Changing Planet: Past, Present, Future
Lecture 3 – Earth's Climate: Back to the Future
Daniel P. Schrag, PhD

1. Start of Lecture Three (0:16)

[ANNOUNCER:] From the Howard Hughes Medical Institute...The 2012 Holiday Lectures on Science. This year's lectures: "Changing Planet: Past, Present, Future," will be given by Dr. Andrew Knoll, Professor of Organismic and Evolutionary Biology at Harvard University; Dr. Naomi Oreskes, Professor of History and Science Studies at the University of California, San Diego; and Dr. Daniel Schrag, Professor of Earth and Planetary Sciences at Harvard University. The third lecture is titled: Earth's Climate: Back to the Future. And now a brief video to introduce our lecturer, Dr. Daniel Schrag.

2. Profile of Dr. Schrag (1:12)

[DR. SCHRAG:] I'm a geologist. I study Earth history, and I'm particularly interested in the climate system, in the oceans, in the atmosphere, and how they've changed over geologic time. I'm interested in all different timescales, from billions of years, to what happened through the evolution of multicellular life, and the early evolution of animals, and even changes in the last thousands or hundreds of years. If you study climate through Earth history, it's hard not to get interested in what's actually happening to the climate today. So a lot of my work now is also on understanding what climate is going to be like in the future, and also what to do about it, in terms of thinking about energy technology, and energy policy. To me, one of the greatest mysteries about climate change is what it's actually going to do to the biological world. For the last decade or so, conservation biologists and ecologists have gotten more and more concerned about climate change. They've started to see changes in species habitats. They've started to see migration of species as the climate changes. Unfortunately, what we haven't paid enough attention to is the timescale of climate change. You know, there's a lot of uncertainty for example, on whether Greenland will melt in the next 100 years. But if you change the timescale, uncertainty goes away. Greenland is unlikely to survive 10,000 years. I can't tell you whether the ice sheet on Greenland will still be there 200 years from now, or 500 years from now, or 2,000 years from now. But in 10,000 years, I can be pretty confident that most of it will be gone. And that's equivalent to seven meters of sea level rise. That means that a lot of low-lying islands around the world are going to be gone, and with them, most of those ecosystems and those species. We're doing an incredible biological experiment. Climate change is not just a climate experiment, it's a biological experiment. And there's still a question of whether this will show up in the geologic record someday as one of the great mass extinctions. The Earth will recover. But the question is how much of this incredible tree of life will make it through this incredible environmental change unscathed.

3. Introduction to the importance of climate (3:29)

[DR. SCHRAG:] Good morning. It's nice to see you all here today. So, today I'm going to talk about climate change. I'm going to talk about climate change on a variety of timescales because climate is one of the features of a planet that really determines whether it's habitable. We heard from Andy Knoll about how life has evolved throughout Earth history and he referred to climate change throughout that time period. What I want to do is explore a little bit, what is it that actually controls the climate of a planet and how does it vary over time. Then we'll look at our current predicament and think about how climate is likely to change over our lifetimes and on into the future. So we can start here with a silly picture of an Earth with a little gas burner heating it up. Of course, you know this isn't actually the way the Earth's climate is controlled. But you know, just like the heater in your houses, the Earth's system does have a heater; it's the sun. But it also has a thermostat and that's what we're going to talk about today, and the thermostat is actually the carbon cycle, that actually keeps the Earth habitable throughout the last 3-1/2 billion years of Earth history. When we actually look at other planets, we can look at our neighboring planets Venus, and Mars, Venus of course is closer to the sun, and Mars is further away from the sun, you can ask the question why do they have the climates that they do. Venus, of course is incredibly hot, 460 degrees Celsius on the surface. Not terribly habitable. And Mars is too cold, as we've heard from Andy Knoll before, about the evolution of Martian climate over the last 4 billion years, it's about -50 degrees Celsius. So it's kind of like the three bears, right? Venus is too hot, Mars is too cold, and the Earth is just right.

4. Earth has been much warmer and much colder in the distant past (5:24)

You might ask the question "well, has that always been the case," and it turns out no. In fact, the Earth has varied quite a bit over Earth history. It hasn't always been constant. Andy Knoll showed us this slide of what Maryland might have looked like 20,000 years ago when there were mammoths walking around. If we zoom out, here is what the Northern hemisphere might have looked like on the left, 20,000 years ago. You can see North America covered with a giant sheet of ice-- the ice sheet where I live in Boston would have been about a mile thick. Ice came all the way down to New York City. There was a big ice sheet over northern Europe as well. There was so much ice on land 20,000 years ago that sea level was about 130 meters lower than today. It's a very different world. And just 20,000 years later you see the modern world with sea level where it is today. What's interesting is that both these climates are actually ice ages. The reason is we actually still have ice on continents. We don't have as much as we did 20,000 years ago, but we still have ice on Greenland, and we have ice on Antarctica, at least for now. This wasn't the most extreme ice age the Earth has experienced. If we actually take another look at one of Andy Knoll's slides-- this is his picture of Earth history showing how we went from anaerobic bacteria and archaea, then eukaryotes and then animals-- what's interesting is these same times of transition between essentially no oxygen and low oxygen, and then around 6 or 7 hundred million years ago when we went from low oxygen to high oxygen, it turns out that both of these times are when we had these extreme glaciations over the Earth. We have evidence that in fact, the Earth may have frozen over completely, something we call the snowball Earth. The last one was around 600 million years ago. And that was probably the coldest climate the Earth's ever experienced. What's interesting is, not only did life survive but the Earth survived too. The Earth recovered to where it is today. And we've also had very warm climates. The Cretaceous, when the dinosaurs were living, was much, much warmer. That was also true in the Eocene about 50 million years ago. It extended from the Cretaceous through the Eocene. And we've had other periods of warm climate, fluctuations between ice ages or time periods like the Cretaceous and the Eocene, when the Earth was so warm that there was no ice at all, no ice on Antarctica, no ice on Greenland-- a completely different planet. Now there's lots of evidence for that warm world in the Eocene 50 million years ago. There were crocodiles living way up in the Arctic. If you look at the perimeter of Antarctica there's evidence for a pine forest. Palm trees living in Wyoming-- pretty cold winters in Wyoming today. Sea level was about 100 meters higher than today, in part because there was no ice anywhere on the continents. And deep ocean temperature was about 12 degree Celsius. Today the deep ocean is about 2 degrees.

5. Methods for reconstructing paleoclimate (8:34)

What I want to talk about is how we know about these past climates, and if we look at the more recent period, just the last 65 million years, since the Cretaceous-Tertiary extinction, a lot of our information comes from sediments on the ocean floor. So here's a drillship that goes around the world's oceans and drills cores into the ocean floor and collects the sediments and when they come back they look like this. This is showing the very top of the sediment layer. If you look through these Plexiglas core liners you can see that the very top there is where the bottom of the ocean is and the sediment begins. And if you look inside the sediment it turns out that in some places the sediment is composed of, almost entirely of tiny little microfossils, microfossils of little algae that we call coccoliths, but also little protists that are called foraminifera. Now there are foraminifera that live up in the surface ocean that are called planktonic foraminifera. These are zooplankton. They eat other organisms, algae in particular and these ones, the one that you see here on the right is a benthic foraminifera. That means it actually lives on the bottom of the ocean and feeds on food that's drifting down through the water column.
Now that shell in all of its detail is only about 100 microns across. So it's a tiny little guy but what's interesting about it is its grown its shell made of calcium carbonate on the bottom of the ocean and its chemistry of its shell actually tells us about the history of temperature of the oceans. I don't want to get into the great detail of this but essentially the ratio of oxygen-18 to 16 in that calcium carbonate shell has an inverse relationship with temperature. So if you grew those forams in the laboratory, and they grew their shell in an aquarium where you fix the temperature, and then you measure the ratio of oxygen-18 to oxygen-16-- these are two atoms of oxygen that have the same number of protons, 8 protons, but one has 10 neutrons, the other only has 8 neutrons. If you look at that ratio and you measure the temperature in the water you would see a nice inverse relationship like this. So now you can go to these sediment cores and pull out these shells and measure the ratio of oxygen 18 to oxygen-16 and reconstruct what the temperature of the ocean was like when those shells grew millions of years ago. And people have done this all over the ocean floor and they end up with a curve that looks like this. So this represents decades of work by many different scientists studying cores from all over the world oceans and this is a picture of how ocean temperature in the deep ocean has changed over the last 70 million years.

6. Modern Earth is in an ice age (11:22)

The first thing you can see is that about 50 million years ago the temperature was very warm, about 12 degrees Celsius-- very different world. As I said there's also lots of other evidence for warmth; palm trees in Wyoming, crocodiles in the Arctic. And you can see that the last 50 million years has been a steady cooling; not always so steady. There's been some fluctuations, but really a descent into the modern world that is on the cold end of the spectrum. We're living today in a relatively cold climate. It was colder 20,000 years ago but in fact, what was going on 20,000 years ago, if we zoom in just on that upper 2 million years, the last little bit of time, you can see that in fact, those records, there's a lot of detail there. You can see these oscillations back and forth. These are the ice ages waxing and waning, so 20,000 years ago, we were at a glacial maximum, and today we are at a, you might call a glacial minimum. We actually call it an interglacial but it's the same idea. We're waxing and waning between these more extreme ice ages and a more mild ice age. Again, though in the context of larger Earth history, we're still in an ice age. So those fluctuations really are between the left hand and the right hand of this slide, a world that has a lot of ice versus a world that has only a little bit of ice.

7. The influence of atmosphere on planetary climates (12:45)

So what I want to do now is step back and say what is it that caused these changes in Earth's climate over Earth history. And how can we explain the difference between Venus and Earth and Mars? And you might think oh, it's really simple. Venus is closer to the sun; it gets more solar radiation so it's hotter. Mars is further from the sun, it gets less radiation so it's colder. And you know that's all true. But here's the interesting thing. A lot of people don't realize that in fact, if Venus had the same atmosphere as the Earth, even though it's closer to the sun and gets about twice as much solar radiation as the Earth, because it's so much brighter than the Earth, you see how it's not dark like the Earth? The Earth has some bright spots too, it has clouds and it has ice sheets, but you see a lot of the Earth is covered with ocean that's quite dark and absorbs a lot of solar energy. Because Venus is so bright and reflects so much light, Venus would actually be colder than the Earth if it had the same atmosphere as the Earth. What actually keeps Venus warm, so hot, 460 degrees Celsius, is that it has an atmosphere 100 times thicker than the Earth, composed almost entirely, 97%, of carbon dioxide, sort of an ultra-greenhouse planet. Whereas Mars has a very thin atmosphere, also mostly carbon dioxide, but 100 times thinner than the Earth's atmosphere, and it is further from the sun and therefore it's very, very cold. So the question is, what causes this sort of variation? Why have these planets ended up like this and what has maintained the Earth in this habitable state for 3-1/2 billion years? Why didn't we become like Venus or why didn't we, once we had a snowball Earth and froze over completely like Mars, why didn't we stay that way? And the answer has to do first with the way our energy balance is achieved on the Earth, but it has to do with the carbon cycle.

8. Animation: Greenhouse Effect (14:42)

Let me quickly review for you how this works. So again, the surface of the Earth is heated by the sun. The amount of energy that comes out of the Earth, geothermal energy, is a few thousand times less than what actually comes from the sun. So in certain places it can be important but overall it's the sun that sets the Earth's surface temperature, not the internal temperature of the Earth. And when the sun shines on the Earth, some of it is actually reflected back to space. Again, more of it if it's on an ice-covered part of the Earth or where there's lots of clouds. And some of it is then absorbed by the Earth. When it absorbs solar energy in the visible spectrum, what happens is the Earth heats up in response, because it's absorbing energy, and when objects heat up they emit their own radiation but in a longer wavelength, and so that radiation then heads back towards space. If the Earth had no atmosphere it would be about 30 degrees colder, so we would actually have a frozen planet. We are habitable because of our atmosphere and because our atmosphere has some greenhouse gases, in particular carbon dioxide and methane, the most important of which is actually water vapor. Water vapor is interesting. We don't often talk about it as a greenhouse gas but the reason it's important is it's like an amplifier. It turns over quickly. It lasts in the atmosphere hours to days to weeks and so as a result you can think of the other greenhouse gases, carbon dioxide and methane, as the dial, say, on your stereo, but it's the water vapor that amplifies the effect because it turns over so quickly. And so what happens is these greenhouse gases, they absorb some of the infrared radiation, the long-wave radiation, and re-radiate it both back to space and downward, but they act like a thermal blanket so they essentially keep the Earth's surface warmer than it would be otherwise. And that's how the greenhouse effect works. And again, this isn't just a theory. We can actually say this is what causes Venus to be 460 degrees Celsius. We know this is... in fact, in the laboratory we measure carbon dioxide by looking at how it absorbs long-wave radiation.

9. Animation: The Geologic Carbon Cycle (16:56)

Okay. But that still doesn't really answer our question, right? It doesn't really explain how did Venus get this way. Why is Mars this way and why has the Earth persisted in this habitable region even though there have been fluctuations over Earth history? To answer that we really have to think about what is it that controls greenhouse gases in the atmosphere, and carbon dioxide in particular. And on long timescales of millions of years, we're talking about planetary evolution now, we actually have to think about where the CO2 in the atmosphere comes from. It turns out that the carbon dioxide in the atmosphere ultimately comes from the inside of the Earth either through volcanism or through release of gases associated with metamorphic events, but essentially the internal processes in the Earth give rise to venting of carbon dioxide to the atmosphere. Now this is a tiny amount. I don't want anybody to worry about volcanoes going off, right? The amount of carbon dioxide coming out of volcanoes is less than 1% of what we put in the air each year from burning of fossil fuels. So volcanoes are not going to change the climate through carbon dioxide emissions any time soon. But here's the thing: they persist for a very long period of time. So if you let this go for millions of years we would end up like Venus, right? This tiny trickle of carbon dioxide, if it were to persist for millions and millions of years would end up building up carbon dioxide to higher and higher and higher levels and then we would be essentially so hot that life couldn't survive. So it has to be something that balances this release of carbon dioxide into the atmosphere and results in taking it out of the atmosphere. And on the Earth, one of these important things, the most important process that does this, is a chemical reaction. This chemical reaction is an interesting one because it actually has three parts. The first part is just dissolving that carbon dioxide in water-- that could happen in clouds, it could happen in rainwater, it could happen in groundwater-- but the result is carbonic acid. You guys probably looked at that in elementary school. Carbon dioxide... you know, seltzer water is an acid. It's not a very strong acid. That's why we can drink it. You can drink soda because of that, but it is mildly acidic. Okay, and when acid reacts with the rocks on the Earth surface, igneous rocks that have come from melting of the Earth's crust, what happens is a chemical reaction occurs that we call weathering. And the net result of that reaction is that it produces calcium carbonate, limestone, chalk. Now, this reaction isn't often talked about when you learn science in high school. But what's interesting is this is probably the most important chemical reaction on the surface of the Earth. This is the reaction that has kept the Earth habitable for most of Earth history. It's a very simple reaction, where essentially you have carbon dioxide plus an igneous mineral-- in this case there's a mineral, anorthite-- and water, going to a clay mineral and calcium carbonate. You can see a picture of what a granite looks like, that's...anorthite is the most common mineral in a granite or in a basalt for that matter. And clay on the right, this is the clay kaolinite which is a very common clay. It's a soft mineral that you see on the Earth's surface in mud or other weathered regions. What's interesting about reaction, the reason it works as a thermostat is that it's temperature-dependent. I want to quickly take you guys-- I know this isn't a chemistry lecture--but I want to take you through a little bit of the chemistry of this just to show you how this works and explain that these are three separate chemical reactions that occur in different places on the Earth's surface and yet, when you combine them all together, they yield this wonderful result. So the first is simply the solubility of carbon dioxide in water. So just saying carbon dioxide plus water produces hydrogen ions-- that's acid-- and bicarbonate ion. It's a very simple chemical reaction. The second is the weathering reaction. And this is the critical one. This is the one that's probably most important in terms of its temperature dependence. This is the mineral anorthite-- you could substitute other igneous minerals as well, but this is one of the most common ones-- plus two of those protons, hydrogen ions, plus water, and essentially that chemical reaction produces this clay mineral, kaolinite, and a calcium ion. And so when you actually combine these two reactions, you can actually see that these weathering reactions on land produce river water, so rain falls on the rock, weathers the rock, produces clay, and then what ends up in the rivers is a mixture of bicarbonate ion and calcium, or other ions like magnesium and sodium. And that's the composition of river water predominantly. And the final reaction actually occurs completely separately in the ocean, where the calcium and the bicarbonate gets washed in from the rivers and then combines to make calcium carbonate. And this is the material that corals use the make their skeletons, that's in the form aragonite, or foraminifera use to make their skeletons. That's calcite, but it's the same mineral, calcium carbonate, the same chemical composition. And so if we actually do a little math and just cross out the things that cancel on the left and right-hand sides of these equations, you can actually see that the net reaction when we add all of this together is the one we just showed. Carbon dioxide plus anorthite goes to clay mineral plus calcium carbonate. So, these three reactions that occur in different places-- one is occurring in rain or in groundwater. The second is occurring as the rain washes over the rock and reacts with the rock and chemically weathers it, and the third is actually completely separate as the rivers wash the water into the ocean and then ultimately in the ocean animals grow, organisms grow and precipitate calcium carbonate as their skeletons. These are three separate chemical reactions but the net result is to take carbon dioxide out of the atmosphere and into the ocean and onto the ocean floor.

10. The geologic carbon cycle as a planetary thermostat (23:17)

And the reason this is a thermostat, is that if the Earth ever got too hot, if the Earth were to warm up for some reason, well, what would happen? Well, the chemical weathering reaction would start to increase. It would go faster and faster. And once that happens, that would essentially turn more carbon dioxide into calcium carbonate, and it would cool the climate. If the Earth ever got too cold, this chemical weathering rate would slow down a little bit, volcanoes would continue to put carbon dioxide into the atmosphere, and the Earth would reestablish the right temperature. So you see how this works as a thermostat. It keeps the Earth from getting either too warm or too cold. Now it's not a perfect thermostat. It's not like the thermostat in your house where you set the temperature and it fixes it right there. And that's because the time of this takes a little while, so it's a little bit more difficult than that. So when we look back at at other planets, we can actually see what's wrong with the other planets. Venus is hot, has too much carbon dioxide. What is it missing? What does the Earth have that Venus doesn't have? Water. So Venus has rock. It has lots of igneous rock, it has carbon dioxide, it doesn't have water. Earth has everything. What is Mars missing? No, it has CO2 in the atmosphere, it has water, it's frozen. It doesn't have volcanism. It doesn't have a source of carbon dioxide that's persistent. And it may have earlier in Earth history.

11. When Earth was very cold: Snowball Earth (24:56)

So the Earth's thermostat works well but it's not perfect. It's not perfect, and the most extreme example is the snowball Earth, when we think that the reflective power of the ice, what we call the albedo, was so extreme that it actually completely covered the planet with ice. So this runaway albedo...in fact the person who discovered this, a Soviet scientist who was thinking about nuclear winter, thought that this was so stable that this never happened, because if this ever happened it would stay there forever. But you know something that this guy didn't. If the Earth froze over completely like that what would happen? What would happen to the chemical weathering reactions, the rock weathering? It would stop. And would the volcanoes stop? No. It turns out volcanoes actually don't care much about the surface of the Earth. They're driven by the deep Earth. And so the weathering would stop, but CO2 would keep coming out of volcanoes, and now you just have to wait. You might have to wait millions of years but eventually carbon dioxide would build up enough... so if you cut off the weathering and CO2 keeps going, eventually you're going to have enough CO2 in the atmosphere and melt the snowball Earth back. That's how the system is self-correcting. So here is actually a picture of me and my colleague Paul Hoffman, and these are one of these glacial deposits. You see those boulders there in the rock; those are actually sediments that were formed, dropped from ice. These are dropstones that came out of ice floating on the ocean, and you can see right where our hands are, above, that's the top of the glacial surface and above that is a thick layer of limestone. This limestone's called a cap carbonate because it actually occurs on top of these glacial deposits everywhere in the Earth, and this, we think, represents the end of these snowball Earth glaciations, during a time of very intense chemical weathering as the system tried to right itself as you went from a very cold climate to a very warm climate.

12. Subduction of ocean sediments affect CO2 levels (26:57)

So we can also try to say, what happened to the Eocene and the Pleistocene? We said the Eocene was very warm 50 million years ago, whereas the modern Earth's climate is much colder. We can explain this very simply in terms of the complete cycle. Another part of the cycle is that after calcium carbonate is buried it actually subducts beneath the continents. Naomi Oreskes talked about plate tectonics and how ocean crust can subduct beneath continents and when it does that it actually brings calcium carbonate down and the amount of calcium carbonate that goes down beneath the continental crust into the trench turns out to affect how much carbon dioxide comes out of the volcanoes. And so one explanation for why the Eocene and Cretaceous were so warm is that there was a lot of subduction occurring over in an ocean basin called the Tethys. As Africa and India moved north towards Eurasia, ocean crust was subducting beneath the Eurasian continent, and all the volcanoes along that margin were streaming out carbon dioxide because of all of the limestone in that region. And then as India and Africa moved north and that basin closed, that subduction stopped, and in the modern Earth, we have a system where most of the subduction is occurring in the Pacific, which has very little limestone. The limestone is mostly buried today in the Atlantic. And so this is probably a long-term cycle. Someday the Atlantic Ocean will subduct again and Europe and North America will come back together and when that happens we'll have another warm climate. We just happen to be in a cold climate today.

13. High CO2 has driven warm periods of Earth's history (28:30)

And when we actually look, and this is our same figure of oxygen isotopes on the left, showing the temperature change through Earth history over the last 70 million years, on the right is a set of proxies of carbon dioxide concentration. I don't have time to get into the details of this but they're things like the stomatal density of leaves or chemical proxies that have to do with the amount of boron in shells and a variety of other ways of estimating past CO2, and you can see that, there's a lot of uncertainty but in general we think that the Eocene and this warm period in Earth history was indeed times of higher carbon dioxide concentration. So it really is the carbon dioxide that's driven this climate change from the warm climates of the Eocene down to the ice age today.

14. The rate of climate change is critical (29:16)

And so finally, when we look at the last little bit of Earth history, these ice ages that have fluctuated over the last couple of million years, we can actually see that carbon dioxide has changed here as well. So this is now carbon dioxide from an ice core over the last 650,000 years and you can see carbon dioxide fluctuating and it matches the temperature changes we've seen perfectly. So during the last glacial maximum 20,000 years ago, carbon dioxide was about 180 parts per million, and in the pre-industrial period it was about 280 parts per million. And you can see that never in the last 650,000 years has it gone above 300 parts per million...until today. This is where we are today in 2012. Very close to 400 parts per million and that's what we're going to talk about in the next part of this lecture, just thinking about what this means. But I think looking back at Earth history we can conclude that the rate of climate change is critical. We'll talk more about this in a minute but in general if things happen slowly, like the ice ages, and it looked like some of those changes were rapid, but they occurred over 10,000 years. Something happens over 10,000 years, plants and animals can move. If it occurs over decades to centuries it's a little more challenging. So let's stop there and take some questions and then we'll move on. Yeah.

15. Q&A: Do you believe in global warming? (30:31)

[STUDENT:] Do you believe in global warming?

[DR. SCHRAG:] Absolutely. Frankly, I'll show you a picture of the Earth's temperature over the last hundred years, and everybody in this room, it's really not a question of belief. You can actually just observe global warming. The Earth is warming up. I think maybe what you mean is, do I believe that humans releasing carbon dioxide from burning fossil fuels is responsible for that global warming, and the answer is yes. And I'll explain why we think that in a little bit. Any other questions? Yeah, in the back.

16. Q&A: How does water vapor amplify the greenhouse effect? (31:09)

[STUDENT:] Could you elaborate on how water vapor amplifies the greenhouse effect?

[DR. SCHRAG:] Sure. Water vapor, as I said is the most important greenhouse gas in the atmosphere because it's a very powerful... it can absorb infrared radiation very effectively. You all know this when you go to the desert. The nighttime in the desert is really cold if it's a clear night. It gets very, very cold and that's because at night, sun goes away, and in a clear sky the heat escapes to the atmosphere very quickly, and so it can be very cold in the desert at night, unless it's a cloudy night. If it's a cloudy night, those clouds actually absorb that infrared radiation and cause a warming, so the desert doesn't get as cold at night, and you can see that right away. So the way water vapor works as an amplifier is that, imagine you increase the carbon dioxide concentration, so the Earth warms up a little bit. More water evaporates, you get a little bit more water in the atmosphere as clouds, more clouds form, and you can then get a bigger warming. Okay, so it's really...but it responds on a very short timescale and so it's really an immediate thing. That's why it's an amplifier, not a driver.

17. The Keeling curve shows the increase in CO2 level (32:20)

So let's go back to this question of what is carbon dioxide doing today. Here are measurements of atmospheric carbon dioxide since 1957. This is a famous curve that a man named Charles David Keeling-- we call him Dave-- started measuring in 1957 when it was about 315 parts per million. He died in 2005 when it was about 385 parts per million and today we're very close to 400 parts per million. I don't think we'll be there next year but we'll probably hit there the year after. You can see there are seasonal fluctuations in the carbon dioxide... and this is from Mauna Loa in Hawaii. That's because the Northern hemisphere has lots of land, and in the spring and summer the plants take up carbon dioxide, and in the fall and winter the soils respire carbon dioxide and put it back in the atmosphere, so it's like the whole Earth is actually breathing in and out. But in general it's going up and we know why it's going up, and we'll talk about this later, but it's because we're burning fossil fuels. In fact, the amazing thing is that only about half of the carbon dioxide that we actually put in the air stays in there. Half of it gets taken up by the oceans and by plants on land.

18. Modern CO2 levels are increasing at a very high rate (33:34)

So I like to think about this, the Keeling curve, I like to think about it in a longer period of geologic time, so to me it's important not just to see the recent rise but to see it in the context of Earth history and again, if you look at the rate of change, and the rate is critical, it looks like the de-glaciation from 20,000 years to about 10,000 years looks pretty fast. But in fact 10,000 years is 100 times slower than what we've done over the last 150 years or so, where we've gone from the preindustrial level of 280 parts per million up to almost 400 parts per million today. And what's interesting is, almost without question, by the middle of the century we will be at around

500 parts per million. That, I guarantee you. The big question is, will we go much higher than that? Are we going to slow down our use of fossil fuels so that we actually stay around 5 or 600 parts per million, or are we going to shoot through that and go to 800 or 1,000 or 1,200, which really starts to go through the next floor.

19. Some of the emitted CO2 will stay in the atmosphere for a long time (34:43)

Now, in thinking about this we have to think about what is it that causes this, and we have to learn a little bit about the carbon cycle. I want to give you a sense of what's really going on here. As I said, only about half of the carbon dioxide we put in the air stays there and that's good news. The Earth's system gives us a little bit of a cushion. It takes about half of the pollution we put in the air and removes it. Now one question you might as is well, okay we're putting carbon dioxide into the atmosphere, it turns out today we're emitting about 10 billion tons of carbon, so all of the numbers on here are in units of about billions of tons of carbon so they're very large numbers. And today we're burning in fossil fuels about 10 billion tons of carbon per year. And you can see that's pretty small compared to photosynthesis on land, which is about 110 billion tons of carbon per year, or air/sea gas exchange of carbon dioxide which is almost a hundred gigatons, a hundred billion tons a year. The reason it's so problematic, though, is that the system was basically in balance before. What was coming out from respiration was the same as what was going in photosynthesis. What was going into the ocean through dissolution was the same as what was coming out. And we perturbed that system. Now we're adding, we're taking fossil fuels that were buried, carbon that was buried in the Earth for millions of years, and releasing it very, very quickly and the Earth is trying to soak it up. The Earth is trying to take care of it. And on short timescales, like the timescale of a year, like I said, about a quarter of it goes into the land--plants are growing faster--and about a quarter of it is actually being taken up by the ocean. And eventually the ocean will take up about 80% of it. That's good. Unfortunately that will take several thousand years for the oceans to mix and take up all of that carbon dioxide. And we'll still be left with about 20% of it, and how will that last 20%, how will the Earth dispose of that last 20% of carbon dioxide? Anyone? What? It's going to stay in the atmosphere for a long time, but ultimately what will happen, the Earth can take care of it. Yes. Calcium carbonate. Chemical weathering reactions will eventually take that CO2 out of the atmosphere and put it on the ocean floor. The problem is, that will happen over a period of about a hundred thousand years, which in Earth history is really not a big deal. So the Earth will be fine; it's just that we have to live on this planet in the intervening period of time.

20. Projecting CO2 levels for the next century (37:21)

So, here, just to give you a sense of what we're talking about of scenarios for the future. On the left are scenarios for the next hundred years. Again, miniscule period of geologic time but interesting to us, and you see these are a range of different scenarios that scientists use to try to think about the future and the green one is one where by mid-century we succeed in reducing our emissions dramatically, and even decreasing them down by the end of the century. So you could see actually, in 2012 today, we're at 10 billion tons of carbon per year, that is on the very high end of this curve. Right now, we are way above that green curve. On the other hand, that dotted orange line you can see goes way up, almost to 30 billion tons of carbon per year by the end of the century. That would be like we continued to use oil and coal and natural gas as much as possible and we would end up...on the right it shows what would happen to the carbon dioxide in the atmosphere, modeling the ocean and the land, and you can see that in the green case we might succeed at staying a little above 500 parts per million; whereas, in the dotted orange case we end up closer to a thousand parts per million. That's the kind of range. The important thing is we're going to have a lot of climate change no matter what we do. Even if we are successful in reducing emissions, we will still be at 500 parts per million. No human in history... in fact, no hominid species has ever seen anything above even 400 parts per million. So we're actually doing something kind of incredible.

21. Decisions today affect Earth for tens of thousands of years (39:11)

As I said, if you look at longer periods of time, all of that carbon dioxide will go away, so initially over the first few thousand years it'll go into the ocean. There'll be some reactions with limestone on the ocean floor; the ocean will become more acidic. This is the ocean acidification that Andy talked about, and that will continue to react and take up a little bit more carbon. But 10 to 20% of the carbon dioxide will actually be left and only will react through chemical weathering over tens of thousands of years. So here's a kind of freaky way to think about this problem. We're actually making decisions over the next few generations that will affect the Earth for tens of thousands of years. It's kind of a heavy responsibility, but

22. Unprecedented CO2 levels make future climate predictions difficult (39:56)

I think this is-- when we hear Naomi Oreskes talk about uncertainty, this is really important. We're performing an experiment at a planetary scale. It hasn't been done for millions of years. No one knows exactly what is going to happen. Carbon dioxide today is higher than any human has seen it before and we have good models and we can predict what is likely to happen, but I guarantee you we will make mistakes. Now we are seeing a rise in global temperature. This is temperature over the last 120 years or so, and you can see it hasn't gone straight up; it's more complicated than that. It went up until about 1940 and then it plateaued, it even went down a little bit, and then since the mid-70's it's gone up really steeply. But that's because it turns out there are other factors that control the Earth's climate including aerosols in the atmosphere that reflect sunlight. When we burn coal we put sulfur into the atmosphere and that actually makes clouds more reflective and reflects light and cools the climate. Sulfur doesn't last very long. It only last a few days or maybe a few weeks, but it still has a cooling effect, and so it can compensate in the short term for carbon dioxide, and that may have been what was going on in the forties through the seventies. And then you see this very recent rise. But a very reasonable question is well, how do we know this isn't natural? How do you know this is due to the higher carbon dioxide? Sure, carbon dioxide is going up and sure, it's a greenhouse gas, but maybe that's a small effect. Maybe what we're seeing today is just part of some natural cycle. The answer is no. The answer is, we know a lot about natural cycles on the Earth's climate, and this isn't one of them.

23. Glaciers are melting at an unprecedented rate (41:40)

Now there's lots and lots of evidence for this, but my favorite, sort of simple set of observations were done by a wonderful scientist named Lonnie Thompson. This is a picture of him on the left. And Lonnie is really an amazing guy. He looks like a very mild-mannered guy from Columbus, Ohio. If you met him he's a very calm and gentle man, but he actually, he's really Indiana Jones. Seriously. This guy is incredible. What he does is he's a glaciologist but he doesn't study Greenland or Antarctica like any normal glaciologist. He decided he wanted to work on glaciers in the tropics. And so to find glaciers in the tropics you have to go to very high mountains. So he goes up to 22, 24, even 25,000 feet in the tropics and he brings 6 tons of solar powered drilling equipment that he has to carry in by hand and then he spends 2 months at a time camping up on the top of these mountains drilling ice cores through these glaciers. He has spent almost 4 years of his life above 18,000 feet. It's unbelievable what he's accomplished. And so what he does is, he actually has drilled all over the world so, South America, Kilimanjaro and in New Guinea. He also has worked in Tibet. This is a picture of him up 24,000 feet in the Andes looking at core coming out of his solar powered drilling equipment. Here's their solar array that they set up on top of these mountains to power the drill. It's really incredible that he's been able to do this. And what he's observed is the most remarkable evidence that explains, that's really proof, that what we're seeing today is not just part of some natural cycle. Here's an example. This is Huascaran, part of the Quelccaya ice sheet in Peru, right on the equator and he took this picture in the late 70's, in 1977, and on the right he went back to the exact same spot but the glacier had melted all the way back. Moreover you see these bands here on the left. What he observed were, these were actually annual layers because, once a year they get a dustier season, a drier season and they get dust, so you can see these layers beautifully in the ice. And through his ice core he could actually show that, for over 1,500 years you could count these layers back. And when he returned to drill another ice core he discovered that this glacier was melting and that the banding was destroyed by melt water, which proves that this hasn't happened for at least 1,500 years, and he can actually show now that glaciers are melting all over the tropics and it hasn't happened for many thousands of years. So this is really good proof that what we're seeing today is not some kind of natural cycle. We're really seeing something remarkable, coincident with the rise in CO2 and the human consumption of fossil fuels. Now, what's going to happen?

24. Predicted consequences of rising CO2 levels (44:40)

As I said, nobody knows exactly what's going to happen, but you can look at some of the predictions and say that we're kind of in a little bit of trouble. And the reason is that we're adapted to the current climate. And so, you know, the Eocene might have been a very nice climate to live in; we would have been very happy with palm trees in Wyoming. It's just that we're kind of adapted to the current climate, that's what we're used to. The models tell us that impacts are going to be severe, we'll have droughts and heat waves and floods and storms, sea level rise and I've talked about some of these, but mountain snowmelt is something that we often don't think about enough. Mountains are actually our natural reservoirs. They store our water for us in the western U.S. and actually in Asia they're very important. Snow falls on the mountains in the wintertime and then melts slowly throughout the rest of the year. I'm not talking about big glaciers; I'm just talking about snowpack. So if you're from California, for example, you know that the Sierra Nevadas in California are the natural reservoir for California. All of the agriculture in California depends on the snowmelt that happens throughout the summer. And what's going to happen is that snow is going to melt earlier and earlier in the year and by the mid-summer, by the end of the century, that snow is going to either be gone or it melted so much that those rivers are flowing at a trickle. This is a really big challenge for agriculture going forward.

25. Climatological data confirms temperatures are rising (46:00)

What about heat waves? Well, we had a really big heat wave this past year. Do people remember the March weather? It was really nice, wasn't it? Early end of winter. It was incredible in the Midwest, actually. This is a map showing the temperature above normal and in the middle of March this was...meteorologists, people who study the atmosphere were scratching their heads. We were talking in the hallways; "Can you believe what we're seeing?" Twenty-five degrees Fahrenheit above normal. In Rochester, Minnesota the overnight low temperature which is usually about 20 or 30 degrees lower than the daytime high actually set the record for the all-time highest temperature. Of course, the daytime was even higher. So, this just doesn't happen. In Chicago you had eight 80-degree days in the middle of March. The previous record was like around 70. And in St. John, New Brunswick, this is up in Canada, March 22nd, I love this, it set the record for any day ever in April. So this was an incredible heat wave. Probably a one in a thousand year event. So if you had to look back at the historical record you'd say, this should happen once ever thousand years. The problem is we've been seeing more and more of these extreme heat waves. You know, the one-in-a-thousand year event is becoming the one-in-fifty year event. Let me give you another example of this. The March heat wave was kind of a nice break for us. Ecologically this was bad for things like maple syrup and a lot of pollination; apples, it was a bad year. But if we look at the heat wave in Europe in the summer of 2003, this was really a big deal. What you see here, this is the distribution of summer temperatures, average summer temperatures for the last hundred years, from 1900 to 2006, and the one on the far right, that's the 2003 summer. I was in Italy that summer. It was scorching hot; really unpleasant. Fifteen thousand people died prematurely in France that summer. It was a really big deal. They lost about 30% of their harvest because crop yield depends on temperature. When the temperature goes above a certain threshold, crop yields begin to drop. And this is what a model predicts. Again, it's just a model and it might be wrong, but this is what a model predicts that climate is going to be like by the end of the century. And you can see that that 2003 heat wave in Europe is now like the average summer. Now, humans are adaptable; we'll be able to deal with this. But it's not going to be pleasant. You guys know what really miserable summer heat is like here in Maryland, and as I said, as temperatures go up, one of the ways we're going to have to struggle to adapt is with agriculture. Our current agricultural systems are incredibly productive, but as temperature goes above a threshold, which is around 29 degrees Celsius, yields start to crash. We saw that this summer. We had a drought and heat wave this summer throughout the U.S., and corn and soybean harvests plummeted. We had record high corn prices because the corn harvest failed in many parts of the country. So, I think the most important thing is yes, we're going to have all these impacts, but I guarantee you there will be surprises. Whatever we do there will be surprises because we can't predict the future perfectly. Now some people take comfort in that. They say "Oh, maybe the scientists are wrong and climate change won't be so bad." And you know what? That's possible. Unfortunately, in my experience, scientists are actually pretty conservative. We actually believe in being 95% confident before we actually like to tell you something is true. And so in general we're likely to be wrong in the wrong direction, that is, most of the surprises are going to be bad ones.

26. Animation: Dramatic Retreat of Arctic Sea Ice in 2012 (50:05)

Here's a surprise I want to show you. Let's go to the video here. This is a picture of Arctic sea ice. So this is looking at what happened this summer as sea ice began to retreat. Another surprise: in 2007 we were really shocked by the retreat of sea ice and this year by mid-September this is what the sea ice looked like. If you know the history of the Arctic, this is incredible. So here's that same distribution of sea ice in mid-September and you can see the yellow line, that's what the average was from 1979 to today. The two regions I want you to notice: one is the Northwest Passage.

27. Arctic sea lanes are now unfrozen and open (50:28)

If you look at the history of exploration: Amundsen, the great Norwegian explorer who was the first person to the South Pole, he actually took three years to get through the Northwest Passage. He had to spend three winters with the Inuit, stuck in ice. This year we could have gone in a little sailboat in a week or two through the Northwest Passage. The Northeast Passage is even more incredible because that was never open before 2010. You couldn't get from the Atlantic to the Pacific around Russia. And now, not only is it open, it's wide open. In the next two decades we might actually see an ice-free Arctic: really quite incredible. Okay. A lot of other things going on.

28. Melting of Greenland and Anarctica (51:27)

We're seeing melting of ice on Greenland. Here is a picture of Greenland from a satellite and this is actually one of the things that Naomi Oreskes was talking about. This is a gravity anomaly. This is actually a satellite that measures the gravitational field of the Earth and essentially what it's measuring is the mass of ice on Greenland. And as Greenland ice melts and loses mass and dumps it into the ocean, the gravitational field of that ice decreases, and you see a negative gravity anomaly. That's what's showing here. And this measures the ice melt, and we can see that in both Antarctica and Greenland, ice has been melting. It's a lot of ice, you know, a few hundred billion tons of ice, it sounds like a lot. The good news is, it's not that much. It's a little less than a millimeter of sea level rise per year, so ten centimeters over a century. That's not so bad. But this summer we also had another surprise because we actually saw for the first time the entire surface of Greenland was melting. And so while it's not melting, Greenland isn't melting that fast today, only about ten centimeters over the century if we assume it's going to stay the same, it's not staying the same. It's accelerating and we don't really understand how the Greenland ice sheet works well enough to make good predictions of what's going to happen in the future. Could it really accelerate to be a catastrophic rise in sea level? We don't know. And there's another problem in Antarctica as well where we might lose ice in the Ross Ice Shelf and this could cause problems as well.

29. Consequences of dramatically rising oceans (52:58)

What would happen if you actually lost a lot of ice from Greenland? Say you lost half of the Greenland ice sheet. Greenland has about seven meters equivalent of sea level, so let's imagine sea level went up 3-1/2 meters or a little more than 10 feet. This is...you see New Orleans you see Miami; this is what actually happens to the U.S. with 3-1/2 meters of sea level. Look at that again. So all that money we spent to rebuild New Orleans...underwater, below sea level, with sea level rise, it's going to make it sort of silly. Here's New York City. This is where I grew up. You can see Hoboken, it was hit hard by hurricane Sandy, lower Manhattan. This is what it looks like today, that's what it looks like with 3-1/2 meters of sea level rise. So, you know, the famous song "the Bronx is up and the Battery is down," literally. And so let me end here with this picture of Sandy because people are arguing about whether Sandy was caused by climate change or not. I think the important thing about Hurricane Sandy is it reminds us of how vulnerable we are to weather-related damage and it's a reminder of how we're going to have to deal with some of these problems even more as climate changes in the future.

30. Q&A: Response to doubt about anthropogenic climate change? (54:18)

I'll stop there for a minute and take some more questions. Yeah, in the back.

[STUDENT:]In a quick conversational setting when you don't have 90 minutes to explain something, what is the best response to someone who expresses doubt in anthropogenic climate change?

[DR. SCHRAG:] That's a really good question and hard to answer quickly. The first thing I'd like to do is just remind them of some of the things I've already showed you, that carbon dioxide is rising, that we know why it's rising, there's no mystery about that, that it's higher than it's ever been in the last at least 650,000 years, if not several million years, and that there's a lot of uncertainty, but that all of the evidence suggests that the Earth should be warming. It's amazing how looking at that graph of the ice age cycle of carbon dioxide, and then the recent rise, a lot of people aren't even aware of that and they are very impressed of that. But it's a longer discussion of how you deal with different types, because there are many different types of climate deniers. Sometimes they're called skeptics, and I think that's actually a bad word, because some of them are not skeptical. Skeptical means that you... you may be skeptical but you have an open mind. And many of the climate deniers don't really have an open mind. They've already made up their mind. They're not really open to being convinced. So you have to quickly figure out if it's somebody who needs education, or if it's somebody whose mind is made up, in which case, it's very difficult.

31. Q&A: Is there concern regarding water vapor from hydrogen cars? (55:42)

Other questions. Over there.

[STUDENT:] One of the ways that I know that a lot of people are seeing cutting back on carbon dioxide emissions is creating hydrogen cars but hydrogen cars emit only water vapor and you were saying that water vapor is actually a very important greenhouse gas. So while it would be good to switch over to hydrogen cars because you don't have nitrites and sulfur and that kind of stuff going into the atmosphere, would switching to hydrogen really be good for the atmosphere?

[DR. SCHRAG:] So in the next segment we're going to talk about energy technology and solutions, and so we'll get there, but the simple answer is, if hydrogen cars ever actually made it to the market in an economical way, and right now I think they're... that's unlikely, but if they were technologically and economically feasible we don't have to worry about the greenhouse gas effects from putting more water vapor in the atmosphere. The reason is, as I said, water vapor is cycling through the atmosphere all the time. Remember, most of the Earth's surface is covered by water and so water is always evaporating and always precipitating as rain or snow. And so that cycle is happening all the time so adding more...you know, when we boil water and put it in the atmosphere, that doesn't make the atmosphere hotter, putting lots of steam in the atmosphere, even though it's a greenhouse gas, because that steam will precipitate out as the next day or a few days later. And so because water cycles so quickly, we actually don't have to worry about adding water as a cause of climate change. It's responding to the carbon dioxide not driving it.

32. Q&A: How can agriculture adjust to rising temperatures? (57:20)

Let's call on someone, here, in the front row.

[STUDENT:] What are some adaptations that agricultural business will have to make in order to survive the increase in temperature?

[DR. SCHRAG:] That's a really interesting question. I just wrote a big report for President Obama on what agriculture and the U.S. Department of Agriculture will have to do to think about what we call agricultural preparedness. And it's a very difficult challenge because right now there is a huge race going on in biotechnology to try to design crops that can withstand higher summer temperatures and water stress during period of drought. And here's the interesting question, this is a little bit philosophical, but it's a very interesting scientific debate right now: there are geneticists, plant biologists, and in fact, the Howard Hughes Medical Institute is actually for the first time funding a series of investigators in plant biology that's really important, but basically, there's an argument that the geneticists think they can design plants that can grow in very hot or very dry conditions. There are people who study plants, plant physiologists, who think that this is nonsense, that natural selection for 400 million years has tried to make plants that could grow in hot and dry places. So that, you know, there are plants bordering the desert. If plants could figure out a way to grow in hot and dry climates, they would have done so, and you would have plants covering the Sahara. It doesn't really look like that. So there's a big question about whether genetic engineering can design things that evolution couldn't do, even though it tried very hard. We've seen amazing things from biotechnology but usually in areas where evolution never had a good reason to do it. Suddenly we're asking genetics to design things that nature couldn't do on its own, even though it tried hard and it's a question of whether we'll succeed.

33. Global climate change: Mitigation and adaptation (59:17)

Okay, let's take up with where we left off. Here's a picture of Hurricane Sandy. You can still see the devastation in the New Jersey shore. New York City, where I grew up, my brother had to leave his house, his apartment for a while because he was without power. It's going to be a while before New York City is back to normal. And that was just one hurricane. And it really brings up the question of mitigation versus adaptation. What I showed you in the carbon scenarios of emissions and carbon dioxide is that no matter what we do, even if we are really successful in reducing our use of fossil fuel, we're still going to have a lot of climate change. We might keep it to only 500 parts per million, but 500 parts per million might actually be kind of extreme; we don't know. Things are changing now at almost 400 parts per million. What will 500 parts per million be? That's the best we're going to do. Now, we can talk about what a solution is. Over the next hundred years we have to eliminate globally the emissions of fossil fuels. The world's still going to experience massive climate change but we might avoid the worst catastrophes you could think of. It's not a very rosy picture. It's kind of a depressing subject to talk about, but this is the truth. If we actually look at the science of the carbon cycle and of the climate system, this is... we have to understand that this is what we're up against. And in some ways it's really not a choice between mitigation or adaptation. In climate the way we use the word mitigation is ultimately reducing fossil fuels, reducing the cause of the warming. Whereas, adaptation is, how do we respond to the warming so that we minimize the impacts.

34. Adapting to sea level rise: A consequence of climate change (61:07)

Let me show you a few examples of adaptation. This is in London. This is called the Thames barrier. The Thames, which runs through the city of London, is a tidal river, and they're worried about more and more flooding as sea level rises and as storm surge increases.

And so they've built this barrier to protect the city of London in case of flooding. They thought they would use it a few times a decade, they now use it several times a year, and they're talking about building another system a little further upstream that will protect it even more. This is an expensive project. This cost England a few billion dollars and it would cost a lot more if they built it today. Another nice example, something that's not driven by climate change but the fact that their land is subsiding, is the Netherlands. You can see in red how much of the Netherlands is actually below sea level like New Orleans, and just like New Orleans this isn't climate change causing this. This is because the ground is slowly subsiding. And for centuries the Dutch have been very good at engineering solutions; building dikes and sea walls to protect their land from flooding from the ocean. And you can see here, this is an example of one of these Dutch structures. This is not cheap to build. This is a very expensive investment, but if you're in the Netherlands, this is a very important investment, because it keeps the ocean from covering the land. And then here is what we do in New Orleans, which is not quite on the same engineering scale as the Dutch. This is right after Hurricane Katrina and you know this would actually be more funny if this wasn't true. The truth is that there were 400,000 people who weren't able to evacuate when Hurricane Katrina actually missed New Orleans and hit Mississippi. If Katrina had made a direct hit on New Orleans the storm surge would have been, they thought, 15 to 20 feet...these walls would have been completely overrun and you would have seen 400,000 people in danger because the city would have flooded in 10 minutes instead of flooding over a period of about 24 hours which is what happened. So we only had 3,000 people die in

Hurricane Katrina in New Orleans. It could have been 100,000 people. I really think it shouldn't be mitigation versus adaptation. I think we have to be talking about mitigation AND adaptation. We need to adapt to climate change. So we're talking about that now in New York City. Mayor Bloomberg is saying, do we want to build sea walls? Do we want to build oyster beds to soften the storm surge? I actually think another type of adaptation is called resilience, which means the ability to recover from damage. So instead of sea walls, you might think of putting a lot of pumps in the subway system. So you know, say, hey, the subway is going to flood every now and then, but let's make sure we can pump it out really quickly so we can recover from it.

35. Sources of energy over the last 200 years (64:14)

But it's not a choice and the reason is if you don't mitigate, the climate system gets a little bit out of control, if we go to a thousand or 1,200 or 1,500 parts per million, at some point the melting of ice, the rising of sea level, the heat waves, they become so extreme that it becomes impossible to adapt. We have to do both; we have to mitigate and we have to adapt because whatever happens we're going to deal with climate change. Now let's talk about the mitigation side. How do we actually fix the problem? Here is a picture of energy use for the last 200 years for the whole world. It's a very interesting figure. In fact, you could say that this picture is really the history of the industrial world. Two hundred years ago the world got most of its energy from biomass. That's basically wood. We burned wood. That's how we got energy. And it was still the dominant form even through 1900 when coal started to really grow, and you can see the growth of coal and then oil and then natural gas, hydro, nuclear...you see hydro in the blue field, there's a little plus next to it? Included with hydro there are the other renewables, wind, solar, geothermal-- they aren't on here. And the reason is if they had their own little field, it would be thinner than the lines dividing these colors. We're just now getting to about 1% of wind in the world energy system. So we are very hopeful but we have a long way to go. This is what the world looks like today and hopefully the next hundred years will look totally different but we have to remember that most of our energy comes from fossil fuels. I want to show you this next figure because it's a funny cartoon. It's from 1861, and it's a picture of the whales celebrating the discovery of oil. This is just to remind us that there is different perspectives on energy transitions. We are hopeful, for example, that we can go to renewables and replace fossil fuels, but every energy choice has consequences. In this case the discovery of oil probably saved the whales. We were getting our oil from whale flesh. Think about that. So when we think about these energy transitions, it's really a challenge, and we've talked about what this challenge is. It's a really difficult job to actually get rid of fossil fuels that make over 80% of our energy today.

36. Three ways to reduce CO2 emissions (66:43)

Now there are three ways to reduce carbon dioxide emissions from fossil fuels. There are only three ways. Here they are. One is you can use less energy. In context, that means either more efficiency or more conservation. The way I think about efficiency is, putting more insulation in your house, or conservation is, turning your thermostat down in the wintertime and putting on a sweater, right? Either way it has the same result. You're using less energy and so you're burning less fossil fuel. The second is non-fossil energy and that would be renewables like wind and solar and hydro, but also nuclear power, because that also doesn't use fossil fuel, it doesn't produce carbon dioxide emissions. Some people have other issues with nuclear, but in terms of reducing CO2 emissions it is certainly on the list. And then the last method is one that's a little more controversial but it turns out that it's going to be essential, and that is burning fossil fuel but taking the carbon dioxide emissions, instead of putting them in the atmosphere, capturing them and injecting them into an underground reservoir, a large underground reservoir where it will actually stay there for millions of years. So it turns out when you analyze carefully possible ways of actually getting to a very low carbon economy, it turns out that we know that we're going to need all three of these. I believe that it's impossible to conceive of a future where all three of these aren't going to be necessary. What we don't know in 2012 is exactly how much of each one we're going to need, but in some ways that's really irrelevant in 2012. This is going to be a very long, hard transition and what we need to do today is work on all three of these. And then let the market decide which is the most economical, which ones do people want the most, and figure it out.

37. Energy use reduction through efficiency (68:29)

Let me show you some quick examples. Hopefully this will give you a little bit of hope that we might actually accomplish this. This is a graph showing the annual electricity use per person in California compared with the rest of the United States. You can see that since about 1970, the United States has continued to use more and more electricity per person, whereas California has been pretty flat. There are a number reasons why this has happened, but one of the reasons is that California has very strict codes about what kind of appliances you can buy, what air conditioners you could use. This is kind of good news for the rest of us. It means that if we actually were to use better air conditioners, use better refrigerators, we might actually be able to reduce our electricity consumption a lot. Right, so a lot of this is going to come from being more efficient and not wasting as much energy. That's a big part of this.

38. Solar and wind energy: Successes and challenges (69:27)

So then there's non-fossil energy. Here's a big solar field. Solar has been getting much cheaper, as has wind. This is windmills in Denmark which was the largest percentage of wind anywhere in the world, 20% wind on the grid. The really cool story of the last few years is this. This is Iowa. Iowa is now 20% wind electricity. It's kind of interesting. Farmers decided this was really great. They'd make money by putting windmills on their farms and they could still farm. This is very exciting. Of course, the challenge with so much wind and solar is that you have to manage its intermittency. What that means is it's not always sunny or windy when you want to use the electricity. So we have to find a way to store electricity and that's very expensive.
Currently the way Denmark does it is they turn to their neighbor Norway and they store it in a big hydroelectric dam. Basically when there's lots of wind and sun and people don't need electricity they literally pump water uphill and put it back in the reservoir and then when they need the electricity they open the hydroelectric power and let the water flow out.
It's a very crude but very simple way of storing electricity and one of the less expensive ways. Batteries are ferociously expensive.

39. Cheap natural gas competes with clean energy (70:48)

Now the good news is this: this is a graph showing the price of photovoltaic electricity, solar photovoltaic electricity over time. You can see that it was almost $5 a kilowatt hour back in the late seventies and today... you know, this is an old slide, it's actually closer to $0.10 now. Ten cents a kilowatt hour and you can see this line saying "retail natural gas electricity," a little bit below $0.20. The problem is that's the way it used to be. That was about five years ago. What's happened in the last five years is something kind of amazing in the natural gas industry. We had some incredible inventions both in horizontal drilling and the ability to fracture rock so we could now get gas out of gas-rich shale. And what we've seen in the last ten years or so is this incredible rise of gas produced from shale in the U.S. So this is natural gas in trillions of cubic feet of gas and it shows the very rapid production of gas from Texas, from Oklahoma, from Louisiana, from Pennsylvania. The environmental consequences of this are being argued about still, but we're getting a lot of gas from shale now. And the problem is so much gas at a cheaper price makes it more difficult for solar and wind to compete. So now solar is...even though it would have been competitive five years ago, the price of solar has come way down, it's not low enough. It needs to keep going down to compete with cheap natural gas.

40. Mitigation through carbon capture (72:19)

Okay. Let's talk about the last little piece of this, which is carbon capture and storage.
Here are oil, coal, and gas: three major fossil fuels that are more than 80% of our energy. We're not going to get to zero soon. We have trillions of dollars around the world invested in energy infrastructure here. We can't just turn them all off. Think about how important energy is to our lives. All of your electric devices, all of the cars we drive...we're not going to just turn that off overnight. And so what we're going to need, at least in the interim and I would argue in the long-term as well, is being able to burn fossil fuels, capture the carbon, and inject them, either into an old oil field... today economically people want carbon dioxide because they can use it to actually get more oil out, from a greenhouse gas perspective that is a little troubling but as an interim step it's probably fine. In the long run, though, we need to inject it deeper underground into these saline formations where it will stay for millions of years. This is actually being done today. Here's an example from the North Sea. The Sleipner project, the Norwegian oil company Statoil had discovered a very large natural gas deposit that was very rich in carbon dioxide, and they had to separate the carbon dioxide before they could sell the natural gas back to Norway, and they were going to just release the CO2 into the atmosphere. The Norwegian government said uh-oh, if you do that we're going to put a big tax on you. And so they said okay, we'll re-inject it and they've been injecting a million tons of carbon dioxide per year since 1996 beneath the ocean floor. Very safe: wonderful project.

41. Burning coal is dangerous to public health (73:57)

I think the important point, though, is that we're going to have to think about how we deal with coal. Because unlike oil and gas, which even though we're discovering a lot more of it in the U.S., it's still limited on a timescale of the next century. Sometime over the next century oil and gas will both get a lot more expensive because we'll start to run out. Not so with coal. We have a lot of coal and if we burn all of the coal in the world we'll send carbon dioxide in the atmosphere to close to 2,000 parts per million. It will literally be catastrophic. So what do we do? It turns out there's a lot of other reasons for not liking coal. Let me just show you this one.

This is a study that was done in Salt Lake City in the late eighties. What happened was there was a steel plant outside of Salt Lake City that accounted for about a third of the pollution in the Utah valley. You can see on the left, this is a measure of particles in the air, a measure of air pollution, PM-10, that's 10 micron particles, and you can see them drop in the winter of '86-'87. That's because the workers at this factory went on strike. So they shut the factory down for one winter. It was like a little natural experiment that was done. So they shut off the steel mill and bam, the air cleaned up. On the right what you see is hospital admissions for children from asthma, bronchitis, respiratory diseases. Isn't this incredible? I mean, to me it's amazing that people don't know this. We had politicians talking about shutting down the EPA. It was the EPA that was trying to clean up the air. It always seemed to me, why don't people say, you really want sick children, is that what you want? We don't talk about the human health component nearly enough and that's a very important issue.

42. The possibilities and problems of climate engineering (75:41)

Okay. So let's get back to how we're going to solve this. I think the answer in concluding is that it's going to be a great challenge. We have to work now. We have to start now because it's going to take a long time. I think quite honestly stabilizing greenhouse gas levels, either by changing behavior or changing technology, is possible but looks unlikely. Now even the most optimistic target, say we were to try to limit CO2 to 450 parts per million. I told you I don't think that's very credible and I think that's right. I think we'll maybe can do 500, probably more like 600, but even 450 parts per million could be a disaster. We don't really understand the climate system enough to know whether 450 parts per million is safe. It may not be safe. So it remains possible that global efforts are going to fall far short of what's required to prevent massive suffering by many people around the world. So what are we going to do about it? Well, there is one thing on the table that may actually be almost as scary as global warming itself. This is a picture of Pinatubo. This was a big volcanic eruption in the Philippines in 1992. After Pinatubo particles from the eruption went into the stratosphere, the upper part of the atmosphere, and what happened is those particles reflected sunlight, and for the next year the climate cooled by about half a degree until the particles dropped out. So people are now talking about these solutions called geoengineering, where we would essentially do what volcanoes do. We would actually take particles, put them up in the stratosphere and they would reflect sunlight, essentially a sunshade over the planet, to try to compensate for the greenhouse gases. This is not some crazy science fiction. There are many scientists really thinking about this, and more scarily there are politicians really thinking about this. And so this is a climate model, on the left showing what happens when you double carbon dioxide to around 550 parts per million, and on the right it's the same, it's doubled carbon dioxide but what they did is they turned the sun down in brightness. They didn't actually put particles in the stratosphere they just turned the brightness of the sun down a little bit. And you can see it takes away most of the warming effect. It's not perfect. And we still don't know what it would do to a storm or to the monsoon or all sorts of other parts of the climate system but it does help. But I think there's some fundamental questions here. How do we do it? What does it do to the climate system? What might go wrong? Remember we're talking about building an engineering system, that we're now going to engineer the whole climate of the Earth for every living thing on the Earth. This is not something we do lightly. One of the big questions that people don't ask enough is who controls it. We often think when we talk about this is if we could control it, our government would control it. But in fact, what if China decided to do this on their own, or India, or some other country in the world? How would we feel about it if we didn't control it at all? These are very big questions that people will discuss more and more and we need to start having public dialogue about this because it's a serious issue. And here's the scary part of this: as scary as geoengineering is it may be better than that alternative which is just letting climate change happen on its own. That's something very serious to think about.

43. Our responsibility is to be educated and to educate others (79:16)

So again, we have to develop new technology but we may also have to change our behavior. But let's just conclude by saying that this is a problem that you and your generation is going to continue to face throughout your lifetime. This won't be the last time you hear about climate change. What I'd urge you to do as young educated people, whether you're scientists or non-scientists, is to become familiar with the facts and ultimately help your parents, your families, your friends, make good decisions. There are a lot of difficult questions about how we deal with this and ultimately we have to make well-informed, thoughtful decisions. So thank you very much.

44. Q&A: Do our CO2 emissions overpower the weathering thermostat? (80:07)

[DR. SCHRAG:]I think we have time for some questions. First one I saw right in the back, right behind the camera. I can't even see you.

[STUDENT:] I was wondering, is there a magic number of parts per million of carbon dioxide that the thermostat tries to reach, and also, is it possible that our rapid use of fossil fuels will overtake the natural cooling system?

[DR. SCHRAG:] So that's a very good question. Is there... first of all as far as the thermostat, the weathering thermostat that I talked about, there is no fixed temperature. If you put more carbon dioxide into the atmosphere from volcanoes, what the weathering tries to do, is make sure that the rate at which you take it out is the same. So let's imagine we're doing a geological experiment, and we suddenly double the CO2 coming out of volcanoes. What would happen is CO2 would start to go up, and then what would happen to the climate? Well, it would warm, right? And so weathering would start to go faster and faster, and it would keep warming until the amount of carbon dioxide coming out of volcanoes was the same as what was getting converted to calcium carbonate, ok, but it would be at a warmer temperature. So the thermostat doesn't fix the temperature. What it does is it fixes the weathering, so that it balances what's coming out of volcanoes. Okay? It doesn't have a fixed temperature. That's why temperature over history has fluctuated and in some ways you could say that the reason the climate hasn't been too extreme, although I would call the snowball Earth pretty extreme, is that the volcanic release of CO2 hasn't fluctuated wildly. If the release of CO2 had fluctuated wildly, like it probably did early on Mars, we would have much more variability in climate. Now as far as your last part about the thermostat, could we overwhelm it? Well, remember that the thermostat works on timescales of about 100,000 years, so the Earth will take care of anything we can dish out on a 100,000-year timescale. It's just that we have to deal with the next 2,000 years of human history, and so we have a little bit of a challenge in the short-term. In the long run everything will be fine.

45. Q&A: How do warming temperatures increase storm severity? (82:14)

How about another question? Here.

[STUDENT:] How are we, in global warming, how is that causing large thunderstorms and Frankenstorms?

[DR. SCHRAG:] Frakenstorms? Oh. Very simply, let me try to explain to you the way scientists think about this problem. The simple answer is we don't understand it perfectly yet. And so again, there may be surprises. That's part of the deal with climate change. There will be surprises because we don't understand the Earth perfectly; it's a very complex system. But in general, as the Earth warms, the air will hold more moisture. That's just simple physics. Warm air can hold more water vapor than cold air. You all know this. Right? So, as the Earth warms up and the air holds more moisture... a thunderstorm is basically a convective event, where hot warm moist air rises from the surface and as it rises in the atmosphere it cools. And that's why you get these big summer thunderstorms. When I come down to Washington, D.C. I try to avoid flying out of National Airport in the afternoons in the summer because they always get, flights get disrupted by those thunderstorms that come through. Okay? As the Earth warms they will have more power because more rain will come because the air is holding more moisture. It's like a sponge full of water that the atmosphere wrings out and global warming is essentially putting more water in the sponge.

46. Q&A: Could cooling by geoengineering slow weathering? (83:38)

Okay. One more question please. Yes. Somebody I haven't heard from. Yeah.

[FEMALE VOICE:]Um, so, if, say, we go on the geoengineering route and we kind of cool down the Earth but we're not intervening in the carbon cycle, and then the rock weathering slows down because we're cooling it down, and we're still pumping carbon into the atmosphere, wouldn't we just kind of compound the buildup of carbon dioxide, because we have lowered rock weathering, and do we know what the implications of that might be separate from warming?

[DR. SCHRAG:] That's a really good question. I think the key thing, and this is frankly why you need to be a geologist to understand climate change. Too many people are meteorologists and they don't think about timescales. There are different timescales for different processes. And if you think about rates, the rate of weathering and the rate of volcanoes putting out CO_2, is a little less than a tenth of a billion ton of carbon per year, about a hundred million tons of carbon per year. Okay? The rate of burning of fossil fuels is about ten billion tons of carbon per year, so it's a hundred times more. So slowing down the weathering a little bit isn't going to affect... we are so out of that cycle that we are overwhelming it on short timescales. The Earth, again, that little bit, that hundred million tons of carbon per year that it's converting from CO2 to calcium carbonate? It's going to keep going long after humans are around. It's going to go for hundreds of thousands, millions of years, so it's going to keep chugging along. It's like the little engine that could. It eventually will take all the carbon dioxide out of the atmosphere, okay, but it operates on a much longer timescale. It doesn't operate very quickly and so that's really nothing to worry about. I'll tell you one interesting thing, though, just to end, is that one of my graduate students and I, we actually invented a way of trying to do this faster. We said, could you actually take this weathering reaction and speed it up, make it go faster and literally, artificially convert CO2 into limestone? Wouldn't that be great? It turns out, much to our surprise, a company came along and actually wanted to buy the patent from us. It was a crazy idea; we never thought it would work. And they actually raised about $150 million to start a factory to make "green" cement. I was always very skeptical because I thought it was a nice idea but it was never going to be practical, and unfortunately, I would have loved to be wrong, but unfortunately I was right. The company collapsed and a lot of people lost money, but the net result is maybe someday, somebody will figure out how to do this better, and smarter than me, and figure out how to take CO2 and convert it to calcium carbonate in some big factory instead of doing it all over the surface of the Earth, and then we could just scrub the CO2 out of the atmosphere directly. But right now that's prohibitively expensive. Okay. Thank you very much.