in advance, you're looking at what is the possible weather that I'm going to be encountering. Do I bring my umbrella or not. That's a huge success of physical science as well.

35:04

Climate models built on that success, but it's a very different problem. It's an initial value problem. To do a good weather forecast, you have to have the best observations you have at a given time so as to integrate a same, similar physics based model into the future. And there's many things that make this problem different. One is we know the theoretical predictability limit, OK. Ed Lorenz at MIT, who's famous for ideas about deterministic chaos, showed us that. So about two weeks, OK? And then the developments of physics based numerical weather prediction, combined with observations, and having so many observations combined with data assimilation, where you blend models and observations, has bought the actual predictability limit from these physics based models very close to the theoretical limit, and that we consider the first revolution of numerical weather prediction. Now you may some of you may have heard of the second revolution of numerical weather prediction, which is that these AI based weather emulators have recently outperformed the physics based models, but with the caveat that they're trained on the physics based model, so they couldn't have done it without the development of numeric physics based numerical weather prediction.

36:19

So now let's go to the other side of the diagram. We're talking decades to centuries, and on this kind of global, the planetary scale, all of Manabe's work is down here, and it kind of bounds and shows that we do have predictability, we do have skill. We can make predictions of climate. But the challenge that we face is we don't know the theoretical limit. It has not been articulate. and that means, you know how much is predictable, especially on the regional scale--so you're talking about 1000 to 10 kilometers--is being tested in real time. So we're looking at the system, we're comparing it to our predictions. And what I'm going to show you next is a series of successes where we think we do see some skill matching the real world and a series of discrepancies. So just as you might be aware, numerical weather predictions fail, especially in summer, especially for precipitation, it's very hard. But what we're doing in climate is really figuring out our successes from our failures.

37:20

So one of the things that we've long expected from these models is that cold waves would become less cold, and indeed, cold waves, like extreme cold temperatures, have become less cold, and this matters greatly for us, obviously, in Chicago. So let's think about this kind of straightforwardly. If we just think of a bell shaped temperature distribution. In the past, we had some extreme cold and if we're just following an increase of the average without changing the shape, then we would expect that these extreme cold events would be, would be fewer. And I'm going to show you work that has actually quantified this. If you look at the x axis, this is over the 40 years. How much, how have these cold temperatures changed in degrees Celsius per decade? The coldest temperatures over Northern Hemisphere land, they have warmed, just as I suggested, by about 0.25 degrees Celsius per decade. So that's the red and black line. That's the real world, as we measure from station data and so on. Now, the blue distribution is from these climate model predictions, and it's not just one number, because we have uncertainty, okay, so we have to sample different models that make different assumptions about these small scale processes, clouds and convection. And also, you know, climate is very noisy, so we want to sample all these different aspects of the noise. And so the good news story here is that this real world line is not that far outside. It's within the distribution of the model predictions. And so this is, I think, a really good example.

38:57

Now we expect the same thing for the hot tail, the warm tail, and we definitely see that as well. In fact, we had a seminar in our department given by Karen McKinnon yesterday, who showed us that. But there are regional hot spots that have emerged, okay, that don't really follow this--you know, the whole distribution shifts without any change in the shape. And here's an example of one of them over Europe. And what this contouring is showing is that in the deepest red, between maybe four and six, is the ratio of how much that in that region the maximum temperature has changed relative to the global mean. And so if it was just shifting with the distribution, the ratio should be one, but instead we see that in this region, it's like up to six. So this place is warming much faster than the global mean, and so it doesn't follow this kind of story that I just showed you in that diagram. And what we're learning is that part of what's going on here is that it's not purely a CO_2 driven global warming.

40:02

So we have to go back to the story of sulfate and the human, the human emissions of sulfate. So sulfur dioxide is shown here in its evolution since preindustrial, 1850, and then there's this very clear point where this is global average, where things turn around. We're not just pumping sulfate into the air anymore. We make these decisions, policy decisions, because some places are just terrible. You can't breathe the air, okay? You have acid rain, that comes later. And so we decide, certain countries, Europe, North America, United States, that we need to intervene. And in the United States, it's called the Clean Air Act. Doesn't actually happen at this exact date, but the point is, we make an intervention, and it starts going down. And so over the satellite era in particular, we've been taking all of this stuff out of the air, so it's been declining, and that has really important consequences. And we can use our models to show that when you clean up the air, by taking out this air, this sulfate that ultimately leads to, and we took it out because we wanted to have cleaner air. We wanted to not have, you know, the acid rain we wanted to have, you know, for public health policy reasons, right? Well, there was an unintended consequence. When you take out the aerosol, which is when it's present, reflecting sunlight back to space, and therefore preventing the sunlight from reaching the ground to warm the surface. You you take it out, then the sunlight goes all the way to the surface. So you've cleaned up the air. What was in the air previously was reflecting sunlight. Now it's no longer there, so the sunlight can go ahead and reach the surface.

41:53

So this is a very different story than the CO2 story. It's talking about what's happening locally in terms of emissions, talking about particles in the air that interact with sunlight. You know, greenhouse gasses are primarily interacting with the infrared part of the light, not the UV visible. And so I think this is a fascinating story for climate, and I suspect it will feature prominently in upcoming assessments.

42:19

Regardless of that, to say, you know, it is another example, just like the ozone story that you may have heard about, that, you know, there we do, we can make interventions, and we can, you know, change the climate. This one had unintended consequences, which was to to add heat waves. But obviously this is also a transient effect. Eventually, if we clean up all the air, you know, this will won't be as much of a problem depending on the baseline.

42:47

All right, let's move on quickly to rainfall, which is another very important hazard. Extreme rainfall has increased. And here's an example of, you know, how profound and striking this increase has been. We're looking at daily precipitation. Let's look over here. The really most rarest, very heaviest precipitation events have increased. The most extreme get more extreme. Precipitation gets more extreme. And that's the real hazard here, and it's for a very clear and fundamental reason. And that fundamental reason is back to the question I had earlier about a non-linearity. In this case, a non-linearity, the nonlinear dependence of water vapor, holding capacity as a function of temperature, it's an exponential. And when you linearize about any given temperature, what that tells you is it's seven for every one degree Celsius increase, you get 7% increase of water vapor holding capacity, and this, fundamentally is what leads to this extreme precipitation gets more extreme behavior.

43:53

Because think of it this way. Let's imagine a day, heaven forbid anybody ever participates in such a day like you get 50 millimeters per day falling. Now imagine that same day in a world where we've experienced warming, let's say 10% of warming, so that I can make an easier calculation, then you get five millimeters on top per day, on top of the 50. Okay, that's pretty bad. And then imagine a more quiescent day where you're only dealing with five millimeters per day. You multiply that by 10% you only get point five, right? Those are hugely different changes, and really the tail is increasing because of this multiplicative, what people sometimes call upped ante, implication of Clausius-Clapeyron. So even though we have a lot of complicated physics in these models, and sometimes we need it to explain certain things but not others. This is a very straightforward consequence of warming Earth's climate. Yeah.

44:51

AUDIENCE MEMBER: If you get more rain, won’t that take more particles out of the atmosphere?

44:57

SHAW: So yes. I mean, if you're talking about those aerosols. There is a process where you can sort of clean and flush them out of the atmospheric column. But here the hazard is the rain itself, right that it falls too much, too fast, and overwhelms, you know, rivers, dams, like all sorts of things, as you may have seen, and carries everything along with it, cars, houses, flash flooding. So think of flash flooding.

45:25

AUDIENCE MEMBER: But it doesn’t take carbon dioxide out.

45:27

SHAW: No, sorry, it doesn't take carbon dioxide out. No.

45:32

Okay, so those were all the successes. There's many more, but I'm already running behind. But then we come to the other side of the coin of making predictions that some things don't look like what we expected them to. And I led recently a review or assessment of this for the World Climate Research Program, and we're calling these discrepancies, so where the real world over the last 40 years has evolved in one way, in a different way, from what we've predicted from these models, that it should okay. And so it's not. We made this map, because it's not just one place and it's not just one type of variable. There's, like, a series of these. And, you know, ongoing work, active area of research, is really, you know, using this fundamentally new type of information to assess why this is happening. It's not clear. These are critical model failures, but we are certainly going to learn a lot by digging in here and trying to, for example, connect the dots, as I'll suggest.

46:30

One of the ones I want to highlight to illustrate for you what this looks like is this drying trend, humidity trend over the United States Southwest. So here's an example. This is the dryness, or vapor pressure, hectopascal units. From 1980 to 2020 we've taken out a baseline, so we've removed the average from 1980 to 1990. So here's the real world, different, different observations of that. So gray and black. Okay, very clear drawing trend. Now, when you look at the models, and we've got many, many different kinds here, many colors, they're all predicting a moistening trend, so exactly opposite. And the observations are down here, and they don't sit anywhere within the model distribution of predictions, with all the uncertainty that we've thrown at the problem.

47:16

Okay, so it's very concerning, active area of research. Many people are trying to figure this out. I have led work in my group, along with a graduate student who's now a postdoc at Columbia University, trying to connect some of these things and point fingers at physical processes in our models that we may not be making the right assumptions about.

47:39

And so what I've shown you here is when the oval has turned to a square, we think all of these are connected to how small scale processes, and the connection between the atmosphere and the ocean, and the assumptions we're making about the turbulent exchange of moisture and momentum right at that interface, which are often highly linearized. It's a very difficult problem. You have bubbles, you have spray, a whole bunch of things. We did our best to make assumptions about how those interactions would go, but we think those need to be revisited. And so we don't have the full answers yet. But you know, nature, the real world, is showing us where we need to go and keep trying to figure it out. And I really think that, you know, as a community, you know we not to redouble our efforts at this critical moment would really be a tragedy. And of course, there's many tragedies unfolding, and so we'll navigate as best as we can.

48:35

AUDIENCE MEMBER: I have a question here.

SHAW: Yeah.

AUDIENCE MEMBER: When you look at this oval map which has oval differences, how do you mathematically average that for the total effect of each one of these areas to get a global average? How is that done mathematically?

48:59

SHAW: Okay, yeah. So you just, you know, take an average, take an integral, take a weighted average in latitude. You have to do a weighted average because, you know, the area at the equator is circumference is different than at the pole. So you're just averaging all of the, you know, grid boxes, all of the values in longitude, you don't have to do any area weighting. It's just a straightforward average. In latitude, you have to area weight. But yes, you're right. If I average over all of these patterns, I get the global the global mean.

49:33

AUDIENCE MEMBER: Is that what was done with the differential equations by the Nobel?

49:38

SHAW: Yes. So when he started, he took the average of the equations in longitude and latitude. I was kind of alluding to that without explicitly saying it, yeah. In these, in these predictions, we can, you know, unwrap the average and do, have the equations fully dependent on latitude and longitude, altitude and time. Now these are very high dimensional, complicated, nonlinear partial differential equations, but we know what they are, and our main uncertainties are the closures where we have a numerical truncation, and so we have to represent small scale processes that we only are knowing the solution of the variables on the numerical grid that we defined. So it's a classic closure problem, very familiar from turbulence, for us, it's a numerical discretization that truncates the scales in space and time. Yeah.

50:37

AUDIENCE MEMBER: I’d like to, just, as I understand I'd like to talk about the model...

The thing that’s there, of course, time and it’s an initial value problem and you’re integrating time stepping forward and sort of...

Now you said everything, the way they started was to relate everything to temperature. So temperature was the main dependent variable. So are you got other dependent variables? Or are you sticking with temperature as the overall thing in these, the evolution of these models?

51:15

SHAW: Right. So we have five equations. No, we have, I highlighted the momentum, right? So there's a time-dependent equation for temperature, a time-dependent equation for momentum, of which there are three components, a time-dependent equation for moisture, and so on, okay? And they're all coupled. And then we have an equation of state, which we know, well. It's, you know, dry, you know, ideal gas, yeah.

AUDIENCE MEMBER: Do you get any chaotic behavior?

SHAW: Oh, there's a huge amount of turbulence in these simulations, not only on large scale, turbulence like the weather systems, which are a form of turbulence, AUDIENCE MEMBER: ...mathematical chaos. Do you see that in the models you use?

51:59

SHAW: Yeah, so that's the numerical...that was for, not for climate models, that was for weather prediction models, yes, yeah, no, it's, I mean, you have to take some of the same physical equations. But again, it's a different problem from the perspective of initial value versus boundary condition.

52:22

AUDIENCE MEMBER: It's got to have the same mathematical characteristics.

SHAW: Right. But what the solution you're finding is different because of the two different types. Yeah, right. So again, Manabe showed us we're not doing an initial value problem. It's not about sensitivity to initial conditions. It's about the sensitivity to the carbon dioxide concentration as you dial it up.

AUDIENCE MEMBER: So you project those things around and test what you're doing, you're jacking around the different things and then looking at what happens.

52:55

SHAW: Well, no, I mean, we, in some sense, we're doing that. That was what we were doing to some degree, when we didn't know in the very early days, you know, we didn't really know how far we would go with CO2 emissions. But now we can do the same thing over the historical record of CO2 emissions. So there's a prediction part, and then there's a projection. Projection means we have to make assumptions about how CO2 will change. And then, yeah, yeah. So we do both. We do both.

AUDIENCE MEMBER: How long does this take?

SHAW: Yeah. I mean, these are state of the art super computers. Yeah, these are, these models are run on state of the art supercomputers. But here at the University of Chicago, we can take those same models, and we can take away some of the complicated physics that slows them down and really follow Manabe's approach, but kind of in reverse. So take the complicated end and take things out to really understand if something's happening in the complicated, full blown, like highly, you know, complicated super prediction, super high-performance computing, demanding super prediction, supermodel prediction, what? I'm sorry anyway.

AUDIENCE MEMBER: On the average your runs are more than a week?

54:07

SHAW: Oh well, yeah, for the long runs, it takes many, many months if you want to make the most physically complete state of the art model predictions, we're talking many months. But if you want to understand, because those all go into publicly available archives, you can go look at those model predictions for us. We can look at them and assess, you know, what features do they share, what emergent patterns do they all seem to agree on? Then we target those to do the Manabe approach in reverse, and then we can be much faster. We can, you know, simplify the clouds. We can take away the continents. And that's the power of his approach that continues today, and we call it a hierarchical modeling approach.

AUDIENCE MEMBER: But you can’t run the equilibrium

SHAW: Well, we can simplify the ocean. We can make it a swamp, and then. We can definitely do full equilibrium, just like Manabe did in that second, that second example. So there's really power in his approach. We do rely on these complicated models because they are meant to best mimic reality with an uncertainty. But when we try to understand the models, we go back to Manabe’s approach, I would call it his approach in reverse, often.

AUDIENCE MEMBER: Is AI beating you?

SHAW: In climate, no. Climate is a much harder problem than weather, for AI, because it's an out of sample problem. Yeah, if you try to extrapolate too much, yeah, they halluc-, as people say, they hallucinate. They don't think, but they so they extrapolate, and they can, they get it very they can get it very wrong, yeah. So not yet. Can I? I'll just finish a couple slides and then we’ll get to it.

55:50

Okay, so here we are. I think what really is the time for climate is we've got this, for regional climate change, is a sense that there's many places and variables we're doing a good job, success. And then there's knowledge gaps that have emerged, and many of us are very actively working on these. And, you know, I think it's exciting to really, you know, imagine us doing even better by learning from how the real world has evolved.

56:15

But I just want to end on one final point, which is that, you know, science always has gaps, and for us as climate scientists, you know, we really want to make clear that knowledge gaps do not justify inaction. And my close colleague Bjorn Stevens, likes to put it this way. You know, the challenge for us as climate scientists is, as a rule, we don't like to talk about what we don't know, because so often it has been used to manipulate or cast doubt on what we do know. And so we are now at a time when we are--we have these gaps. They are clear, but they don't justify inaction. We know that for every ton of CO2 emission, this will add to global warming, this will increase heat waves and lead to more extreme precipitation changes. And that, in itself, is enough. It's, you know, based on very successful physics-based prediction. And that is, in itself, enough for policy. What we, the knowledge gaps that we're pushing into is adaptation and mitigation and these sort of questions. And that's, you know, part of the science that's evolving that I'm very happy to be to be part of. I think we're going to learn a lot in the next decade. But of course, we do face many challenges. And it was a really pleasure to be here. I'm happy to take general questions. That's the end of my presentation. Thank you very much.