**U. of Queensland Climate Denial Course - Lecture 3**

 **Science of Global Warming**

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**0 Introduction**

John Cook - research communication fellow

Welcome to Week 3 of Denial101x. Last week, we looked at all the evidence that global warming is happening. So this week, we ask the question - what’s causing it? We answer that in three parts. Firstly, Gavin Cawley and Andy Skuce examine how carbon moves around our climate system, otherwise known as the carbon cycle. Understanding the carbon cycle helps you understand the effect of humans adding billions of tonnes of carbon dioxide to the atmosphere. Secondly, what’s the effect of adding carbon dioxide to the atmosphere? Well, carbon dioxide is a greenhouse gas which means it traps heat. Mark Richardson and Sarah Green look at the greenhouse effect in more detail. Lastly, if an increased greenhouse effect is causing global warming, then we should expect to see human fingerprints all over our climate. So finally in week 3, Dana Nuccitelli, Mark Richardson and Sarah Green will take us through the observations that scientists have been collecting, looking for human fingerprints that would indicate human-caused global warming. I also interviewed scientists studying the carbon cycle as well as a leading expert in human fingerprinting Ben Santer. He authored the famous statement in the 1995 IPCC report about the balance of evidence suggesting a discernible human influence on global climate.

**1 Upsetting the natural balance**

Gavin Cawley - University of East Anglia

Over the last few centuries, the amount of carbon dioxide, or CO2, in the atmosphere has risen by around 40%. To explain why this is the case, we need to understand how the carbon cycle operates. The carbon cycle describes the flows of carbon between the atmosphere, the oceans and the biosphere. Carbon sources release carbon dioxide into the atmosphere. Carbon sinks absorb carbon dioxide out of the atmosphere. Some of these flows are the result of natural processes. For example, when plants grow, they absorb CO2.

However, human activities also play a part. We release CO2 into the atmosphere when we burn fossil fuels. Land use change, such as deforestation, also releases CO2. Ice cores provide invaluable information on how atmospheric CO2 has changed over time. As the Antarctic ice sheet formed, it trapped small bubbles of air, which stay trapped for thousands of years. Cores drilled deep into the ice show us that prior to the industrial revolution, atmospheric CO2 had been fairly stable for several thousand years. The carbon cycle was in a state of natural balance. Carbon sources were roughly matched by carbon sinks.

Human activity has upset this natural balance. Fossil fuels were formed millions of years ago, from the remains of plants. When these plants died and were buried, their carbon was taken permanently out of the active carbon cycle. When we burn fossil fuels, we release this carbon back into the atmosphere. As a result, CO2 levels have been rising. Scientists became more aware of this after 1958, when accurate measurements of CO2 concentrations were first made at the Mauna Loa observatory in Hawaii. Together with the ice core record, we see that atmospheric CO2 began to rapidly grow soon after the start of the industrial revolution. It would be a bit of a coincidence if this were a natural phenomenon!

Furthermore, the increase in atmospheric CO2 has closely tracked the amount of CO2 we’ve been releasing. This would be an even greater coincidence, if the rise in atmospheric CO2 were due to natural processes! In fact, the amount of extra CO2 in the air has consistently been only about half of all the CO2 we have released into the air. So the evidence is clear that humans are raising CO2 levels. But not everyone accepts this.

One myth is to argue that because the CO2 that humans release is small compared to the CO2 released by nature, our influence must be negligible. This is incorrect, because it only looks at half of the carbon cycle. It fails to consider that carbon sinks also absorb CO2 from the atmosphere. It’s the difference between total sinks and total sources that governs the rise in atmospheric carbon dioxide.

There’s a simple analogy that demonstrates that the rise in CO2 is caused by humans. Imagine my wife and I share a bank account, which pays no interest and attracts no bank charges. I pay in $1000 per month and take no money out. If the balance rises by only $500, then I know that my wife has taken $500 out more than she has put in. Now I don’t have any direct knowledge of my wife’s transactions. But whether she put in $1,000,000 or only $1 per month, I still know she is taking out $500 more than she puts in. The account obeys the principle of conservation of money.

Likewise, the carbon cycle obeys the principle of conservation of mass, the carbon we release doesn’t just disappear, it must either be removed by natural sinks, or it ends up in the atmosphere. In other words, the change in atmospheric CO2 depends on the difference between the total sources and total from sinks. CO2 levels are rising more slowly than we’re releasing CO2. This means the natural environment must be a net carbon sink; it soaks up carbon, it is taking more CO2 out of the atmosphere than it puts in.

Nature has been a net carbon sink every year, for at least the last fifty years. This fact alone establishes that the increase in atmospheric CO2 is not a natural phenomenon. In fact, nature is actively resisting the rise! I don’t need to know the details of my wife’s transactions to know that she was opposing the rise in our bank balance. In the same way, we don’t need to know exactly the strength of the individual sources and sinks to know that nature is opposing the rise. We only need reliable measurements of atmospheric CO2 and human emissions, which we already have.

The error here is taking an overly-simplistic view of the carbon cycle. In this case, considering only CO2 sources and ignoring CO2 sinks altogether. Scientists have developed complex models in order to understand how carbon moves around our carbon cycle. They have done this for a good reason, as Einstein is often paraphrased, Everything should be made as simple as possible, … but no simpler.

**2 The CO2 rise is man-made**

Andy Skuce - Independent Geoscience Consultant

In the past 150 years, human emissions have put a lot of carbon dioxide in the air. We now measure a concentration of about 400 parts per million. This is about 40% higher than at any time in the past 400,000 years. Of all of the conclusions of modern climate science; this is one of the most reliable. But, despite all of the evidence, some people persist in claiming that the recent rise in carbon dioxide is all natural— for example, they say that instead of it being caused by humans, it all came out of volcanoes. Now, it is quite true that volcanoes emit some carbon dioxide and that—over very long periods of geological time—those small amounts can add up to make a really significant change to the atmosphere. However, over a couple of hundred years, the emissions aren’t large enough to make a difference.

There are two main classes of volcano: there are the ones that erupt under the ocean and the ones that erupt into the air. Both kinds are linked to the goings-on at the boundaries of the tectonic plates and to the upwelling of hot rock from the Earth’s mantle-- the layer below the crust. The undersea volcanoes are by far the more numerous, making up about 90% of the world’s volcanoes, although few of us have ever seen them. These volcanic chains are where new ocean crust is produced. But undersea volcanoes don’t produce very much carbon dioxide—only about 100 million tonnes per year—about the same amount as an average US state emits.

Humans produce about 350 times as much carbon dioxide as the undersea volcanoes do. Carbon dioxide not only gets produced at the ocean ridges; it also gets consumed there. What happens is that the newly formed basaltic rock undergoes chemical changes when it contacts seawater. This reaction absorbs carbon dioxide from the water at a rate of about 150 million tonnes per year. The mid-ocean ridge volcanic processes as a whole, therefore, probably consume more carbon dioxide than they emit.

We are much more familiar with the kind of volcanoes that erupt into the air. The biggest chain of these is the famous “Pacific Ring of Fire”. This is a belt running all the way around the ocean from New Zealand to Japan, then to Alaska and down to the Andes. Old oceanic crust is consumed at these places and they form volcanoes that produce much more carbon dioxide than the ones under the sea. The magma in these volcanoes comes not just from the Earth’s mantle, but also from the melting of the more carbon- and water-rich rocks in the crust.

One reason these types of volcano tend to be more explosive is because of the larger amount of water vapour and carbon dioxide in their magma. Mount Etna in Sicily is one of the most prolific carbon-dioxide producing volcanoes in the world. It produces about 13 million tonnes per year, but this amount is still only about half as much as what Sicily’s five million people emit from burning fossil fuels. Dormant volcanoes and volcanic lakes together emit as much carbon dioxide as the actively erupting volcanoes do. Altogether, volcanoes that emit carbon dioxide into the air produce much more than undersea volcanoes: about five times as much.

Volcanic rocks on the surface undergo weathering and this chemical process absorbs carbon dioxide out of the air—about 180 million tonnes per year—that’s approximately one-third of the amount put into the air by volcanoes. If we add up all the sources of volcanic carbon dioxide, we get 640 million tonnes per year. Once we subtract the carbon dioxide that the reactions with volcanic rocks consume, we are left with a net 310 million tonnes per year. This last amount is roughly equal to the human emissions from the country of Turkey, that’s less than one percent of all human emissions.

Human emissions for the planet as a whole in 2012 were 60 to 120 times bigger than volcanic emissions. Carbon dioxide emissions from cement-making alone are 3 to 6 times bigger than those from volcanoes. Not only are volcanic emissions much too small to account for the rising carbon dioxide levels in the air, but—over the past few thousand years—natural emissions and natural sinks have been in rough balance.

The carbon dioxide composition of the air started to change really quickly after the 1950s. We can readily explain this as being due to the greatly increased rate of consumption of fossil fuels after the end of the Second World War. On the other hand, if volcanoes had suddenly started to erupt many times faster in the second half of the twentieth century, we surely would have noticed. After all, volcanoes don't just silently produce carbon dioxide, they also throw out huge quantities of ash and magma and they often cause havoc for humans living nearby.

Only about 40% of the carbon dioxide emitted from any source remains in the air, the rest goes into the oceans and is taken up by plants on land. If we add up the carbon dioxide emissions and convert them into concentrations in the air, we see that emissions from humans over the past hundred years fit the observations like a glove, but the volcanoes don’t even come close. People who incorrectly blame volcanoes for the change in the air take the fact that volcanoes do indeed produce some carbon dioxide and then they jump to the false conclusion that this amount is enough to explain the increase we have measured. And they haven’t done the basic arithmetic that shows that it isn’t nearly enough to make any real difference at all in such a short time period. We know what caused the recent rise in carbon dioxide concentrations. We did.

**3 Taking up residence**

Gavin Cawley - University of East Anglia

Fossil fuel emissions have caused atmospheric CO2 levels to rise by around 40% over the last few centuries. But it’s interesting to ask how long would it take for a return back to pre-industrial levels if we stopped emissions tomorrow. To find out, let’s have a closer look at the carbon cycle. Vast amounts of carbon dioxide, or CO2, flow between the atmosphere, oceans and stores of carbon on the land. Each year, the ocean absorbs 80 billion tonnes of carbon from the atmosphere, but only releases 78 billion tonnes back into the atmosphere. Likewise, plants extract around 123 billion tonnes of carbon from the atmosphere each year for photosynthesis, but also release 119 billion tonnes when they die and decay.

So nature emits large amounts of CO2 but it also absorbs large amounts of CO2. They almost match, but not quite. The result is that the natural environment is a net carbon sink. It removes about 6 billion tonnes of CO2 from the atmosphere each year. Nevertheless, an enormous amount of CO2 is constantly moving back and forth between the various parts of the carbon cycle. This vigorous churning does not affect the total amount of CO2 in the atmosphere, but it does have an interesting consequence that is important in understanding the rise and fall of atmospheric CO2.

If we follow the path of an individual CO2 molecule, we find it only remains in the atmosphere for a short time, before being exchanged with a molecule of CO2 from the oceans or land based vegetation. The important thing to notice though is that this is a straight swap and does not affect atmospheric CO2 levels.

This is most easily understood by a simple analogy. Imagine my wife and I share a sweet jar where we keep our jelly beans. At the start of our marriage, my wife had no jelly beans, but I had already stashed away 589 green jelly beans. Each month, my wife put in nine red jelly beans and I put in 198 green jelly beans. However, I also take out 203 jelly beans, selected at random, and I eat them. Now, our sweet jar will rise by four jelly beans a month. This rise is caused by her red jelly beans, because I’m taking more beans out of the jar than I’m putting in. So how long should we expect a red jelly bean to remain in the jar, before I take it out and eat it? It turns out the average time that a single bean stays in the jar is the number of jelly beans in the jar divided by the flow of beans out of the jar.

This is known as the “residence time”, and this turns out to be only about four months. We can also calculate the proportion of red and green jelly beans in the jar as the months pass. It seems counterintuitive, but the number of green jelly beans quickly rises while the number of red beans stays relatively low, even though my wife’s red beans are solely responsible for the rise! This is because my large exchanges of jelly beans are constantly replacing red beans with green ones, even though overall I am taking more jelly beans out than I’m putting in. This analogy provides a simple model of the carbon cycle.

Each red jelly bean represents the release of 1 billion tonnes of carbon from human sources into the atmosphere. Each green jelly beans represents a transfer of 1 billion tonnes between the atmosphere and the natural environment. Even though the rise in atmospheric CO2 is caused by humans, a single molecule of CO2 has a residence time of about four years in the atmosphere. However, we’re not really interested in the fate of a single CO2 molecule. We’re interested in a much more important question: if we add lots of CO2 into the atmosphere, how long does it take to return back to normal?

This is known as the adjustment time and is around 50-200 years. It is governed by the difference between total uptake and total emissions, rather than their individual magnitudes. Since the start of the industrial revolution, we’ve raised CO2 levels by 40%. If we were to stop all fossil fuel use tomorrow, most of this excess CO2 would be taken up over 50 to 200 years. However, a full return to pre-industrial levels would take many thousands of years.

One myth about the carbon cycle is that CO2 has a short residence time, and so CO2 levels would fall rapidly if fossil fuel use were cut. However, this is a red herring. If we’re really interested in how long it would take, it is the adjustment time that matters. And this is not the same thing as the residence time, it is much longer. Even though a single molecule of carbon dioxide only stays in the atmosphere for around 4 years, it will actually take the atmosphere between hundreds to thousands of years to return back to the normal after we stop releasing CO2.

**4 From the experts : carbon cycle**

Joanna House - University of Bristol, Corinne Le Quéré, Professor Tim Osborn, Professor Dan Lunt, Professor Lonnie Thompson, Professor Pierre Friedlingstein and Professor Mauri Pelto

House: The carbon cycle is, very simply, it's about the cycling of carbon through natural

systems - through plants, through soils, through the ocean - and back out into the atmosphere.

Le Quéré: In the natural carbon cycle, there's a lot of fluxes of carbon dioxide, so the carbon goes in and out of the ocean, in and out of the terrestrial biosphere every year. House: The carbon is constantly flowing between these different systems and large amounts of carbon moves all the time.

Le Quéré: I mean in the terrestrial biosphere, in the trees and the forests, it's very easy to see. If you live in a place that has a forest area with seasons, you see in the winter the trees they have no leaves, and the spring comes and the leaves build up. This is all good carbon dioxide that goes in the leaves. And in the fall and in the autumn when the leaves fall down then their carbon is emitted back in the atmosphere. So you have a huge signal there of CO2 going in and out of the atmosphere.

House: So the ocean will take up the CO2, it dissolves in the surface of the ocean and

also when the ocean will release CO2 to the atmosphere and that depends on the concentration of CO2 in the atmosphere and the concentration of CO2 in the ocean. And they form a balance with each other. There's a continuous massive exchange of carbon dioxide between the atmosphere on land and the atmosphere on the ocean. That is roughly in balance until we introduce human change.

Osborn: The experiment that we're inadvertently perhaps conducting with the climate system is to move huge volumes of carbon from these stores undergrounds in the form of fossil fuels and bringing them to the surface and burning them and adding this carbon to the atmosphere.

Le Quéré: What we're doing now is putting everything out of balance, so we're adding carbon to the atmosphere. It's new carbon. It's not part of the natural cycle. It's one that we've dug out of the fossil reservoir where they were stored, and we've put them back in the atmosphere. This is new carbon, and it puts the system out of balance.

House: Although the human emissions are much smaller than the natural fluxes, the natural fluxes approximately are in balance and so they're not causing an increase of carbon dioxide in the atmosphere. The human emissions, however are very rapid, and the natural systems don't have time to respond to them. And so you get a net imbalance of raised carbon dioxide concentrations in the atmosphere.

Lunt: It's unequivocal that the amount of carbon dioxide in the atmosphere is increasing

and is increasing fast and is increasing faster than ever.

House: Oh the rate of change now is incredibly rapid, and what's more it's pushed us outside the bounds of what we've seen in terms of atmospheric concentration throughout the Ice Ages.

Thompson: We have not had levels of C02 at 400 parts per million by volume in 800,000 years of history.

House: In the Earth's past throughout in and out of the Ice Ages, the concentration of

CO2 in the atmosphere ranged between about 180 parts per million to 280 parts per mission. And it took thousands of year for it to change between those states. The difference is now it's gone up to 350 and even topping 400 parts per million on a single day basis. And that's happened over a period of a couple hundred years.

Friedlingstein: Every single generation is emitting more than the previous generation

because emission of CO2 increased exponentially. We emit it so far, if you start from the beginning, which is like the industrial revolution in 1750 or something, when we start to burn fossil fuel, from that time up until today we emitted something like 2000 gigaton of CO2. More than half of this has been emitted over the last 50 years.

Thompson: And we know where that CO2 is coming from because we do the isotopes of the carbon. We know it's coming from fossil fuels.

Le Quéré: So carbon is increasing in the atmosphere, but it doesn't entirely stay there, so about half of the emission and maybe a bit more than half of the emission that we put in the atmosphere ends up in the natural environment. It ends up in the ocean and in the forest.

Friedlingstein: The carbon cycle today absorbs about half of the emissions we put

in the atmosphere, so we emit, as I said, 40 gigaton of CO2 per year, about half of it, 20 gigaton of CO2 are taken back from the atmosphere by the land and by the ocean. House: There's a multitude of different processes that remove carbon dioxide from the atmosphere. So for example, CO2 from the atmosphere dissolves in the surface of the ocean and then that's turned over and taken into the deep ocean. Really for that amount of CO2 to be completely removed from the atmosphere it has to be completely dissolved and go down into the deep ocean. And then we're talking about geological timescales - so hundreds and thousands of years.

Le Quéré: So what happens when we put carbon emissions into the atmosphere, new carbon from burning fossil fuel or from different station, what happens is this takes a long time for this carbon to readjust in the land and ocean. Eventually if we're prepared to wait long enough, so that's thousands of years, a lot of this carbon, maybe 70 percent will end up in the ocean, and the reason this takes time is that you have different adjustment times, so the CO2 goes in the surface ocean, it takes about 1 year to dissolve. But how it is transported from the ocean's surface to the intermediate and to the deep ocean depends on the ocean circulation. The ocean circulation takes hundreds to a thousand years to mix the entire ocean. That's the timescale that is really relevant here is taking a molecule of CO2, we've put it in the atmosphere, how long is it going to take before it ends in the deep ocean?

House: So about 65 to 80 percent of the carbon dioxide pulse that's put into the atmosphere will be removed within about 2 to 200 years. The rest of it, the remaining 35 percent, will take between 2 and 20 millennia to be completely removed from the atmosphere. So roughly you have to think whatever we're doing today, whatever CO2 is being emitted, roughly a third of it is going to stick around essentially forever really when you consider it in our lifetime.

Pelto: We can't change the atmosphere, the chemistry, with one of the main constituents carbon dioxide by 25 percent and expect nothing to happen. You change your diet by 25 percent. You decide you're going to start consuming 25 percent more calories, and you don't change your exercise or anything else. You can't realistically expect nothing to happen. And that's what you have to understand. If we change fundamentally our atmosphere chemistry, we can't expect climate to stay the same.

**5 The Greenhouse effect**

Mark Richardson - NASA JPL/Cal tech

They say it all started with a Big Bang, and white noise on an old TV helps to show that. That white noise reaches us in the same way that the heat causing global warming does. This heat comes from the greenhouse effect. What do the Big Bang and the greenhouse effect have in common? We’ll talk about the link later, but let’s start with just the greenhouse effect. It is measured every day by instruments like these. And if we look at our nearest neighbour, we can see what it’s capable of. Venus has big thick clouds so less sunlight reaches its surface then reaches ours. But its atmosphere is about 95% carbon dioxide. This causes a superpowered greenhouse effect. At the surface, it’s hot enough to melt lead.

How can a simple gas like carbon dioxide be so powerful? The greenhouse effect works like this. We see the Sun on a clear day because the gases in our sky are transparent. The Sun's rays get to Earth's surface and warm us up, because light is a form of heat. This heat has to go somewhere or we'd just get hotter and hotter. Earth glows with infrared, a form of light that’s invisible to the human eye. Greenhouse gases let through visible light from the Sun, but absorb this infrared. They slow down its escape and keep Earth warmer.

We know how to slow down the escape of heat to keep ourselves warmer. It's called a blanket. Even though the blanket itself doesn’t give off heat, we still put one on to keep warm. The infrared heat given off by Earth is invisible to the human eye, but we can see it with this infrared camera. Let’s look at an example with a cup of cold water and a cup of hot water. If we look at them, we can’t see which one is hot. But the camera shows that hot water glows more brightly in the infrared than cold water. A similar thing happens in the atmosphere.

Greenhouse gases are special because they absorb infrared. But they also glow in the infrared. The glow from the Earth's surface goes upwards. Greenhouse gases absorb some of this heat. Then they glow in every direction, including down towards us. This recycled heat is how the greenhouse effect warms us. We measure it every day here, at the Reading University atmospheric observatory. This is a pyrgeometer. It has a special 'window' that only allows infrared light through to be measured. Even during a cloudless night, it measures the constant, warming, greenhouse glow.

Even though the greenhouse effect is an observed fact, there is a myth that claims it doesn’t exist. This myth misinterprets a law of physics called the ‘Second Law of Thermodynamics’. This law says that, even though heat moves in both directions, overall, heat flows from hot to cold and not from cold to hot. The myth says that the greenhouse effect doesn’t exist, because it would require heat going from the cooler sky to the warmer surface. This is a misrepresentation.

The greenhouse effect obeys the law. A square metre of Earth's surface sends 500 Watts upwards. So it works like a ~500 Watt heater. The greenhouse effect sends back down about 330 Watts of heat. In total, 170 watts goes from the warmer surface to the cooler sky. Heat overall goes from hot to cold, but the greenhouse effect sends some back to warm us up. The myth misrepresents the second law of thermodynamics. Meanwhile, observatories measure the greenhouse effect every day, all over the world. We know it’s there.

And this is where the Big Bang and static on an old TV screen come in. Outer space is very cold, about 270 degrees Celsius below freezing. But a tiny part of that static on the TV screen is the remains of the electronic noise from the Big Bang. This noise contains energy, it's heat. So despite being unbelievably cold, some heat flows from frigid outer space to a balmy living room. Earth sends a lot more heat into space than the other way round, so thermodynamics is safe. Even though we can't see it, we live under the faint glow of the Big Bang, and the much bigger glow of the greenhouse effect. This keeps us much warmer than we'd otherwise be.

**6 Re-enforcing feedback**

Sarah Green - Michigan Technological University

Do sparks cause fires or do fires cause sparks? This is a difficult question because both statements are true. Questions involving cause and effect can be tricky, and this is true in discussions of climate change, as well. In order to understand major climate changes, such as ice ages, studying past climates through the ice core record can help scientists identify causes and effects more clearly.

The most famous ice core is from Vostok Station in East Antarctica. This core is over 3-kilometer-long, goes back over 400 thousand years, and shows us four different ice ages. Another famous ice core, called EPICA, reaches nearly 800 thousand years back in time. In looking at the core data, we can immediately see that temperature and carbon dioxide have similar patterns. When CO2 levels are high, the Earth is warmer. When CO2 levels are low, the earth is cooler. But correlation is not causation.

Does CO2 cause warming or does warming cause CO2 to increase? In fact, both statements are true. The ice core record tells us that a bit of warming caused CO2 to increase, which, in turn, caused more warming in a reinforcing feedback loop. Confusion about the ice core record has spawned the myth that because warming caused CO2 to rise, CO2 cannot cause warming. This myth is an example of a false dichotomy, also known as a false dilemma. The dilemma is false because it’s not a case of either/or, both can be true.

So how does global warming lead to increased CO2 levels? Consider the following: when water is heated, gases, such as carbon dioxide, are driven out because water can’t hold as much gas when it’s warm. You can check this fact using two cans of soda. When opened, a warm soda will fizz much more than a soda that has been chilled. In the same way, a warmer ocean releases much more carbon dioxide into the air. And the ocean holds a lot of carbon. This release of carbon dioxide creates a feedback mechanism. Warming oceans increase atmospheric carbon dioxide, and carbon dioxide increases global warming.

But how did this feedback loop start? Let’s take a closer look at the end of the last ice age when the Earth warmed up to our current balmy temperatures. That warming started about 20 thousand years ago and took from 7 to 8 thousand years to progress; a relatively short time on geological time scales. When we zoom in on that range in the Vostok core, we can see that Antarctica apparently started warming up before carbon dioxide increased. This observation connects to the myth that temperatures rose before CO2, so CO2 can’t cause warming.

But wait, Antarctica doesn’t represent the whole planet. We have data about the end of the last ice age from other sites. In this figure, Shakun and his colleagues combined all of the available data to create a global picture of temperature and CO2 increase. From their data we can see that the dramatic increase in CO2 (yellow dots) came before most of the warming of the planet (blue line). The temperature increase lags CO2 because so much heat is absorbed by the ocean. Since the oceans are so big, they take hundreds of years to heat up.

This data clearly points the finger at CO2 as the primary cause of global warming, but we still have two questions: What started this feedback loop? and Why did Antarctica warm before the rest of the Earth? These two questions are related, and scientists love to figure out mysteries like these. What they found is that orbital changes started a bit of warming in the northern hemisphere. That heating caused the oceans to start releasing their stored CO2. The CO2 built up slowly at first. Its heat-trapping effect built up too. This feedback loop got stronger as CO2 caused heating and heating caused the oceans to release CO2.

The data tell us that warming was not even over the whole globe. The melting of the massive glaciers in the northern hemisphere changed the ocean circulation and trapped heat in the southern hemisphere. So Antarctica started warming first, while Greenland actually cooled a bit at the same time. Let’s return to the myth that CO2 cannot cause warming because some warming was observed before the major increase in CO2.

This myth is an example of a false dichotomy or false dilemma. The myth can be rephrased as two options: either increased CO2 caused warming OR warming caused increased CO2. A false dilemma makes you believe that there are only two possible options and that one negates the other. But science reveals a third option that allows for both of these statements to be true: an increase in CO2 caused warming AND warming causes an increase in CO2. And the explanation from science is that changes in the Earth’s orbit triggered warming that started the feedback loop that increased both CO2 and warming.

**7 From the experts: The greenhouse effect**

Naomi Oreskes, Dr. Ed Hawkins, Professor Mike Mann, Professor Simon Donner, Professor Richard Alley, Professor Eric Rignot, Professor Jonathon Bamber, Professor Lonnie Thompson.

Oreskes: It's simple. It's basic physics and chemistry. It's physics and chemistry that we have known since the 19th century that Carbon dioxide's a greenhouse gas. That means that it's relatively transparent to visible light but relatively opaque to infrared or make it even simpler: light comes in, heat gets trapped so if you put more carbon dioxide into the atmosphere more heat gets trapped. And sooner or later the earth has to warm up. That's basic physics, and there isn't really any other possibility.

Hawkins: I think what a lot of people don't realize is that the history of climate change

is a very long one. History of climate science it started with Joseph Fourier back in the eighteen twenties.

Mann: Despite what you might have heard this is not new and controversial science. We have known about the greenhouse effect for nearly two centuries. Joseph Fourier, a scientist who's well known for the mathematical technique known as the Fourier series. He is the same scientist who produced the law of heat conduction. He's the guy behind the law that governs how heat moves through substances. He understood that there was a greenhouse effect.

Donner: It's all just basic science. It's physics and chemistry. And the key thing to know is it this isn't some new thing that Al Gore cooked up a few years ago. It's rooted in the basics of physics and chemistry. The experiments on this started two hundred years ago. So yeah you might see some headline that questions some aspect of it in the news you know tomorrow, but that can't affect the core because the core is so grounded in what we know at this point that you'd have to tear up most physics and chemistry textbooks for us to be wrong.

Hawkings: So the next person in the story is John Tyndall who's an Irishman. He did some very careful experiments in London in the eighteen sixties on the absorption of all infrared radiation by various gases He tried lots of different gases. He had normal air and water vapor and carbon dioxide and methane and other hydrocarbons measuring how much infrared radiation is absorbed by these gases and he found that various greenhouse gases as they're now called, carbon dioxide and methane and so on, they absorb infrared radiation in this laboratory experiment and so this is the basis for what we now call the greenhouse effect.

Lewandowsky: Climate science is a hundred and fifty years old. We know that CO2 is a greenhouse gas and if that were false then airplanes would fall out of the sky because the rest of physics would be false.

Hawkins: In the late 1890s we have a Swedish Professor Svante Arrhenius, who is the next person to start investigating this problem and again he was mainly concerned with explaining ice ages: what could cause these large temperature changes in Earth history but also at this time it is becoming realized that the emissions of greenhouse gases from human activity could potentially be changing the composition of the Earth's atmosphere and, therefore, the role of carbon dioxide could be more than just explaining Earth's history.

It could be potentially changing how things change in the future and this is becoming more important in the late 1890s so Svante Arrhenius he went away and again did some very simple relatively simple calculations on what would happen if the amount of carbon dioxide in the atmosphere was doubled, a kind of thought experiment if you like, and he came up with a number around about four degrees or so for the changing global temperature if you double carbon dioxide in the atmosphere. They're the first estimate if you like of what we now call climate sensitivity.

Alley: And the physics behind that causing warming are the same physics that the Air

Force used to put sensors on heat-seeking missiles and in some really fundamental sense if you denied the global warming effect of our CO2 you are claiming the Air Force doesn't know what to put on their heat-seeking missiles. It's absurd.

Hawkins: My scientific hero in this story is an amateur meteorologist called Guy Stewart Callendar, and he was professional steam engineer and that was his day job. But in the evenings and weekends he used to collect temperature measurements from around the world and he was a very avid meteorologist. He took measurements in his back garden and he just enjoyed collecting data from temperatures all over the world. And in the nineteen thirties he started to put together a global average temperature. He put together readings from 150 stations all over the world and averaged them all together to try and get an estimate of what the globe was doing instead of just looking at 1or 2 locations. And what he saw was the earth was warming up over the previous fifty years.

Rignot: The first thing about climate warming is the physical basis we've known it

for centuries. This is nothing new in the science of climate change today. You bring more CO2, more greenhouse gases in the atmosphere, it warms it up. It's undisputable. The rate of emissions was thought to be far too slow to affect global temperatures back in the late eighteen hundreds but by the start of the 20th century the rate emissions had gone up an awful lot and and so it begun to realize that perhaps the rate of human emissions of greenhouse gases could affect the global temperature.

So Callender also collected for the first time the available carbon dioxide measurements and he showed the carbon dioxide in the atmosphere had gone up because of human activity, and he linked that to the rise in temperatures that he saw. And he did again some simple calculations like Arrhenius had done and showed that carbon dioxide could explain about half of the observed temperature rise that he'd see in his data.

Oreskes: And if you read the work that scientists were writing say back in the nineteen fifties and even forties and thirties when they first started worrying about this, this is what almost all them said: well we don't know for sure when this will happen but sooner or later unless we're missing something the earth has got to warm up and guess what? That sooner or later has passed right and here we are

Bamber: Over time the evidence has become more and more overwhelming that we're having a very damaging effect on the climate system because primarily because of our love affair with oil and fossil fuels.

Lewandowsky: We know that fossil fuels have thermal properties, so we know that's gonna warm the planet with further fossil fuel emissions. There's absolutely no doubt about that happening.

Thompson: So the evidence is very clear where we're headed and the fact that the humans are driving it. It's a matter of physics and chemistry and at the end of the day science is about what is and what is is we're changing the climate system.

**8 Structure of the atmosphere**

Mark Richardson - NASA JPL/Cal tech

Climate scientists are like detectives at a crime scene. They want to solve the 'case' of what's causing global warming. They’ve found human fingerprints all over the climate. We call them fingerprints because they’re unique pattern of changes. In one case, we’re changing the very structure of the atmosphere. How are we doing this? When we burn coal, oil and gas we release greenhouse gases and strengthen the greenhouse effect.

Greenhouse gases allow most sunlight to pass through and warm the Earth’s surface. But they absorb infrared light given off by the Earth. Greenhouse gases also have their own infrared glow. This glow goes in all directions, and sends some heat back down to the Earth’s surface. As we release more greenhouse gases, the atmosphere gets better at absorbing infrared. At the same time, the greenhouse infrared glow gets stronger.

Near Earth’s surface, greenhouse gases absorb a bit more of the infrared that passes through the air. The greenhouse glow sends some of this trapped heat back to the surface where it is absorbed again. Heats cycle between the surface and the atmosphere. With more greenhouse gases, more heat gets trapped in this cycle and temperatures rise. High up in the atmosphere, about 20 kilometres and above, we are much closer to space. Outer space barely absorbs or emits infrared at all. There is basically no heat coming from above. Meanwhile, more greenhouse gases boost the greenhouse glow. The extra glow, or heat, that goes upwards can escape.

Above about 20 kilometres, adding greenhouse gases cools the sky. This happens even while the lower atmosphere warms. Scientists predicted this pattern before 1970. Now, satellite measurements confirm this prediction. So what does this pattern look like? Here are two different simulations of warming through the atmosphere. The pictures go from the Earth’s surface at the bottom to space at the top. Red means getting warmer, blue means getting cooler. On the left is what greenhouse warming should look like. There is cooling at the very top and warming everywhere else.

We mentioned greenhouse warming has this unique fingerprint. For example, if the Sun were to get hotter, the pattern of warming would look like the box on the right. Here we see warming at the top of the atmosphere as well as at the bottom. Satellites have measured the cooling in the upper atmosphere. So the pattern that we expect to see from the greenhouse warming has been confirmed.

One myth distorts the fingerprinting evidence. It uses a red herring by focusing on this hot spot, about 6 kilometres up in the tropical atmosphere. Simulations expect this area to warm faster than the surface, but real-world measurements have not yet conclusively proven whether this hot spot exists. The myth says that the lack of conclusive proof of this hot spot casts doubt on greenhouse warming. But this is a red herring because the hot spot is irrelevant to greenhouse warming. It is simulated for natural warming as well as greenhouse warming.

But let’s see why we expect the hot spot to exist. Earth’s surface can cool by sweating. Water evaporates from the surface and it carries heat with it. As it rises, air cools. Cooling with height is called the ‘lapse rate’, and is why it’s colder on the tops of mountains. As moist air rises and cools, some of the water condenses out. If it condenses into big enough blobs, it falls and we call it rain. When it condenses, it dumps the heat that had been carried up by evaporation.

Warming means more evaporation and more rising vapour. When it condenses, it releases its heat. This has the largest effect starting about 6 kilometres up in the tropics. This is where we expect to see the tropical hot spot. This is difficult to measure and it hasn't yet been proven whether it’s there or not. If it’s not there, scientists will have to explain why.

But using the hot spot to cast doubt on greenhouse warming is a red herring. It’s a sign of changing moisture in the tropics, not of greenhouse gas warming. A real fingerprint of greenhouse warming is warming near the surface while the atmosphere above about 20 kilometres height cools. This has already had a spectacular effect. The cooling upper atmosphere has contracted like a balloon in a freezer. Satellites that brush the top of the atmosphere have literally felt it falling away.

**9 Measuring from space**

Sarah Green - Michigan Technological University

One of our strongest pieces of evidence that the Earth is heating up is the balance of energy for our planet. The temperature of any object is a result of the amount of energy going into it and the amount leaving it. When the incoming energy and outgoing energy are balanced, the object reaches a constant temperature. If we turn up the crank and add more energy, the object will heat up, and also emit more heat to its surroundings, until it reaches a new, warmer balance. It’s very much like adding a blanket to block outgoing heat so that an object will warm up.

This same process is true for the whole Earth suspended in space. And physics tells us that CO2 acts like a blanket for the Earth. Satellites now measure both the incoming and outgoing energy for the whole planet so we can measure the effect of our atmospheric blanket. The fact that more energy is coming in than going out must be rather vexing to people who promote the myth that there isn't enough CO2 to cause global warming, often stated as "CO2 is just a trace gas". This myth is jumping to conclusions.

Just because there’s a small amount of something doesn’t mean it can’t have a big impact. There are plenty of real world examples of small amounts having large impacts. For example, it doesn’t take much arsenic in drinking water to be hazardous for your health. And in this case measurements show that "trace" CO2 is changing the energy balance of Earth. Satellites measure the sunlight reaching the edge of the Earth very accurately because they are outside the influence of the atmosphere. About a dozen satellites have provided this data since 1978. These satellites show that average energy input to the Earth is 340 W/m2. So, what happens to that energy when it reaches the Earth's outer atmosphere?

This picture shows the energy budget for the surface. Energy is divided into shortwave radiation, which is the visible and UV light, shown in yellow, and longwave radiation, which we think of as heat, shown in red. The Sun's rays are high energy, shortwave radiation, which is visible light in all colors of the rainbow, along with the UV light that we can’t see but which causes sunburn. About 30%, 100 Watts per meter squared, of the Sun's energy is reflected directly back to space from the atmosphere, clouds, and the Earth's surface. All this reflected light gives Earth its lovely glow when seen from space. The red arrow shows outgoing heat from the Earth, which is also measured by satellites. That energy is like the warmth you feel radiating from a hot stove. Four NASA CERES instruments are currently collecting detailed energy pictures of the Earth. We can now see how much of the Sun's energy bounces back to space, and the amount of energy emitted by the Earth as heat.

The data from these satellites combined with measurements of ocean heat gives the net imbalance of energy for the Earth. This graph show the 5-year averages since the start of these measurements in 1985. The current energy budget for the Earth shows an extra 0.6 W per square meter coming in than going out. So, surprise! we’re getting hotter! The claim that “CO2 is only a trace gas” is an example of a red herring: that fact may be true, but it is irrelevant to the discussion of its real effects on the planet. You are certainly familiar with lots of other substances where trace amounts have a big effect. A blood alcohol level of 800 ppm means you’re drunk; ibuprofen works at 3 ppm; the arsenic limit in drinking water is 0.01 ppm. Even though each extra molecule of CO2 contributes only a tiny amount of warming, its effects add up over the whole Earth and grow each year.

**10 Daily and yearly cycle**

Dana Nuccitelli - Environmental scientist

There’s a common myth that global warming is caused by the Sun rather than humans. That myth fails to account for the available evidence. If the Sun were responsible, we would see an entirely different pattern of global warming. In that scenario, we would expect to see the Earth warming most when sunlight is bombarding the surface the most – during the daytime, and during the summer season. That means that if the Sun were responsible, we would see days warming faster than nights, and summers warming faster than winters.

Scientists predict that human-caused global warming should result in certain specific \*patterns\* of warming. Because these patterns are consistent with what we expect to happen as a result of the increased greenhouse effect, they’re considered “fingerprints” of the human influence on the Earth’s climate. As far back as 1865, physicist John Tyndall predicted that warming caused by the increased greenhouse effect should cause nights to warm faster than days, and winters to warm faster than summers. He was able to make this prediction by knowing that at night and during the winter, the Earth’s surface cools by radiating heat out to space. Greenhouse gases trap some of this heat, slowing that nighttime and winter cooling. Even though the sun doesn’t shine everywhere on the earth all the time, the greenhouse effect is at work 24/7.

The moon gives us a good counter-example because it doesn’t have an atmosphere. During the day, there’s nothing between the Sun and the Moon’s surface to block incoming sunlight. At night, there are no greenhouse gases to trap the outgoing heat from the Moon. As a result, the difference between day and night temperatures is extreme. Daytime temperatures on the moon reach 120 degrees Celsius, or 250 degrees Fahrenheit. Nighttime temperatures fall below minus 200 degrees Celsius, or minus 330 degrees Fahrenheit.

At the other extreme, Venus has a runaway greenhouse effect, much bigger than the greenhouse effect on Earth. Its temperature is an intense 460 degrees Celsius, or 730 degrees Fahrenheit. It’s like this day and night, all year long. Venus doesn’t even have seasons because its greenhouse effect is so strong. As these two examples illustrate, the bigger the greenhouse effect, the smaller the difference between daytime and nighttime temperatures. We know humans are increasing the greenhouse effect on Earth by burning more and more fossil fuels. If the greenhouse effect is increasing, then the difference between nighttime and daytime temperatures, and between winter and summer temperatures, should be shrinking.

These expected patterns of global warming give scientists a clear test to determine whether the evidence matches the fingerprints of human or solar-caused warming. It took over 130 years before John Tyndall’s prediction was confirmed, but over the last few decades, surface measurements have found nights warming faster than days, and winters warming faster than summers. The difference between nighttime and daytime temperatures, and winter and summer temperatures, is shrinking, just as Tyndall anticipated would happen due to the increased greenhouse effect. Fingerprints in the Earth’s climate change, like these changes in global warming patterns, clearly point to humans, and not the Sun, as the culprit responsible for global warming over the past century.

**11 Human Fingerprints**

Ben Santer - Lawrence Livermore Labs

My name is Ben Santer. I’m a climate scientist. I study the nature and causes of climate change at Lawrence Livermore National Lab in Livermore, California. Human fingerprints—what have we seen? Back in mid-‘90s, when the first fingerprinting studies were being performed, one of the criticisms of that early work was, “You folks are only looking at surface temperature. You’re only doing this fingerprinting with changes in land- and ocean-surface temperature. If there really is a human-caused climate-change signal lurking in observations, go see it throughout the climate system. Look in ice. Look in the ocean. Look in ocean heat content. Look in rainfall patterns, the amount of moisture in the atmosphere, the vertical structure of atmospheric temperature change, extreme events.”

That’s what’s happened in the last 20 years now. Scientists have interrogated many, many different aspects of the climate system, not just looking at one number, the average temperature or average moisture, or average pressure, but looking at complex patterns of change in hard observations, the latest, greatest satellite observations, the latest, greatest climate model simulations, and the red thread running through all of this fingerprinting work is natural causational alone doesn’t cut it. It doesn’t explain the changes in all of these things that we’ve actually observed.

My focus has been, in the last 10 years or so, on two things. One is the vertical structure of temperature changes in the atmosphere. If you look from the surface of the Earth right up into the stratosphere, 20 miles above the surface of the Earth, what we’ve actually observed in weather balloon measurements and satellite measurements is this complex pattern of warming low down and cooling up high. The lower atmosphere, the troposphere, has shown warming pretty much across all latitude bends, and the upper atmosphere has shown cooling over the last 30 to 40 years or so. It turns out that that pattern of warming low down and cooling up high is really distinctive. We know of no natural mechanisms that can generate something like that, sustained for three or four decades. Volcanoes can’t do it. The sun can’t do it. Internal climate variability can’t do it, nor can some combination of natural causes: volcanoes, the sun, and internal variability generate that complex pattern of warming low down and cooling of the upper atmosphere.

The only thing that we know of that can generate that distinctive fingerprint is human-caused increase in heat-trapping greenhouse gasses, and human-caused depletion in the upper atmosphere of stratospheric ozone. It’s been fascinating over my career to look at ever-better satellite observations and ever-better model simulations and see that fingerprint pattern of human effects literally emerging from the noise. The best information we have now from our most recent research is that the chances of getting a fingerprint match between that human fingerprint pattern of warming low down and cooling up high and purely natural causes is infinitesimally small. The signal-to-noise ratio is greater than 10. That’s what our research tells us. There’s just no way of explaining what we’ve actually observed without invoking a strong human effect on climate.

The other thing we’ve looked at is water vapor. We’ve looked at satellite-based estimates of the moistening of the atmosphere, and that moistening is kind of interesting because it’s consistent with very basic physics and with very basic theory. We know from something called the Clausius-Clapeyron relationship that, for roughly every one degree Celsius warming of the lower atmosphere, you expect about a seven percent increase in the total amount of water vapor in the atmosphere. That’s exactly what we see in models and in observations, and, again, it’s the pattern matches that are so intriguing there. We see the largest increases in water vapor over the warmest areas of the tropical oceans in both models and in observations.

The bottom line from both the temperature work and the moisture work is: what we’re seeing is simply not natural. We have not looked at the daily cycle. One of the things we are looking at that I’m really excited about is looking at the annual cycle. Most fingerprint-detection work has actually focused on annual averages or decadal averages. People try and beat down the noise of natural climate variability by averaging in space and in time. That means that one really neglected aspect of change, of human-caused change, is the seasonal cycle.

What we’re now exploring is whether one can use these formal fingerprinting techniques that we’ve successfully applied to things like water vapor and temperature to the seasonal cycle, and the answer seems to be yes. We know why that should be. We know in the case, say, of ozone depletion, that has a really clear signature in terms of the seasonal cycle. Other things like biomass burning or changes in sea ice—again, there’s some clear expectation that these things should affect the seasonal cycle, both the size of the seasonal cycle, the timing of the seasonal cycle.

For a starter, that’s what we’re seeing: some identifiable human fingerprint in the march of the seasons, which is scientifically, rather—or should I say it—scientifically gratifying, but as a human being and as a citizen of this planet, it’s kind of disturbing to think that we’re now at a point where humans have a detectable signature on the seasons themselves, perhaps not unexpected, again, given what we know about the effects of different factors like human-caused changes and greenhouse gasses, ozone, biomass burning, and defects they should have on these seasonal cycle, but still it’s kind of staggering that we might be at a point where we can actually identify these things.

We know that people care about that stuff because that really has implications for plants and animals, for phenology, for the timing of events in the natural world, so detection of human effects on the seasonal cycle is not purely of academic interest to a couple of folks at AGU. The 17-year statement—where does it come from, and what do we know about human effects on climate on different time scales?

Let me back up a minute. A few years ago, I testified in front of Congress. One of the witnesses in those hearings claimed global warming stopped in 1998, a claim that one has heard a lot in the last few years. This witness claimed that roughly 10- to 15-year periods with little or no warming of the Earth’s surface or the lower atmosphere were evidence of absence of human effects on climate. The witness also claimed that no computer-model simulations, when run with human-caused changes and greenhouse gasses, could produce such hiatus or pause periods—again, 10- to 15-year periods with little or no warming.

The witness engaged in what I like to call science by eminence of position: eminent physicist, member of the US National Academy of Sciences, but provided no evidence to document or support those claims that were made to Congress. We decided to do the science to look at those claims and see whether they were correct or not. Well, they weren’t. As we and others have shown, computer models, even run with historical estimates of human-caused changes and greenhouse gasses, can, just like in the real world, produce short periods with little or no warming. That’s noise, noise in the system. Our expectation never was, as climate scientists, that each year would be inexorably warmer than the previous year in response to human-caused changes and greenhouse gasses.

You expect to see some warming signal, but that warming signal is imbedded in the rich year-to-year and decade-to-decade noise of phenomenon like El Niños, La Niñas, Pacific Decadal Oscillation. That noise isn’t going to go away just because humans are, through burning fossil fuels, changing the chemical composition of the atmosphere. What we did back then is we looked at all of the world’s computer-model simulations pretty much then available to us. We showed, first of all, that even models run with historical greenhouse gas increases could, by chance, produce 10- to 15-year periods with little or no warming. We also looked at so-called control runs. Those are simulations with no human-caused changes and greenhouse gasses or particulate pollution, no changes in the sun or volcanoes, just rich internal climate variability of these models—again, things like El Niños, La Niñas, other oscillations of the climate system.

What you could do was then look at those model simulations of a world without us but with this natural climate variability. You could ask this question: how long would an observed warming trend have to be in order to rise above the model estimates of noise, of internal climate variability? It turned out that the answer was 17 years. We were very, very careful to say, “We’re interrogating these model control simulations, and we were not making any kind of prediction at all.” That’s important. Some critics out there such as Mr. Anthony Watts of the “Watts Up With That?” blog have maintained that our 2011 paper where we published this analysis of models and observations made a specific prediction about the next 17 years.

That’s a complete misrepresentation of what we actually did. Again, what we were doing was looking at signal to noise, saying, “How long would an observed record have to be relative to model control runs before that observed record was unusual?” Of course, in the real world, of the last 17 years, we’ve had many things going on simultaneously, not just internal climate variability. As we and others have shown, there’s been volcanic cooling. There’s been an uptick in volcanic activities since the beginning of the 21st century. That’s not natural climate variability. That in fact is an external factor. There’s been an unusually long and low solar minimum during the last solar cycle—again, not pure internal climate variability—so folks like Mr. Watts who have maintained that all that is going on in the real world is natural climate variability, so the Santer, et al paper is incorrect, are really fundamentally misrepresenting the complex climate system where multiple things, the sun, volcanoes, internal variability, human influence, are happening simultaneously.

Perhaps he can convince some of his followers of the correctness of his interpretation of our results, but he’s wrong, and if you really feel so adamantly that the entire scientific community published incorrect science, then it’s incumbent on him to set the record straight, to publish stuff in the peer-reviewed literature, but sadly he has not done that. Instead, his focus has been on trying to cast doubt on the motives and reputations of individual scientists, rather than to try and truly shed light on complex scientific issues—a shame. What actually drives scientists—I hear this a lot.

Perhaps this kind of criticism was best phrased by Pat Michaels, who famously said, “Climate scientists are like lab rats waiting for their next cocaine fix,” the idea being that we’re all just in it for the money or to alter world systems of government, to get rich somehow—baloney. I have absolutely no time for people like that who make those kind of claims. It’s been my privilege over my career to know men and women who are motivated by desire to understand. That’s why they do it. That’s why they get up in the morning: to try and understand the complex climate system, the factors that influence it, to, maybe for one to two moments in their scientific career, have a tiny piece of the puzzle that nobody else in the planet has. That’s why you do it: for that joy of understanding, for nothing else.

In my opinion, it’s pure projection behavior. The folks who make those kind of allegations are doing quite well for themselves. They’re doing well not because they’ve made fundamental scientific advances. They’re doing well by portraying themselves as the lone wolf howling against the establishment, but they’re not creating understanding. I was the convening lead author for the Detection and Attribution chapter of the IPCC’s Second Assessment Report back in 1995. It was unpaid work. It was in addition to my normal responsibilities as a scientist funded by the US Department of Energy. I thought that it was worthwhile to do.

A clear assessment of the science, clear explanation to the public and policy makers and other scientists of what we do—that seemed to me to be an important and worthwhile thing, which is why I signed on. I had no idea what I was signing up for. In the end, I do think that the IPCC is still the best mechanism we have for explaining complex scientific issues to both our peers and to the general public and to policy-makers, but it is tremendously difficult. You’re in a quest for the holy grail of total objectivity. Think about that for a minute: how difficult it is to put aside all the subjective filters through which you see the world, your familiarity with these research methods or what scientists A or B and you don’t like scientist C and D. You’re asked to put all that aside and for a couple of years work on the best possible portrayal of our current state of understanding—really, really tough, no matter how objective you are, but you have dozens, hundreds of scientists around the world looking over your shoulder, providing input, criticizing you.

It’s this fierce marketplace of ideas. It’s not, as some have portrayed it, like Judy Curry, for example, some old boys’ club where people are just slapping each other in the back, saying nice things. That’s not the way science works, not in the IPCC, not at AGU. Again, it’s fighting for those—that supremacy of ideas, of theories, of understanding—really hard, really draining, very glad I did it in the end. In my opinion, what the IPCC comes out with at the end of this lengthy process is lowest common denominator stuff.

A good example of that is what they’ve concluded with regard to sea level rise in the fourth assessment report in 2007 and the fifth assessment report in 2013. They—IPCC scientists found that one of the things we don’t understand particularly well at the moment is the contribution to sea level rise from ice sheets on the move, from the dynamics of melting ice sheets. What they felt they could assess and assess well was the thermal expansion component, so how much sea level rises because of the expansion of warming ocean water.

Basically, they punted on the ice sheet contribution and said, “This could be pretty large, but we don’t have the science to reliably assess that at the moment, so what we’re going to do is stick to the things that we know well.” That is the antithesis of the IPCC as alarmist scare-mongering organization. That’s not the way this organization works. Again, to pass muster, to get science through this lengthy multiyear complex review process, you have to have stuff in there that is well known, that is well understood, that is not speculative. There are many, many examples like that where, rather than going for the big headline, the IPCC instead decided for the things that are really well known, that are not controversial in our field.

Well, one of the tactics was to piggyback off geopolitical events. That was the time of ethnic cleansing in Bosnia, for example. The Global Climate Coalition, this consortium of energy interests, produced a document entitled, “The IPCC Institutionalized Scientific Cleansing.” They argued, that we, the scientists involved in Chapter 8 of the Second Assessment Report, the Detection and Attribution chapter, were guilty of scientific cleansing, of purging our chapter of all uncertainty. That was a lie. That was the astonishing thing to me: that these things were demonstrably untrue. Twenty percent of our chapter was specifically devoted to discussion of uncertainties in observations, in climate models, in the statistical techniques used to compare models and observations.

That was really difficult, I think, to get to grips with, to wrap my arms around: lying, lying as a calculated strategy and getting away with it, too, being able to make the most outrageous claims. Now their claim back then was—and this was from Fred Singer—that changes to the IPCC report had been made by shadowy, political operatives for political purposes. They were not under the control of scientists. They had not been approved by the IPCC. All of that stuff was made up, and yet there were a lot of people who wanted to believe those kinds of messages, who wanted to believe, even back then, in shadowy conspiracies on the part of evil scientists to somehow manipulate world governments and world opinion. That was hard: this sense that, no matter how hard you tried, some people were not going to be accessible to rational debate. They were lost. You could never reach them, no matter how compelling your scientific arguments were.

Then there were the politicians who got involved who decided to investigate my funding, why the Department of Energy had allowed me to work on IPCC-related matters. I guess that was a harbinger, the shape of things to come for the next few decades. Go after the scientist. Go after their integrity. Go after their funding. Make life miserable for them. Let other people see what’s happening. They’re probably being employed more extensively and more successfully, too. I think an additional weapon in the arsenal is Freedom of Information Act requests, which are being used not really to advance understanding or, again, shed light on complex scientific issues but as a tactic to threaten, to intimidate, to throw a spanner in the works to take up your time. Then there’s the power of the Internet, which really was not available back in 1995, to harness your supporters to go after individual scientists, send them threatening e-mails or worse, and let them know, “We’re watching you. We don’t like you. We don’t like what you do.”

That’s new. That’s a new trick in the arsenal: hacking e-mails, releasing them, all of these things. The technology has moved on since 1995, but it’s the same playbook: don’t really focus on the science and advancing understanding, contributing,

but tear down, destroy. Well, the letter was a letter of support. It was “An Open Letter to Ben Santer”—I think was the title of the thing. It was published in the Bulletin of the American Meteorological Society. I had no knowledge that this letter was being written. It was by Rick Anthes, the President of UCAR, the University Corporation for Atmospheric Research, Susan Avery, and two other signatories—I don’t remember their names at the moment—but it was very, very gratifying. I think, in the middle of all of that stuff that was going on in the summer of 1996, the scientific cleansing charges, the charges that chapter 8 had been tampered with for political purposes, the charges of irregularities in my own personal research. Those were very, very serious allegations, and, here, people who I haven’t met, who didn’t know me, were coming to my defense, writing this letter and saying, “Hey, this is not the way to have a debate about climate science, the implications of climate science by going after individuals.”

That was the silver lining for me, that many people who had no knowledge of me or what had happened in Madrid were willing to say, “Hey, this is not the way to have a responsible discussion. Don’t try and demonize individual scientists here.” That felt really good, as did “The New York Times” piece by Bill Stevens, also in the summer of 1996, when that came out and gave some real in-depth discussion on what had actually happened. Up to that point, all the attacks were out pretty quickly, but really no space, not much space, was given to the responses to kind of criticisms that I just mentioned: the scientific cleansing, political tampering, irregularities in research. I guess

that’s a strategy, too: you overwhelm the press with lots of allegations, and they receive front-page coverage, but the detailed thoughtful responses to those allegations—those are not news really.

The IPCC did respond, I believe. In the end, Bert Bolin, the Chairman of the IPCC and the co-chairs of the IPCC, Sir John Houghton and Luiz Gylvan Meira Filho, did respond to “The Wall Street Journal” addressed these charges and said, “Hey, these are wrong. These are just incorrect. We were there. Chapter 8 was discussed at this Madrid plenary meeting of the IPCC. There was a clear understanding that the language of the chapter needed to reflect the discussions of the governments present at Madrid, of the scientists present at Madrid. Ben Santer did not behave improperly.” That was obviously gratifying.

We’ve monitored levels of carbon dioxide and other heat-trapping greenhouse gasses for over half a century now at dozens of locations around the world. Those measurements tell a really clear story. Levels of atmospheric CO2 have increased about 40 percent. CO2 is a greenhouse gas, traps heat that would otherwise escape out into space. By looking at lighter and heavier isotopes of carbon, we know that most of that increase in carbon dioxide is us, is burning of fossil fuels—no doubt, no ambiguity.

The real pedal to the metal question has always been how much climate change comes from that human-caused change in levels of heat-trapping greenhouse gasses. That’s where all the fingerprinting comes in, that not just our group but dozens of groups around the world have done. Again, as I mentioned earlier, we’ve looked everywhere, not just the surface temperature but in the oceans, in the upper atmosphere, in water, in continental runoff from major rivers, in ice. No matter where you look, nature alone can’t explain the changes that we’ve seen. The best explanation of all of these independently measured things in the real world is a strong human influence. I wish it were otherwise. I truly do. I have a son. He’s going to be living to see 2100. He’ll know. My real concern is that he doesn’t look back one day and say, “Hey, my dad knew this stuff. He knew what was going on. Why didn’t he try a little bit harder? He had knowledge; he had understanding of what was actually going to happen.”