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I'm Kerry Emanuel, and it's been a great delight to walk you through some of the elements of climate science. I thought it would be useful to do a wrap-up session where we review some of the key points that we tried to make in this course.

So what are those key points? Climate has changed on many different time scales throughout the history of the planet. Such climate change is thought to have been caused by variations in absorbed sunlight, which includes variations in the sun itself, orbital variations, and aerosols such as produced by volcanoes, changing concentrations of key greenhouse gases, and changing continental configuration. Transfer of radiation to the atmosphere is affected primarily by clouds and by trace quantities of greenhouse gases. Of these, carbon dioxide is the most important on long time scales, owing to its long lifetime in the atmosphere.

CO2 is increasing owing to industrial processes and changes in land use. The basic response of surface temperature to increasing concentrations of carbon dioxide was predicted more than 100 years ago. The global mean response to changing carbon dioxide appears to be well-captured by radiative-convective models, such as the ones you used in this course. Circulation of the atmosphere and oceans redistributes energy and strongly affects the distribution of water vapor, clouds, and aerosols. Aerosols can have strong direct and indirect effects on climate. Simple and complex climate models indicate the possibility of substantial climate change in response to increasing concentrations of carbon dioxide and other greenhouse gases.

Let's begin with the first point. Climate has changed on many different time scales through the history of our planet. We talked about this rather extensively early on in the course. But there been very spectacular variations in our climate in the distant past.

For example, it's thought that the Earth went through some very extreme climate fluctuations centered around 500 million years ago. Varying between an ice-covered planet, or snowball earth, and an earth that had no ice whatsoever, even at the poles. And very warm temperatures at the poles with alligators wandering around Greenland, what is today Greenland, and so forth [this was less than 500 million years ago; alligators were not around then!].

Much more recently, we've seen rather extreme variations in the form of the great glacial cycles, or ice ages. The last glacial maximum was about 22,000 years ago. And what you see here is a depiction of what the Laurentide ice sheet might have looked like at that time, with ice extending down to the mid-Atlantic coast, for example, in the eastern part of North America, and covering the Western part of Canada all the way to the Pacific.

22,000 years is a blink of an eye, geologically. So to go from that state to our current balmy climate is quite a large change. And that was accompanied by rather spectacular changes in things like sea level. This diagram, which you might remember from earlier in the course, shows sea level going back to the last glacial maximum, about 22,000 years ago. You can see on the scale on the right, that then, sea level was around 130 meters, almost 400 feet lower than today. And in the course of a little bit more than 10,000 years, rose to current sea level values, about 7,000 years ago. So the last 7,000 years, sea level has been remarkably stable by geological standards. And it's probably not an accident that what we know as civilization developed during those 7,000 years.

We do know, by now, that these great glacial cycles were probably caused by variations in solar radiation incident in polar regions that are traceable to orbital variations. And the total amount of forcing change that may have caused these ice ages in the polar regions, was only about 10 watts per meter squared, giving rise ultimately to global mean temperature variations on the order of five degrees C.

So, the elements of climate change, the causes of climate change, include things like varying sunlight. Not just because of orbital variations, but because the sun itself changes. And because of aerosols in the atmosphere, such as those produced by volcanoes, which block sunlight. In addition to changing sunlight, there are changes in concentrations of key greenhouse gases, and changing continental configuration.

Let's go back to the orbital variations. This actually has a long illustrious history, but we focus on the Serbian mathematician Milutin Milankovic who early in the 20th century, resurrected the idea that variations in Earth's orbital parameters were responsible for ice ages. And there are three key elements of those orbital parameters. There's the tilt, or obliquity, of the Earth's rotation axis with respect to the plane, the ecliptic, about which the Earth orbits the sun. There is a precession of the Earth's rotation axis around that perpendicular, like a top. And then there are variations of eccentricity of the Earth's orbit, the degree of eccentricity, that take about 100,000 years.

When you put this all together, you get variations in the total amount of radiation received in the Arctic, in the high-latitude Arctic. Here is a chart which we also showed earlier in the course, going back a million years at the left, to the present at the right, showing two quantities. From Milankovic's mathematics, essentially the total amount of radiation received over the summer in high latitudes, that's in red, and the time rate of change of the ratio of two isotopes of oxygen in deep sea sediments that reflect the total volume of ice on the planet. And one can see the beautiful correlation between those two curves. We're really fairly confident that the great glacial cycles of the last three million years or so were ultimately caused by orbital variations.

In addition to orbital variations, the sun itself fluctuates. And this is interesting. It's an active area of research, still. What you see on this chart, is a very short period of time going only back to the middle of the 19th century. Showing at the top, the Earth's mean surface temperature. The light red line shows the annual temperature, global mean temperature of the planet. Whereas the bold line shows a 25-year moving average of that quantity. Where one can see that beginning around 1920, the earth has been warming up.

The blue curve in the middle of this diagram shows carbon dioxide concentrations deduced from ice cores in the smooth part of the line, and from direct measurements of the atmosphere in the wiggly part, which also shows the annual variations.

At the bottom of the diagram, we see estimated variations in solar output over the last 150 years or so. The light yellow line shows the annual variations and exhibits the well-known 11-year sunspot cycle. The dark bold orange line is the 25-year moving average of that.

So by comparing these three curves, one can see some indication of a solar influence on our climate. So for example, the warming of the early part of the 20th century might well have been due mostly to solar variations. But the warming of the last 30 or 40 years or so seems to have been driven principally by increasing greenhouse gas concentrations.

Volcanic aerosols are also very important, particularly on short time scales, in controlling the climate. Here again is a record of the Earth's surface temperature going back to about 1750. Focus on the bold black line in this diagram, one can see these downward spikes. And we've added to this diagram, in blue, the big volcanic eruptions that occurred over this period of time. And one can see that those big volcanic eruptions are accompanied by downward spikes in global mean surface temperature that last typically a few years.

Another key point that we tried to get across in this course is the physics by which radiation passes through the atmosphere, and is absorbed, scattered, and reflected by clouds and by trace quantities of greenhouse gases. This notion has a long history, going well back to the 19th century. And we talked a little bit about this history. One of the more fascinating characters is the Irish physicist John Tyndall, who developed the apparatus that you see on the left of this diagram, for measuring the infrared absorption by various gases in our atmosphere.

It was Tyndall who came up with some of the most essential results that allow us to understand how our climate behaves. The key result is that the main constituents of our atmosphere, which are molecular oxygen and molecular nitrogen, and to some extent argon, make up 99% of the mass of our atmosphere. But they're almost entirely transparent, both to solar radiation and to terrestrial radiation. So, if that's all there were, we wouldn't have something called the greenhouse effect. The greenhouse effect depends upon trace constituents of more complex molecules, particularly water vapor, carbon dioxide, and nitrous oxide. There are a handful of other trace gases that make a difference as well. And of course clouds are condensed water. All this together is responsible for the Earth's present global mean surface temperature being around 15 degrees C, as opposed to about minus 18 degrees C, if those gases were absent.

This is really a remarkable, and to many people, a deeply counter-intuitive feature of the Earth's climate. Here's a pie chart, which we showed earlier in the course, of the gaseous constituents of the atmosphere, showing the majority is molecular nitrogen. Most of the rest is molecular oxygen. Argon is the green sliver on this diagram. And all the greenhouse gases are concentrated in the little orange sliver on this pie chart, which you might or might not be able to see in this video. It is a really tiny amount of greenhouse gas. And it is that sliver of greenhouse gas which makes all the difference between a frozen planet covered with ice, and our present balmy climate.

Now, it's even worse than that in a way, because the most important greenhouse gas is water vapor, which constitutes about a quarter of 1% of the mass of the atmosphere. And, although it's the most important greenhouse gas, unlike, for example, carbon dioxide, it has a short lifetime in the atmosphere, about two weeks. And it's controlled mostly by temperature. So rather than considering it a forcing agent, we consider it a feedback, it responds very fast to changes in the temperature.

So that means that on time scales of hundreds or thousands of years, the climate is really strongly influenced by other greenhouse gases like carbon dioxide, methane, nitrous oxide, that together comprise about 0.04% of the mass of the atmosphere. And that is really astounding that that tiny amount of greenhouse gas can so strongly influence the climate. The focus of this course is the recent phenomenon of global warming, which is driven by an increase, principally in carbon dioxide of about 43%, since the dawn of the Industrial Revolution. It's hardly surprising, given the importance of these greenhouse gases, that increasing one of them by such a large percentage would have an important effect on climate.

We learned about how radiation is transmitted through the atmosphere. It's summarized in this diagram, which shows the Planck blackbody curves for the sun at the left on the top here. And for the earth, at the right. And the coloring below this curve shows the amount of solar radiation that's transmitted to the surface. And on the right hand side, the amount of infrared radiation that's transmitted upward to space.

One can see that much of the solar radiation gets through, because the atmosphere is relatively transparent to solar radiation. But not very much of the infrared radiation goes directly to space from the surface. And that's, again, thanks to the presence of greenhouse gases and clouds. And you can see the percent of absorption and scattering in the middle diagram on this panel. And the contribution to this from the various greenhouse gases like water vapor, carbon dioxide and so on. So the essence of the greenhouse effect is that these trace gases absorb upward-going infrared radiation, and re-radiate that energy both upward to space, and down toward the surface.

The surface has to get warm enough, not only to balance the incoming sunlight, but to balance the back radiation coming from our atmosphere itself. The astounding fact is that on average, the Earth's surface receives about twice as much energy from back radiation from the atmosphere, as it does directly from the sun.

Now, we focus on carbon dioxide because it has the longest lifetime of these trace greenhouse gases, or at least the ones that are important. And that's illustrated by this diagram, which we reviewed, which is the concentration of carbon dioxide going back 1800, and projected forward all the way to the year 3,000, under various hypothetical scenarios. So as we go up along this curve, we're going to do the thought experiment of completely turning off emissions when greenhouse gas, when carbon dioxide concentrations reach 450 parts per million, 550, and so on. And let's watch what happens to the greenhouse gases once we shut off emissions.

Well you can see that there's initially a rapid decay, taking only a few decades. But then a much longer decay taking thousands of years. And this is the essence of the problem here, is that once we put carbon dioxide in the atmosphere, it takes natural processes thousands of years to remove it again. Which is one of the problems we face when we talk about global warming.

Now, carbon dioxide is increasing because of burning of fossil fuels and changes in land use. That's very clearly established. This is a diagram going back 2,000 years, showing carbon dioxide concentrations from ice cores, those are the green dots. And from direct measurements beginning in 1958, that's the blue curve you see on the right. You can see that, in the pre-industrial era, the concentration hovered around 280 parts per million. But beginning in the early part of the 19th century, they started to go up, and at an ever increasing rate. In fact, as I am talking to you here, in February of 2014, we're just crossing the 400 parts per million mark.

The basic response of the climate to increasing concentrations of carbon dioxide was predicted more than 100 years ago by this Swedish chemist, Svante Arrhenius. Doing calculations with pencil and paper, and understanding some of the physics of greenhouse gases, Arrhenius made this statement, that doubling the percentage of carbon dioxide in the air would raise the temperature of the earth's surface by 4 degrees centigrade. And if the carbon dioxide were increased fourfold, the temperature would rise by 8 degrees. The physics of the problem are such that the rise is logarithmic with carbon dioxide. So we talk about doublings, for example.

Now, four degrees is a lot. And you can compare that to the estimates made by a very large team of international scientists, and just released in the fall of 2013, that estimated that doubling carbon dioxide would increase the Earth's surface temperature by between 1.5 and 4.5 degrees. So Arrhenius's estimate is within that range. Really remarkable, considering that he did it without supercomputers, without lots of measurements, about 100 years ago.

This is in some sense a kind of confirmation of Arrhenius' prediction. We see here the carbon dioxide concentration in blue. This is actually the natural log of the carbon dioxide concentration going back to about 1880. And in green, the Earth's mean surface temperature. And we can see that, although there are departures, in general the Earth's surface temperature has followed the carbon dioxide concentrations. So this is an example of a successful prediction made about 100 years ago. What would happen to the Earth's surface temperature if we increase one of the most important greenhouse gases?

In the course of 12.340x, you learned how to operate a very simple one dimensional climate model in which the main processes are moist convection, and radiative transfer. This model was developed over the last few decades at MIT. And this shows the results of experiments you can do yourself with the model, doubling CO2 from its current concentration, doubling it again, and so on. Until we go up to four doublings. And this graphs the surface temperature calculated by that model in equilibrium. for each of those doubllings. And if you fit a straight line to that set of experiments, you get about three degrees centigrade increase per doubling of CO2, right in the middle of the range of the IPCC from 1.5 to 4.5, based largely on supercomputer models where you actually have to call the power company before you turn them on. So you don't really need these models if all you're after is the surface temperature [or really, its sensitivity to increasing CO2], but of course the global climate models give you much more than just surface temperature.

But the climate is more complicated than just a single column. The atmosphere and the oceans transport heat laterally, and they redistribute energy. And the circulation of the atmosphere also strongly affects the distributions of water vapor, clouds, and aerosols. So here's a chart showing as a function of latitude, from the South pole here, and the North Pole here, the total northward heat transfer by the oceans and atmospheres in petawatts. That's 10 to the 15th watts [1 PW=10^15 W]. So the black curve is the total. It's negative in the southern hemisphere here, being the transport is toward the south. It's about zero at the equator. And it's positive in the northern hemisphere.

Black curve is the sum of what's transported by the oceans and the atmosphere. The red curve is the atmosphere by itself. And the blue curve is the ocean by itself. So you can see that most of the transport's done by the atmosphere, but a substantial fraction of it is nevertheless carried by the oceans. Which is quite remarkable when one considers what different fluid media they are, and the fact that they're driven by very different processes, that they should transport even the same order of magnitude of heat is somewhat surprising. But without that transport, our climate would be very different. And that's why we can't just rely on one-dimensional models. If we shut down that transport, the poles would get very cold, and the tropics would get very hot.

The ocean plays an incredible role in climate in a number of different ways. One other way, besides simply moving heat around, is that when you change the climate, typically most of the change in the energy content of the whole Earth system is in the oceans. This chart shows the heat content of the first 2000 meters of the ocean, going back to about 1960. The red that you see at the end is with somewhat more accurate measurements. But one can see that from the '60s to the present, there's been a fairly steady increase in the heat content of the ocean. One of the consequences, and one of the signatures, of global warming.

Now this chart takes what you saw in the last slide and compares it to the total heat content of the rest of the Earth system, which is the land, the atmosphere, and land ice. That's the red curve. By comparing these two, one can see that the vast majority of energy that has been put into the system by increasing greenhouse gases, has in fact gone into the ocean. The ocean is 1,000 times more dense than the atmosphere at sea level, and it has about four times the specific heat capacity of air, so it's not surprising that most of the energy has gone into the oceans.

Aerosols can have a strong effect, both directly and indirectly, on climate. Here is a chart, which we saw earlier in the course as well, going back to 1850, showing the radiative forcing estimated to be produced by various kinds of aerosols. So this is in watts per meter squared, and can be compared to the number for four watts per meter squared, one gets from doubling carbon monoxide. So although these forcings aren't individually as large, as we're getting from increasing carbon dioxide, collectively, they amount to quite a bit.

So for example, the orange curve you see on this diagram is due to black carbon, BC. The black curve is due to sulfates, which reflect solar radiation and cool the climate. The blue curve is an estimate of the total aerosol forcing. You can see that not just greenhouse gases are changing, but by burning coal, forests, and so forth, we're putting material into the atmosphere in the form of small particles, which reflect and or absorb sunlight. There is also an indirect effect of some of these aerosols in changing the optical properties of clouds, which are terribly important for the Earth's radiative balance.

Both simple and complex climate models indicate the possibility of substantial climate change in response to increasing carbon dioxide concentrations. When we look forward, when we use our global climate models to ask what will happen in the future, we see a large uncertainty. Why is this? Because after all, after everything that we have talked about in this course, there are still many aspects of the climate system we don't understand very well. I could start in on a list of that, and it would take up a lot of time, but we did talk about some of these processes in the process of going through the course.

What you see on this chart is a range of estimates of increases in the global mean surface temperature owing to a doubling of carbon dioxide. You might think of this as a probability distribution. This particular chart was created by running essentially the same climate model with all kinds of different assumptions and parameters [all of which are within the bounds of our uncertainty about different physical processes in the climate system], and by running many, many versions of the model, many, many times, we get some estimate of the probability distribution of surface warming that doesn't look very different, in its essence, from what you get by running completely different climate models.

So this if for a doubling of CO2. And what we see is that in all probability, the warming will be somewhere between two and four degrees, as estimated by the CO2. But there is a tail out here of somewhat larger warmings. And this is essentially what we confront socially. That is, we confront a risk problem, and risk, by its very nature, is uncertain. We can gamble that the warming will be between two and four degrees, or maybe less than three degrees, for a doubling of CO2. And we might be able to adapt to that. But we're taking a big risk, because if we get the temperature changes out here in the tail, those could lead to truly catastrophic effects. That's why this is such an important problem.

Now, in addition to that, when we talk about doubling, we have to be very careful to mention that in all likelihood, mankind will do more than simply double carbon dioxide concentrations. So what you see here is an estimate of the carbon dioxide content of our atmosphere, with the concentration, in parts per million, looking backwards in time to 1950 and projecting forward to 2100, about 85 years from now. These different scenarios really depend on projections about what we're going to do. How much greenhouse gas will we produce. But you can see that we cross the doubling, which is this light blue dash line, anywhere from the year 2050, out to maybe 2080 or so, depending upon which one of these scenarios we follow. But it's quite possible that by the turn of the next century, we will have done something more like tripling carbon dioxide content. So doubling CO2 at this point in history is a rather conservative prediction of what we'll do.

We need to get on top of this problem. We need to study it more. We ought to try to beat down that uncertainty. All of that will require engaged and gifted students, as you are. As we talked about before, the consequences of this doubling or tripling of CO2 have uncertainty, but we can also state with some confidence something about the time scale over which the changes will occur. We've already seen the graph at the top, which is projected changes in carbon dioxide concentration, under the simplifying scenario that at a given concentration, we suddenly stop emitting greenhouse gases. As we mentioned before, there's an initial decay that takes only a few decades, but the long term decay back to normal concentrations, pre-industrial concentrations, takes thousands of years.

The bottom graph, using a climate model, shows the corresponding evolution of the global average surface temperature. And you can see basically, that whenever we stop emitting, if we were to do that suddenly, the temperature change that we will have caused is going to be there for thousands of years, unless, we find some way artificially of taking the carbon dioxide out of the atmosphere again. That in a nutshell, is the problem.

Well, thank you very much. It's been a wonderful pleasure to have you all attend the course. My co-instructors, Dan Cziczo and David McGee, join me in hoping that you got something out of it, and wishing you well for the future. I'd also like to take the opportunity to thank the team of TA's that have been supporting this course, and the great team we have at MITX and edX in running this course technically. Good-bye.