**U. of Queensland Climate Denial Course - Lecture 5**

**Current Impacts**

**Table of Contents Page**

Introduction

1. Overview 1

Climate Feedbacks

1. Climate is sensitive 2
2. Water vapor amplifies warming 3
3. Role of clouds in climate change
4. Methane clathrate feedback 5
5. Clouds and water vapor 7

Environment

1. Adaptation takes time 15
2. Ecological impacts 16
3. Polar Bears 19
4. Ocean acidification 20
5. Coral bleaching and ocean acidification 23

Society

1. Overall Impacts 25
2. Carbon dioxide is a pollutant 26
3. Agricultural Impacts 27
4. Experts: Impacts on society 28

Extreme Weather

1. Extreme weather 31
2. Heat waves 32
3. Hurricanes 34

Bonus materials

1. Making sense of the slowdown 36
2. Tree growth and warming 38
3. Water in the Atmosphere 38

**1 Overview**

John Cook - Communications research fellow

In the last few weeks, we’ve examined the reality of human-caused global warming. This week, we’ll look at the global impacts of this change in an effort to answer the question: how is climate change affecting human societies, natural environments, and the species we share them with? We’ll examine how things like longer and hotter heatwaves, more intense rainfall and other forms of extreme weather cause impacts that ripple through every aspect of society.

As usual, we’ll hear from a range of experts, from scientists who have meticulously collected data for decades to biologists and filmmakers who have witnessed the effects of climate change before their very eyes. We’ll also travel here, to Heron Island Research Station on the Great Barrier Reef, where scientists are researching the combined impacts of global warming and ocean acidification on coral reefs. As we look at these different impacts, we’ll debunk a number of myths that try to downplay their significance.

**2 Climate is sensitive**

Dan Nuccitelli - Climate blogger

We know that humans are burning fossil fuels and releasing billions of tons of carbon pollution every year. This has increased the greenhouse effect, trapping more heat in the Earth's atmosphere. That leads to an important question. How much will global surface temperatures increase because of this extra heat? If we double the amount of carbon dioxide in the atmosphere, the heat trapped will cause a direct warming of about 1.2°C, or 2.2°F.

But there are also effects called “feedbacks” that can either dampen or amplify that warming. For example, when ice melts, the Earth's surface gets less reflective, causing it to absorb more sunlight and warm even further. A warmer atmosphere also holds more water vapor. Since water vapor is another greenhouse gas, this increases the greenhouse effect and causes further warming. These are amplifying feedbacks.

Clouds are especially complicated. Changes in cloud cover can mean more reflection of sunlight, a dampening feedback. But changing clouds can also trap more heat, since they also contribute to the greenhouse effect, which is an amplifying feedback. What’s the total effect when you add up all the different feedbacks? The end result is called climate sensitivity - the increase in global temperature from a doubling of the amount of carbon dioxide in the atmosphere.

There are several ways we can calculate climate sensitivity. We can look at how Earth’s climate has behaved in the past. How did global temperatures change in response to a change in heat? We can use complex climate models that simulate all the different feedbacks. Or we can combine modern measurements with simpler mathematical models. All these independent methods find a fairly consistent answer. If we double the amount of carbon dioxide in the atmosphere, global temperatures will rise between 1.5 and 4.5° Celsius, or between 2.7 and 8° Fahrenheit. The best estimate for climate sensitivity when combining these methods is around 3 degrees Celsius. Remember, direct warming from the increased carbon dioxide greenhouse effect is only about 1.2 degrees Celsius. Reinforcing feedbacks roughly double or triple that warming.

Three degrees warming may not sound like very much. But the difference between an ice age and the current warm period is only about 4 to 5° Celsius, or 8 to 9° Fahrenheit. Seemingly small temperature changes make a big difference when you’re talking about the whole planet. However, there is one myth that argues that climate sensitivity is low and therefore global warming is nothing to worry about.

This myth actually contains two fallacies. Firstly, it cherry picks among the different methods used to estimate climate sensitivity. It only looks at some of the attempts using modern measurements and ignores estimates using past climate change or global climate models. Each method has its strengths and weaknesses.The strength of looking at past climate change is that it gives us estimates based on actual past events in Earth’s history However, the weakness is that those changes happened under conditions that aren’t identical to today’s climate. So they’re not perfect analogues.

The strength of global climate models is that they let us estimate how sensitive the climate is under today’s conditions. The weakness is they’re limited by how well we understand all the processes that influence the Earth’s complex climate system. For example, most climate models don't take into account factors like the response of the permafrost in the Arctic. As the Arctic warms, melting permafrost will release trapped methane, which will increase the greenhouse effect and amplify global warming. But because the amount and timing are uncertain, this effect is usually left out of the models.

The strength of using modern measurements with simple models is that it’s relatively straightforward. We don’t need to understand all the intricacies of the Earth’s climate. One weakness is that this approach relies on the accuracy of our recent climate measurements. For example if we’ve underestimated the amount of heat going into the oceans, or overestimated the size of the global energy imbalance, this method will underestimate the climate sensitivity. Another weakness with this method is that we don’t know if the climate feedbacks will behave the same way in a hotter world decades from now as they do today. Scientists using this method assume that’s true, but it might not be. Climate models suggest it’s not. And if it’s not, estimates using modern measurements with simple models will be wrong.

Studies using the historic climate change and global climate model methods have arrived at consistent results, estimating the climate sensitivity between about 2 to 4.5°C global surface warming if we double the amount of carbon dioxide in the atmosphere. In recent years, a few studies using modern measurements with simple climate models have arrived at somewhat lower estimates, around 1.2 to 4°C. Considering the full body of evidence and research into the shortcomings of this third approach, those lower estimates may very well be overly optimistic. But even if the lower estimates of climate sensitivity are right, we’re still on track to experience warming at dangerous levels. It just means that we’ll reach the most dangerous levels of global warming about a decade or two later than we expected. That’s not enough to justify refusing to take action to reduce carbon pollution and slow global warming.

**3 Water vapor amplifies warming**

Keah Schuenemann - Metropolitan State U of Denver

In this lecture, we’ll be looking at the greenhouse gas water vapor. It’s actually one of the reasons why our climate is so sensitive to small changes - water vapor amplifies a small amount of warming and makes it a big warming. Let’s explore why. Water vapor and carbon dioxide are both greenhouse gases, meaning they both absorb the earth’s outgoing heat, raising global average temperatures through a blanketing effect called the greenhouse effect.

For example, maybe you’ve experienced water vapor as a greenhouse gas because on a humid, summer night, temperatures stay hot because the water vapor doesn’t allow the heat to escape. There’s a lot of water vapor in the air, but the amount varies based on location and height. Carbon dioxide concentrations are small, only making up about 0.04% of the air. Carbon dioxide is emitted through burning fossil fuels and deforestation, both caused by humans, while water vapor comes from evaporation of liquid water off of bodies of water, mainly the oceans.

The amount of evaporation depends on the global temperature. A warmer Earth has a more humid atmosphere. The warmer it gets, the more evaporation off the surface of the ocean, putting more water vapor into the warmer atmosphere. Another reason for higher humidity is that warmer air can “hold” more water vapor than cold air. As the globe warms, evaporation from the oceans causes water vapor to build up. But water vapor is a greenhouse gas. So this excess water vapor causes the atmosphere to warm even further. This allows even MORE water to evaporate into the atmosphere, causing an EVEN FURTHER warming due to a stronger greenhouse effect. This is an amplifying feedback, a self-reinforcing loop. In fact this feedback is the most important of many fascinating feedbacks in our climate system. It takes a small warming, amplifies it and makes it a big warming.

Water vapor feedback play a big part in making the Earth’s climate sensitive to small changes. If the global climate and the global average temperatures stayed relatively the same, the water vapor feedback wouldn’t be kicked into gear. But because we’re increasing carbon dioxide from burning fossil fuels and deforestation, the earth is getting slightly warmer, kicking this feedback into playing a large role in the climate system.

It’s like having a skateboarder at the top of a hill, let’s call him Water Vapor. He’s sitting comfortably at the peak, stably sitting steady at rest, in equilibrium. His buddy, let’s call him Carbon Dioxide, comes along and gives him a little nudge. Well, this gets him rolling down the hill faster and faster as he goes down. Without Carbon Dioxide pushing Water Vapor just a little bit and getting him started down the hill, he would have stayed comfortably at rest at the top of the hill. This is how amplifying feedbacks work, they amplify changes once they are set into motion!

The same thing happens in the atmosphere. Carbon dioxide acts as the trigger for the water vapor feedback. Humans don’t control how much water vapor is in the atmosphere, that’s up to the weather. We CAN control carbon dioxide concentrations, though, and by letting our carbon dioxide levels get high enough to warm the atmosphere, we are therefore responsible for triggering the water vapor feedback, amplifying the warming from carbon dioxide. If carbon dioxide warms the atmosphere 1 degree Celsius, then water vapor can cause the temperature to go up another 1 degree.

But some climate myths take this science out of context. Let's look at an example. One myth related to water vapor claims, “Forget carbon dioxide, water vapor is the most important greenhouse gas. It controls the Earth’s temperature.” This implies if water vapor is a strong greenhouse gas and we have it in large concentrations in the atmosphere, then adding a small amount of the greenhouse gas carbon dioxide can’t make a big difference in global average temperatures.

The fallacy here is jumping to false conclusions. It is true that water vapor is a greenhouse gas, but that doesn’t mean that carbon dioxide is not. It ignores the fact that they play very different roles in the climate system. In other words, this myth is trying to use information about water vapor to distract you to imply that an increase in carbon dioxide isn’t a problem. It also oversimplifies the science. But now you know that water vapor doesn’t control the Earth’s temperature, but instead is controlled BY earth’s temperature.

Carbon dioxide IS important because it controls the Earth’s thermostat. If carbon dioxide levels go up, the temperature gets warmer. As a consequence, water vapor levels increase. Water vapor IS the most dominant greenhouse gas, but the only way we can keep levels under control is by keeping temperatures low through lowering carbon dioxide emissions!

**4 Role of clouds in climate change**

Peter Jacobs George mason University

As a kid, I loved to lay on my back in the grass, and look up at the clouds. I would see so many crazy shapes- elephants, dinosaurs, even dragons. Climate skeptics look up at the clouds and see something even more unlikely- a challenge to the science of climate change. Unfortunately for us, it’s all in their imaginations.

Clouds affect the Earth’s climate in many different ways. But the two most important ways are through the albedo effect, and through the greenhouse effect. “Albedo” is a term that means how much a surface either reflects or absorbs light. In much the same way that wearing a white t-shirt will keep you cool in the summertime by reflecting sunlight, clouds reflect some of the sun’s light back out to space before it can be absorbed.

Thick clouds tend to have a high albedo- that is, they reflect a lot of sunlight. Putting thick white clouds between the sun and the open ocean dramatically increases the amount of sunlight that gets reflected back to space. Low, thick clouds are most important for this cooling effect. By contrast, higher, thinner clouds don’t reflect a lot of sunlight. But they do trap heat through the greenhouse effect. Both cloud types have a cooling albedo effect and a warming greenhouse effect. But for low clouds, the cooling effect is much more important. And for high clouds, the warming effect is more important.

The low clouds are more important and overall clouds cool a lot more than they warm. But knowing how clouds affect Earth’s temperature overall doesn’t tell us how clouds and their impact on climate may change as we warm the planet. If we see relatively fewer low, highly reflective clouds as we heat up the ocean, we would have more warming overall. If we get relatively more low clouds, we could see less warming than we otherwise expect with increasing greenhouse gas levels.

What does the available evidence tell us about how clouds will change in the future? Over the past 10 to 15 years, we have gathered enough information to begin to see how clouds change in response to changing ocean temperatures. At least over the short term. Changes in ocean temperature occur due to ocean natural cycles such as El Nino. We can look at how these changes relate to changes in cloud cover.

Overall, such changes over the past decade or so seem to point to a small warming effect. But we can’t quite yet rule out a small cooling effect. While these studies of short-term variations are helpful for our understanding, some caution in over-interpreting their results is warranted. Longer-term temperature changes caused by greenhouse warming may affect clouds differently than short term variations caused by El Niño.

But if clouds were somehow to counteract warming like a thermostat, this would imply the Earth can’t and hasn’t warmed up very much over its history. However, we can reconstruct climates from Earth’s past during hotter greenhouse periods. When we do so, we see large increases in temperature. This rules out clouds acting like a thermostat and limiting the amount of warming. Short term observations in the present, and long term reconstructions from the past seem to be saying the same thing- clouds won’t counteract greenhouse warming. Climate models agree. On average, climate models predict a reduction in low clouds that will lead to a modest amount of additional future warming.

Moreover, climate models that tend to model cloud behavior more realistically also tend to show clouds are likely to contribute more to warming in the future than models with less realistic clouds. Climate denialists are fond of invoking cloud behavior to play down the threat of greenhouse gas emissions. They claim that as greenhouse gases increase and we start heating up, clouds will cool the Earth more. Either due to an increase in low cloud cover, or a reduction in high cloud cover. They claim, in effect, that clouds will act like a thermostat to keep warming in check.

To claim that clouds will prevent serious global warming, denialists rely on oversimplification. They act as though clouds only have an overall cooling effect. While clouds do cool the Earth, this ignores the facts that they also warm, and that the total effect of clouds presently is not the issue. Rather, what matters is how that effect changes, if at all, in the future. Denialists then take this oversimplification and jump to a conclusion. They assume that because clouds cool now, and there is some uncertainty about their future behavior, that means clouds will act like a thermostat to prevent too much warming.

To support their claims, they have cherry-picked data, relying on information from records with known biases. Or in some cases selectively choosing start and endpoints within a larger dataset to produce the opposite result as using the whole record. The assumption that clouds will save us is simply not supported by the balance of evidence available to us. Our direct observations over the past decade suggest that the impact of clouds on future warming will be modest.

And, if anything, cloud changes are amplifying warming a bit. This agrees well with our most advanced climate models, which likewise suggest clouds won’t cool us off, but rather will modestly increase warming. And we know from the climates of Earth’s ancient past that there is no magical cloud thermostat that keeps the planet from heating up. Increased CO2 levels have repeatedly led to hotter climates over Earth’s history.

**5 Methane clathrate feedback**

Andy Skuce - Independent geosciences consultant

First, what are clathrates, anyway? Methane clathrates or hydrates are ice-like substances that trap methane gas in a cage of water molecules. They form where there is a combination of high pressures and low temperatures. We find clathrates at or just below the seabed, usually in ocean depths of greater than 500 metres. When they are dredged up from the deep, they fizz out methane and can be set alight. The picture on the left shows white streaks of clathrate in a lump of dredged-up mud that’s about a foot across. The photo on the right shows methane gas burning as it is released out of the hydrate cage.

Clathrates are also found in the Arctic, in places where there are thick sections of permafrost. In these conditions, clathrates can form at depths as shallow as 200 metres below the surface--either on land or under a shallow ocean shelf. These diagrams show the conditions where clathrates are stable. Typical conditions for permafrost clathrates are shown on the left and for deep sea clathrates on the right. Clathrates become unstable as soon as the temperature goes up or the pressure goes down.

\*\*So, why should we care about Arctic clathrates? We care because -Firstly, there is more carbon stored in clathrates than there is in the entire atmosphere. The great majority are found beneath the deep seabed, with about one percent in areas of continuous permafrost, according to the latest estimates. -Secondly, it would take the release of only a fraction of one percent of the world’s hydrates to double the concentration of methane currently in the atmosphere. That would make for a big addition to man-made global warming. -Finally, the clathrates found in the Arctic are the most vulnerable to climate change, because this area is the most rapidly warming place on Earth.

On the other hand, here’s why we don’t need to worry too much-yet. The good news is that the clathrates are quite well protected from man-made global warming. It will take a lot of time for the recent man-made global warming to reach them— probably thousands of years or more for the majority of clathrates that occur in deep oceans or that are buried under hundreds of metres of frozen rock.

More good news--for the atmosphere at least--is that when deep sea clathrates become destabilized, most of the methane gets consumed in the sediments on the sea bed. Some methane may still make it into the water, but, even then, the methane in the bubbles is absorbed before it gets to the surface. The released methane will locally deplete the oxygen in the sea water and also worsen ocean acidification. Some of it will eventually be released to the atmosphere as carbon dioxide.

There are clathrates located on continental margins at the upper limits of their stability range that are emitting methane into the seawater today. However, this is a process that has been going on for many thousands of years and--because the water is so deep there--the methane does not reach the atmosphere. Nevertheless many people—a few scientists and many lay people—are concerned that methane hydrates might be destabilized on a large scale by recent global warming and that they pose a serious and imminent threat to the Earth’s climate.

For example, a recent article in the journal Nature estimated the economic impact of warming provoked by a sudden release of 50 billion tonnes of methane from the shallow seas of the East Siberian Arctic Shelf. The paper was criticized by many scientists for failing to make clear that it was looking at the consequences of a \*\*very unlikely\*\* occurrence. Studies in this remote part of Siberia are in their infancy, because it is difficult and expensive to operate in the harsh conditions there. Nevertheless, recent research has shown that there is methane bubbling up from the frozen seabed in that area. The Siberian shelf is quite shallow, averaging around 50 metres, and some of the methane released makes it to the atmosphere, especially when storms stir up the water.

One thing that we don’t know yet is if the methane emissions in this area have increased recently as a result of global warming, or if they are just part of a slow release that has been going on for many thousands of years. We also don’t know if the methane is coming from normal biological processes at the seabed--or from destabilizing clathrates. Some of the gas may be sourced from organic matter buried much deeper in the sediment column--gas that has found its way up through holes in the permafrost. Our knowledge of where clathrates naturally form makes it look unlikely that there should be any present near the seabed on this shallow shelf. There have been no actual samples or geophysical indications of clathrates there yet.

Another argument against large-scale, present-day clathrate destabilization is that in geologically recent periods—in the early Holocene (8000 years ago) and at the time before the last ice age (120,000 years ago)—when temperatures were a little warmer than today. There is no record of a massive and sustained methane release from destabilized hydrates. Nor is there evidence of any sudden global climate catastrophe at those times.

It is a myth, therefore, that catastrophic clathrate destabilization is already upon us. Although the theoretical potential exists for this to become a problem after a long period of human-caused warming, we are not there yet. It would be \*\*jumping to conclusions\*\*to suggest that we are at risk of an imminent climate catastrophe from large quantities of clathrates suddenly becoming unstable. But if we continue to fail to limit emitting carbon dioxide from fossil fuels, we will certainly bring forward the day when clathrates do become a problem.

However, there is still plenty to worry about in the Arctic As this picture shows, there are plenty of potential sources of greenhouse gases in the Arctic apart from clathrates. Some of these sources of carbon dioxide and methane are already active today and many of them will grow in importance over the next several decades as the region quickly warms and the permafrost thaws and glaciers and ice sheets retreat. These human-accelerated natural emissions may add a fraction of a degree to the average global temperature by the end of the century.

Of all the stores of Arctic carbon, in the short term, clathrates are probably the best insulated from man-made warming, because they are only present far below the surface. Nevertheless, clathrate destabilization remains a concern for the climate over the centuries and millennia to come. Luckily, it’s not happening just yet and, in the estimation of the IPCC, is \*\*very unlikely\*\*to be a big problem during the rest of this century.

**6 Clouds and water vapor**

Steven Sherwood - Professor University of New South Wales

My name is Steven Sherwood, and I’m a professor at the University of New South Wales in Sydney, Australia. I do research on clouds and water vapor and climate, and how all those things are connected. There’s a global water cycle, and globally the amount of water that evaporates from the oceans has to come out, fall out of the atmosphere as rain. They can’t stay in the atmosphere for very long—maybe about a week.

That whole cycle is really driven by the radiation balance of the atmosphere. The atmosphere is losing energy because it’s radiating infrared radiation to space and to the surface, and that has to be also balanced by the heat that’s released by the precipitation. If you put all these things together, we can say something about the rate of this global water cycle and how it does increase as the climate warms up because the energy flows increase, and so all of that happens a bit faster.

It doesn’t necessarily mean, though, that we’re going to all have more rain in a warmer climate because also it means that the land surfaces are evaporating faster as well. By and large, in a warmer climate, we can expect it to physically be drier in the sense that if you put a pan of water out somewhere, it would evaporate faster in a warmer climate. We would also get more rain, but if you take the ratio of the rain that you get to how long that water lasts in that pan, you’re losing in a warmer climate. This is something that you can work through with some thermodynamic calculations, but this is what comes out.

It’s supported by our fancy climate models. When we run them, they do show the aridity of most continents on Earth becoming more severe in a warmer climate. Now what might help us is that, with higher CO2, plants don’t need as much water, so the plants, might actually be okay, but this is a huge area of uncertainty, and I think it’s pretty important. Over oceans and land, precipitation and evaporation should happen faster in a warmer climate, but what happens over land is what we call the potential evaporation increases much faster than any of those other things.

The potential evaporation is how fast a pan of water would evaporate. What that means is that trying to keep water around for use becomes a lot harder. The actual evaporate—you can’t evaporate water that doesn’t rain, so the actual evaporation might not go up that much, but the atmosphere’s trying to evaporate water a lot harder as the climate warms up. In the climate system, the way we understand it, is that there are things that we call forcings that drive changes to the global energy budget. Therefore, the global temperature is a response to that. Then there are things that we call feedbacks.

The way feedback works is that when the Earth starts to warm-up—but, say, because of an import of heat—that warming triggers other changes which have their own effects on the energy balance of the Earth. If they, in turn, cause the Earth to absorb more sunlight, for example, then that’s what we call positive feedback because it means that the whole system will end up having to warm even more before finally it comes to a new balance.

The biggest feedback that we know about comes from water vapor. This water vapor feedback has been part of thinking on climate since the very beginning. Even Arrhenius in 1896 took account of the water vapor feedback when he computed global warming, but that’s always been—or it has been controversial for a long time because people have come up with various ways that it might not happen, and there’s been some important details in what determines the water vapor concentration in the atmosphere that we haven’t known.

We do know that an atmosphere at equilibrium will have more water vapor when it’s warmer, but our atmosphere isn’t in equilibrium, so there was this problem of saying, “Well, you know, how do we know that the actual water vapor amount is going to do what we think?” I would say, in the last 10 years, we have developed a good enough understanding of what controls the actual water vapor amounts in the atmosphere as opposed to this theoretical equilibrium so that we can say confidently that, yes, we will get this doubling of climate change from water-vapor feedback.

Even the reasonable skeptics or semi-reasonable skeptics out there who have questioned this feedback in the past that I know of have basically moved on and said, “Yes, okay, there is this water vapor feedback,” and the real focus of discussion now is on clouds and feedbacks from them because they’re definitely more uncertain.

In the atmosphere, there are several greenhouse gasses. Carbon dioxide is the one that you keep hearing about. There’s also water vapor, which is natural. It gives us all of our rain. It gives us our clouds. If you just look at the greenhouse effect of that water vapor, it’s more than the greenhouse effect of the carbon dioxide. You might think, “Why do we care about carbon dioxide?” Well, the problem is that carbon dioxide, once it’s in the atmosphere, stays there pretty much for centuries. Some of it stays there for millennia.

Water vapor only stays there for about a week. Moreover, the amount of water vapor that’s in the atmosphere is so tightly controlled by the circulation of the air and the temperature of the air that you and I could boil as much water as we wanted, and we wouldn’t have one iota of effect on the amount of water vapor or the greenhouse effect of what’s in the atmosphere.

What actually happens is, when we burn fossil fuels, it puts carbon dioxide into the atmosphere. It increases the greenhouse effect of that. Then once that warms the Earth, the Earth will increase the amount of water vapor in the atmosphere. We can’t do anything about it, so it acts like a feedback and it—because it’s a strong greenhouse gas, it means that the water vapor feedback can be strong, and it is strong. That’s why it can double the impact of the carbon dioxide change or any other change to the Earth’s energy budget.

The water vapor feedback itself roughly doubles the sensitivity that you would have. That’s really the major one. There’s ice, so in a warmer climate, ice will melt, and ice is bright—it reflects sunlight to space—so if you lose that, you’re absorbing more sunlight, and that’s another positive feedback but it’s a lot smaller than the water vapor one.

Then the big unknown is clouds. Clouds reflect a lot of sunlight to space. They also exert their own contribution to Earth’s greenhouse effect. Either of those capacities of the clouds or characteristics of the clouds could change in a warmer climate. One of the big unknowns in topics of research right now that occupies people like me is to try to figure out what the clouds will do. The behavior of clouds that we see in our models is that they increase warming somewhat. They add a bit more positive feedback to what’s already coming from water vapor and ice melting.

For a long time, people regarded that as a black box result that we didn’t understand and really didn’t trust at all. Lately, looking more carefully at why it happens in the models, we start to see a couple of pretty straightforward things that we do understand. The most important one of those is simply the fact that, in a warmer climate, the part of the atmosphere that we call the troposphere gets thicker, and the part that we called the stratosphere gets thinner. The clouds, which form near the boundary between those two, move up, and their greenhouse effect gets stronger. They then give you another positive feedback. We think we’re on pretty solid ground in that one.

Other things happen in our models that are more diverse or different between different models, and so they are not well understood. There are also—it’s very hard to tell from observations what’s going on. We don’t have long records of clouds, and the records that we do have that go back a few decades suffer from the fact that a new satellite is launched every five years, and its sensors are a little different, and you can’t exactly compare.

One of the things we’d like to be able to do is look at the—observe variations in today’s climate and use those to tell us what clouds would do in a warmer climate. It turns out that it’s fairly tricky to do that, and the reason is that the natural variability of the system from year to year or month to month includes a lot of things going on that don’t really happen in a hundred years, over a hundred-year time-scale, when you warm the planet. A lot of people have tried to infer cloud feedbacks from, say, satellite observations over the last 10 to 20 years, but I don’t think any of those studies have really nailed the problem.

We’re going to have to work on this for some time to come, but what you have to do is you really have to understand all those other factors that are there and the year-to-year variability and take them into account. That’s something that we haven’t figured out how to do yet. We don’t really have a way of proving what the feedbacks are, but I think we’re making some progress in understanding the cloud ones, and it’s looking less and less likely that they are going to do anything to reduce climate change. In the last IPCC report, we concluded that it was likely that they exert a positive feedback. It’s the first time the IPCC has made a claim about even the sign of cloud feedback.

There were definitely differences of opinion about what to say about that, but

there were at least as many people who wanted a stronger statement as there were who wanted a weaker one. There’s really three ways to try to put balance on what we call climate sensitivity, which is the overall amount of warming that you get in the system from something like a doubling or quadrupling of carbon dioxide or something else like that.

One of those is to try to figure it out from first principles, be really smart, put together a model of the system, and use the model that tell you what it’s going to do. This is tough. We’re doing it, and it gives us a range of results, but there are a lot of feedbacks that happen in these models, and they depend on a knowledge of the physics and the processes that goes beyond what we currently know how to confidently capture and put in. However, it gives us an idea of what to expect.

You can also go back and look at the paleoclimate record, which we have evidence on paleoclimate going back, depending on how strong of an evidence you want, through the Phanerozoic, about the last 600 million years, but particularly over the last 60 or 70 million years. A lot of people look 50 million years ago. People look over the quaternary in the last million years, and they’re getting more interested in periods of time in between. Many of these time periods will—from any of these time periods, you can get an estimate of the global temperature, and you can get an estimate of the influences that—the things like CO2.

CO2 almost always was higher when the climate was warmer and almost always goes lower when the climate was colder. In some cases, we know why the CO2 is higher or lower. It was because of changes in volcanism. That’s kind of like what we’re doing except slower, so you can use that. When we try to put together what the sensitivity looks like from that information, it’s kind of similar to our climate models, giving us numbers like two or three or maybe four degrees for a doubling of CO2.

The third way that you can do it is you can try to get it from recent observational record, just the 20th century. Let’s look at the time period where humans actually started doing something. Over this time period, we have much better information, but so far we’ve got a pretty puny climate change. It’s still less than one degree. It’s also—there’ve been a lot of different kinds of human influence, most importantly the fact that we’re putting a lot of air pollution into the atmosphere, carbon and soot and sulfate, and it’s really hard to tell how much of an impact that’s having. All of this makes it kind of hard to answer the question this way either.

We have three imperfect ways of doing it. They all kind of tell us that the sensitivity is significant, but they don’t, any of them, tell us exactly what it is. The warming pattern that you see in any model in the tropics is you see some warming at the surface, and then, as you go up in the atmosphere, you see the warming getting stronger and stronger until you start getting close to the top of the troposphere layer, and then it starts to go away. There’s this kind of maximum that exists about 10 or 12 kilometers above the surface in the tropics. A lot of people have been looking at observations over the last 10, 20 years to try to find this, and many of them don’t find it. It has become a big controversy because every time someone doesn’t find it, they write a paper, and then a bunch of people will want to be skeptical about it and feel vindicated.

The problem is that we don’t really have any good observation systems that measure atmospheric temperatures accurately enough over a long period of time to do a—to give us a really believable picture of what this pattern of warming looks like. We even have trouble at the surface. We’ve got thousands that—there’s around 10,000 surface observing stations on Earth. Despite that, there are arguments about how much the surface has warmed over a period of several decades, particularly in the tropics where we actually have relatively few stations.

The situation surface is great compared to what it is as you go up in the atmosphere where we have only a few dozen radio sun stations in the tropics. You can turn to satellites to try to get this, but they have their own problems. They are not well-calibrated. There’s new satellites every few years, and they also don’t have very good—they can’t really tell the difference between what’s happening at 12 kilometers and what’s happening at 6 kilometers in the atmosphere. In my view, none of these observing systems is definitive.

There are some that do show this heating maximum in the tropical troposphere. It continues to be a subject of research and debate as to whether there is or isn’t evidence of something different from what our models are saying. The tropical hotspot occurs because of basic tropical meteorology, thermodynamics of gasses, okay? We’ve got a gas near the surface that’s got a lot of water vapor in it, and when it mixes with the upper troposphere, that water vapor condenses, and it releases heat, and so for that reason any temperature change at the surface is multiplied in the upper troposphere, and that should happen no matter what causes the change.

We really have to distinguish between two different questions here. One is: is the tropical surface warming? The other is: is there something about the ratio of warming at one level versus another level that’s different from what we think? If there is, that’s telling us something really interesting about atmospheric mixing and thermodynamics. It’s not necessarily telling us anything about global warming. If the surface isn’t warming and we think it is or should be, then that would be telling us something about global warming potentially. We need to keep these 2 things separate, I would say.

Probably the most well-known fingerprint of carbon dioxide-induced warming is the cooling of the stratosphere that you get when you add CO2 to the atmosphere, and we certainly see that. There’s no question that the stratosphere has been cooling. A complication there is that ozone depletion also contributes to it, so it’s again hard to say exactly how much of that is from carbon dioxide or from ozone depletion, especially since the ozone-depletion rate isn’t very well measured. Otherwise, it’s not easy to find fingerprints of human-caused warming versus, say, from the sun. I think the stratosphere is probably the main one.

My research is on clouds and how they’re connected to climate. Clouds are a very important feedback mechanism on climate. They are also really important for determining how weather systems evolve in our atmosphere. They may even be important for how circulations in the atmosphere are affected by things like climate change.

One of the things we see happening right now is that the tropics, which has a pretty well-defined edge, according to how the circulations go in the atmosphere—that edge has been moving outward for the last 30 years, and nobody really knows exactly why. None of our models are able to predict a rate of expansion that is any more than maybe about a third of what we observe. There’s something funny going on there, and some of us think that clouds might have part of the responsibility for making this happen so much faster than what our model says should happened.

There’s a lot of other things going on in the world that are happening faster than the models say. We see rainfall patterns in the tropics enhancing at a very rapid rate, so places that get some rain over the oceans are getting a lot more, and places that got less rain over the oceans are getting a lot less. That’s happening faster than we expected, and, again, clouds may be involved in that. That’s just to name two examples, there are a lot of other things as well.

One of the problems that I’m really interested in right now, and there’s a kind of growing international movement, as exemplified by a new grand challenge that’s been organized by the World Climate Research Programme, to really look at what role clouds play in all of these various global-scale phenomena, not just feedbacks and global warming but a lot of other stuff.

**7 Adaptation takes time**

Dana Nuccitelli - Climate blogger

There’s a popular myth that humans and other species will simply be able to adapt to the Earth’s changing climate, so we have nothing to worry about. This is the fallacy of jumping to conclusions. Unfortunately, just because adaptation exists, it doesn’t mean that species can adjust to any new situation. And history tells us that’s not necessarily true. There have been 5 events over the past 450 million years during which more than three-quarters of the species on Earth went extinct. Species are good at adapting to changes in their surroundings, but there’s a limit to how fast they can evolve.

Humans are changing the Earth’s climate so fast that species are already struggling to keep up. We’re changing it as fast or even faster than during previous mass extinction events. If we continue on our current path of warming the planet by burning lots of fossil fuels, scientists anticipate that more than 40% of species could be at risk of extinction by the end of this century.

The bad news is that if we continue with business as usual reliance on fossil fuels, we’re headed on a path towards the Earth’s sixth mass extinction. If we fail to change our course, it will take millions of years for the planet to recover from this human-caused mass extinction event. The good news is that we’re still relatively early along in the process. Although it will be a difficult task, there is still time to change course and prevent a huge loss in the Earth’s biodiversity.

Species evolve through the process of natural selection. The members of the species that are best adapted to threats survive to pass on their genes to the next generation. The problem is that this process is a slow one. Humans are causing the climate to change rapidly, in a matter of decades, while big evolutionary changes generally take thousands of years.

In Earth’s history, there have been five catastrophic events where most species weren’t able to adapt fast enough to avoid extinction. These are called Mass Extinction Events. In most cases, these events were triggered by huge volcanic eruptions. Those eruptions pumped loads of particles and carbon dioxide into the atmosphere. The particles blocked sunlight, causing a period of sharp cooling. The carbon dioxide increased the greenhouse effect and caused long-term warming. Most species were unable to adapt to these big climate changes.

The first mass extinction event happened 445 million years ago, when 86% of species went extinct at the end of the Ordovician Period. Scientists think that this mass extinction was the result of an intense ice age caused by unusual volcanic events, followed by a warm period 1 million years later. Most species weren’t able to adapt to these big climate changes.

360 million years ago, 75% of species went extinct at the end of the Devonian Period. Scientists think that this mass extinction event was also due to a series of relatively rapid environmental and climatic changes.

250 million years ago, about 85% of species went extinct at the end of the Permian Period. This mass extinction event is also known as “the Great Dying” because nearly all marine species went extinct. Scientists think this event was caused by a massive volcanic eruption covering much of modern-day Siberia. The sulfur ash pumped into the atmosphere by the eruption caused global cooling by blocking sunlight, and created acid rain. The carbon dioxide released into the atmosphere from the eruption later caused global warming. Trapped methane, another greenhouse gas, may have been released from the warming oceans, causing even further global warming.

65 million years ago, 76% of species went extinct at the end of the Cretaceous Period. This is when dinosaurs went extinct. This mass extinction event was caused by a combination of volcanic eruptions and a large meteor impact. Scientists are concerned that we may now be entering the Earth’s sixth mass extinction.

Based on the fossil record, it’s normal for about 40 species to go extinct per year. Over the past 1,000 years, the average extinction rate has been 24 times as large as that natural rate. Over the past 500 years, extinctions are happening at least as fast as the rate that triggered the previous 5 mass extinction events. The good news is that mass extinction events usually happen slowly, over hundreds of thousands to millions of years. However, if we lose all currently threatened species, we’ll be on a course for a new mass extinction event in just over 500 years.

**8 Ecological impacts**

Professor Jonathan Bamber - Bristol U, Dr Jon Bridle - Bristol U, Professor Jeremy Kerr - Ottawa U, Associate Professor Lisa Alexander - South Wales U, Dr Christine Hosking - Queensland U

Bamber: It was curiosity driven, but over time the evidence has become more and more

overwhelming that we're having a very damaging effect on the climate system.

Bridle: And we know the organisms face environmental changes all the time. We know that they're dealing with the environment changing on a daily basis, on a weekly basis. The issue is how much climate change is going to take that beyond the bounds that they're used to experiencing.

Kerr: The thing that I'm especially concerned about is actually increasing incidence of

weather extremes; heat waves kill things and weird heat waves in the middle of winter time kill things really fast.

Bridle: And what climate change is doing is increasing the probability of extreme events,

so that not only is the mean changing, the mean changing actually doesn't seem that much, a few degrees, but the probability of extreme 15 degree differences is becoming much more frequent.

Kerr: The early evidence is alarming to me because it suggests that we're losing populations from places that are experiencing increasing frequencies in intensities of hot summer weather.

Alexander: They've worked out that there is a threshold temperature above which they get mass extinction events in fruit bats. It's something like 42 degrees.

Kerr: One of the interesting things for me as an ecologist, of course, is that you don't

need a thermometer to tell that climate is changing. We see this in hundreds of species across Canada. They are shifting north at a pace, which is incredible and the only explanation that we have yet been able to come with any biological meaning for is that this coincides with rapidly warming temperatures. So if you get really hot, dry conditions in places near the southern edges of species ranges, this wipes them out, so it actually looks like it is possibly the mechanism for range loss at the southern boundaries for species ranges. It might actually be these increasing intensities of those kinds of events.

Hosking: Climate change is very much pushing koalas eastwards towards urbanising centres, so what we're getting almost is a real impact change from increased weather extremes to the west of their range. Over long long periods of drought and heat wave and the koala just can't thermoregulate.

Bridle: The question about whether, the issue about whether or not the organism is going to be able to track the environment sufficiently fast, I think in many cases they won't be able to.

Kerr: We have shown that even butterflies, the ultimate in mobile species, short generation times, highly mobile on an individual level. Even butterfly species are not able to keep up with the rapidity of northern climate change.

Hosking: The adaptation measures for koalas are not great. They're not a very mobile species. For instance, if their climate envelope has shifted 300 kilometres eastwards, a koala just can't think, "I'll just hop over 300 kilometres." They're not that mobile. A male may travel up to 20 kilometres maximum if he's leaving his home range and leaving his mother and wants to create his own territory. But a female koala, if she has adequate habitat, will only move 4 or 5 kilometres, even smaller home range, if the conditions are favourable for her. So to expect a koala to move hundreds of kilometres under such rapid climate changes we're experiencing now is impossible. This is why we're getting real population crashes in those areas.

Bridle: One of the other things that we really value about biodiversity is these interactions between species. It's not just this species looks like this and lives here. It's actually the interactions it has with all other things it interacts with in its lifetime. Those things, particularly in a season environments, they depend on organisms syncing their emergences or their emergence times or their behaviours with one another.

Kerr: The timing, the emergence periods for species around the world have shifted, so

they are coming out by and large earlier. Species which are locked to things like the seasonal differences in light availability, so the timing of day length, for flowering plants that's particularly important. Most of the time that is not how it works for animal species. In the case of pollinators, for instance, and the flowers that they may be associated with. What we are beginning to see is that where their timing more or less used to be matched up, there's, because of the rapidity of climate change, that timing is kind of being ripped apart, so there's a bit of an overlap problem in terms of when some pollinators emerge and the flowering plants that they're associated with will emerge perhaps a little bit later.

Bridle: And that it always use kind of these environmental cues, which is incredibly fantastic amazing things that organisms do to match so they can survive winters, so they know when to go in, they use environmental cues to decide when to go into diopause when to hibernate and then when to emerge. The difficulty is with climate change, those cues are no longer as coordinated as they were and they're no longer as useful, so for example the temperature and the photo period, so that they day length no longer has the same correlation that it used to have. It has a different correlation and this means all organisms may start to make mistakes. Not only for their own survival, they actually have to come out at the right time to actually exploit their resources. So pollinators have to emerge at the same time as the flowers. Otherwise the flowers don't get pollinated and the insects don't get fed.

Kerr: The other thing that happens is that they run out of host plants, so butterflies

can move really fast but their plants are not fabulously mobile as you might well expect. If they run up against the boundaries of their obligate host plants, they're out of luck. They can't go any further than this.

Hosking: The trees are also being affected by those droughts and heat waves. The trees are drying out so the koala's not getting the nutrition and the moisture through the leaf content because, of course, that's what they're completely dependent on, they have a very limited diet. Their food source is getting affected as well. Their climate envelope that I've modelled suggests that anything over about 37 degrees stresses them and, of course, now in Australia we're experiencing a week of days in the 40s, so those prolonged extremes in climate are really affecting the koala.

Bridle: The same with butterflies. 75 percent of the species we define as specialist, they

have a particular species they depend on, their ranges haven't tracked. They haven't responded to climate change effectively. They are effectively condemned to extinction in increasingly fragmented patches.

Kerr: When you're a global change biologist a lot of the time it feels like what you're

studying is like global catastrophe that's unfolding in slow motion and it's important stuff. It's really important that globally the oceans are acidifying or that we are losing species at the rate at which we lost them at the end of the age of the dinosaurs. I mean, this is disaster movies, it's just unfolding at a hundred year time scale. We have to tell people that that's what's happening. Failing to do this, adding unnecessary layers of caution that is inaccurately conveying that these processes may or may not be happening is doing the public a disservice.

**9 Polar Bears**

Dana Nuccitelli - Climate blogger

Polar bears survive by hunting seals. To reach their prey, they need a platform of ice floating on the sea where seals live. Sea ice in productive hunting areas is particularly important for polar bear survival. The problem is that Arctic sea ice is melting, due mainly to human-caused global warming. As the planet has warmed, the Arctic region has warmed the fastest of all. One reason is because the reflective ice has been replaced by dark oceans, which absorb more heat from the sun. About 70% of the Arctic sea ice has disappeared over just the past 35 years.

Not all the Arctic is the same. Sea ice behaves differently in different regions. In some regions, like Canada’s Hudson Bay, the sea ice is seasonal. It melts each summer and re-freezes in the fall. As a result of global warming, the ice-free seasons in these areas have gotten longer and longer. This is endangering the polar bear populations in those regions.

In other regions, the sea ice is more persistent, and polar bear populations are in better shape, for now. In areas called “divergent ice regions,” sea ice retreats from the shore during the summer, like a retracting bridge. Over the last few decades of warming, the sea ice in these regions has retreated further and further away from the shore. This leaves the polar bears with two options. They can come ashore and forego hunting until the ice returns in the fall. Or they can swim long distances to reach the remaining ice pack, where there may be few seals to hunt. It’s in these seasonal ice and divergent ice regions that polar bears are most endangered by global warming and the vanishing Arctic sea ice.

However, there are also areas in which global warming doesn’t yet threaten polar bear populations. One of these is called “convergent ice regions,” where sea ice forms along the shore. For now, there’s enough sea ice in these regions to allow polar bears to continue successfully hunting seals. However, scientists expect that even in these regions, sea ice and polar bear populations may be gone by the end of this century.

Similarly, there are islands in the Arctic far enough north that sea ice stays in place along their coasts even in the summer. These are called “archipelago ice regions.” They provide hunting opportunities for polar bears. However, even this island sea ice will eventually melt if the planet warms too much. Scientists have tracked 19 different polar bear populations in the Arctic. The different groups live in a variety of these ice regions.

Scientists found that the populations of 4 groups are declining, 5 are stable, 1 is increasing, and 9 don’t have enough data to say for sure. The declining populations tend to live in regions with seasonal or divergent ice. The stable populations usually live in regions with convergent or archipelago ice.

For example, in Western Hudson Bay where the sea ice is seasonal, the polar bear numbers have declined by 22% over the past 30 years. In the southern Beaufort Sea, a divergent ice region, the polar bear population has shrunk 40% in just six years. The population included 1,600 bears in 2004, but shrunk to 900 bears in 2010. Only two of 80 polar bear cubs tracked by scientists during that time survived, while the usual survival rate is about 50%.

Some polar bears in the area survived by staying on land during the summer, feeding on whale carcasses. That’s not a long-term solution for the local polar bear population. Polar bears need sea ice to hunt, and warming melts sea ice. So the connection between human-caused global warming and the endangerment of the polar bears is crystal clear.

However, one myth argues that polar bear numbers are greater now than in the 1970s so they’re in no danger from global warming. And it’s true that in the mid-20th Century, polar bear populations may have been in even worse shape than they are today. But this claim is an oversimplification.

Melting sea ice is not the only thing affecting polar bear numbers. In the mid-20th Century, polar bear hunting was widespread and over 1,000 bears were killed each year. As a result, polar bear populations dwindled. Fortunately, the countries where polar bears lived all enacted hunting regulations between the 1950s and 1970s. Thanks to these regulations and conservation efforts, polar bear populations recovered. We ended the previous threat to polar bear populations from hunting. But we replaced it with a new threat from human-caused global warming. This is melting the sea ice they need to hunt on for food.

**10 Ocean acidification**

Ove Hoegh-Guldberg - Queensland University

One of the most significant features of our planet is the fact that 70% of its surface is covered by an ocean. In raw economic terms, the goods and services provided by oceans represent more than $20 Trillion each year. Coral reefs are one of the jewels of the ocean. Despite representing less than 0.1% of the earth’s surface, coral reefs generate 29.8 billion US dollars of global net benefits and support an estimated 850 million people, many of whom depend on reef organisms for their daily protein.

But the biological bounty of our oceans is dependent on the temperature and the concentration of carbon dioxide. As humans have added carbon dioxide to the atmosphere, an increasing amount has been absorbed by the upper layers of the ocean. This has caused an effect called ocean acidification. As you will see, what appear to be small changes in ocean acidity, as measured in ph units, in combination with rising temperatures, can have large impacts on the ocean ecosystems that ultimately affect millions of people.

So far, around 30% of the carbon dioxide generated by human activities has been absorbed by the ocean . Once carbon dioxide dissolves into the ocean, a number of chemical reactions take place. There is an increase in hydrogen ions, which lowers ocean pH. Then some of the hydrogen ions react with carbonate ions to form bicarbonate ions - reducing the quantity of carbonate ions. Now, carbonate ions are important for calcification, the process by which marine animals and plants build their skeletons and shells. Hence any decrease in carbonate ions makes calcification much more difficult.

So adding carbon dioxide to the atmosphere decreases the pH and the concentration of carbonate ions. This leads to a decrease in calcification and a range of other negative effects on the calcium carbonate balance of coral reefs. Another important part of the chemistry associated with ocean acidification is that it takes tens of thousands of years to reverse. The only way the ocean can get less acidic is from materials being washed gradually into the ocean from rocks on land. It is sobering to think that the bad decisions we’re making today will have consequences for at least the next 300 generations of humans.

But how are we so sure the ocean is acidifying? Well – the theoretical chemistry behind the effect of carbon dioxide on oceans has been known for at least 100 years. Based on carbon dioxide levels in the atmosphere, ocean pH should have decreased by 0.1 units since the industrial period. This may seem like an impossibly small amount of change, but the pH scale is exponential. A 0.1 decrease on the pH scale translates to a 26% decrease in carbonate ion concentrations - dramatically changing the availability of this essential ion.

Ocean acidification has been confirmed by measurements taken by oceanographers. Here is just one dataset confirming those chemical changes in the ocean as a result of rising CO2. CO2 in the ocean, shown in blue, is rising, as carbon dioxide in the atmosphere, shown in red, is increasing. Ocean pH - shown in green - is steadily decreasing. This is what scientists predicted.

Geological studies of ocean pH are also giving us interesting insights. Ocean pH has been very stable for a long time. But there have been periods in Earth’s history when it was lower than it is today. This figure pulls together our understanding of how ocean pH has varied over the past 400 million years. The green and the blue lines are from the past – with the decrease being due to high levels of carbon dioxide in the atmosphere. When you compare those periods with values from today - shown in grey - you can see how different the world’s oceans were at those earlier times.

Note, however, the red line shows where we are headed if we continue on the current carbon dioxide emission trajectory. Talk about back to the future! It is also crucial to notice the rate at which we are changing ocean chemistry is extremely high. There is overwhelming evidence that the current rate of change in ocean pH is faster than any other time in the past 65 million years, if not the past 300 million years . Given the well-known sensitivity of marine life to increased pH and carbon ion concentration, this represents a serious challenge to the biology of life in the ocean.

This is a challenge that we’ve been exploring at the University of Queensland. In an experiment with Associate Professor Sophie Dove and our research team at Heron Island, we exposed small sections of coral reef growing under different scenarios of the future. That is, different amounts of changes in temperature and carbon dioxide. Some of the tanks were exposed to a reduced emissions future, other to conditions consistent with a business-as-usual future. We also looked at what would happen if we had not polluted the atmosphere with carbon dioxide in the first place - a treatment we referred to as the ‘preindustrial treatment’. This is the world that Darwin and other scientists saw.

We compared each of these ‘treatments’ to the present-day environment. Take a look at these videos to see what happened in those four treatments over the course of a year and a half. As you see, the top two conditions, the preindustrial and present-day treatments, maintain healthy corals. The bottom two conditions however, reveal a complex set of changes. With mild increases in carbon dioxide and temperature typical of the reduced emissions future, a few corals and other organisms survive. It’s not pretty, but reefs like this might well be able to recover if we stabilise ocean conditions in the long run.

In the business as usual future in the bottom right - where carbon dioxide and temperature increase dramatically - no corals survive. This is a future where marine resources that support people today will have largely disappeared. Looking back over the geological record, it is apparent that corals have survived periods in Earth’s history when conditions were warmer and more acidic than today.

This can lead to the myth that things are okay because coral reefs will eventually return. However, this is very misleading. It ignores the fact that recovery after a mass extinction event takes a very long time. For example, the last mass extinction event that took out the dinosaurs also affected coral so strongly that it took coral reef ecosystems about 10 million years to recover. 10 million years is about 40 times longer than the human species has been on the planet!

Many scientists believe that humans are driving another mass extinction event - from which it will take a similarly long time to recover. Try telling the tour guides on the Great Barrier Reef that there’s no need to worry about climate change because reefs will eventually come back in a few hundred generations! So - in summary - there are real concerns about ocean acidification, based on real-time experiments, models and lessons from the past.

Given this, it’s very puzzling why some people focus on the name ‘ocean acidification’ in order to distract from the issue. This particular myth says that BECAUSE the ocean is not acidic, and that it is not going to get acidic anytime soon, that OCEAN ACIDIFICATION must be a lie. This myth is a \*misrepresentation\* of the situation.

To understand this distraction, let’s look at the pH scale. As you can see, ‘basic’ or ‘alkaline’ conditions range from 14 down to 7 on the pH scale, and acidic conditions range from 7 down to 0. The pH of the ocean is approximately 8.1, so it is correct to say that the ocean is not acidic. However, we know from direct measurements of the ocean that the pH is decreasing, which is referred to as acidification. We are taking an alkaline ocean and are moving it in the direction of acidity.

This is just like adding cold water to a hot bath, and calling it ‘cooling’. But the bath will still be warm even though we have cooled it with cold water! Consequently, saying that ‘ocean acidification is a lie’ is a MISREPRESENTATION. It focuses on semantics rather than the physical reality of our ocean becoming more acidic as carbon dioxide floods into it.

And this completely ignores the fact that ocean acidification is a really big issue. While we have much to learn, evidence shows that the changes we are inflicting on the ocean and on hundreds of generations of people to follow, are potentially very serious - and represent an experiment that we should not be conducting on ourselves or on our planet.

**11 Coral bleaching and ocean acidification**

Sir David Attenborough - Natural hisory film maker, Professor Ove Hoegh-Guldberg - Queensland U, Charlie Veron - Corla reef science, Professor Gregg Webb - Queensland U, Dr Jon Bridle - Bristol U, Professor Jeremy Kerr - Ottawa U.

Attenborough: The two effects of climate change that I think we can be absolutely certain about, beyond any question, is that the temperature of the ocean is rising and the acidity of the ocean is rising.Work has been done here in Heron Island and elsewhere that makes it absolutely clear as to what the effect those two factors will be on coral growth.

Hoegh-Guldberg: So I still remember in the early 80s, for example, when the lab that

I was in at UCLA in California, Los Angeles, the first bleached samples coming out of the Caribbean and being sent to my professor and people going, "We don't know why this is happened, but large amounts of coral have gone white. We're calling it bleaching."

Veron: I've worked on every major coral reef region in the world now with very few exceptions and that's a lot. That's 66 expeditions; that's 6000 hours of SCUBA diving. Working on corals, not playing. I've come back to the same place 20 years later and I've seen drastic deterioration in coral reefs.

Hoegh-Guldberg: As we pump more CO2 into the atmosphere from the burning of fossil fuels, about 30 percent of it is actually being absorbed by the ocean. In once sense, that's been quite good because we've had less greenhouse gases so less of a warming effect, but that CO2 going to the ocean has had its own chemical impact on the ocean. Veron: It wasn't until the early 1980s that I really got alarmed about what was happening

to coral reefs, and then I realised it was happening to oceans everywhere.

Hoegh-Guldberg: We're not only stressed these systems from temperature point of view, we've also imposed a rapidly changing chemistry and that chemistry is, well, I think it's fundamental to their biology, the biology of most organisms.

Veron: Something like a third of all marine species have some part of their life cycle

in coral reefs. It's a huge proportion and so when coral reefs go down, it's not just the extinction of corals, that's almost trivial in this thing, it's the entire ecosystem goes down and takes with it, it will take with it a third of all marine species.

Webb: The other horrible thing about corals is they commonly grow best right at the tolerance of the temperature that will inevitably kill them. They like to live on the edge, thrill seekers in so many ways, and so if you make it a little bit warmer and they don't have time to adapt then you get coral bleaching issues.

Hoegh-Guldberg: We're really in the early stages of changes that are probably happening, well they are according to the IPCC at a rate that's the highest in 65 million years. Much slower and less significant changes have had huge impacts on life and ecosystems.

Bridle: We can look at what happened in the past where mass extinctions happened because of rapid climate change or because of habitat loss, and I think what we generally see, I mean, I'm no expert at this, but what we generally see is that similar types of organism go extinct as those organisms which we now see on red lists that are very sort of critically in dangered.

Hoegh-Guldberg: Well, the mass extinction events, I think, show us what's possible with

actually a lot slower change. which is pretty frightening. When you think about the rates of change we're seeing, apart from the cretaceous boundary event when you have an asteroid hit the Gulf of Mexico, made the Gulf of Mexico. It's hard to think that a lot of these other ones happened over thousands of years. Yet we're doing equivalent changes over a few decades. I suppose these mass extinction events tell us that we can have some major effect with even a lot lower rates of change.

Veron: It's not the amount of carbon dioxide, it's the rate at which it's building up. For

so much of the animal life in the oceans, they're not genetically equipped to accommodate such rapid change.

Hoegh-Guldberg: Coral cover on the Great Barrier Reef has dropped by about a half since the early 1980s. In a way that's like demonstrating that adaptation isn't effective enough to drop that decline.

Kerr: If evolution was working to give them the tools to adapt to changing climatic conditions, they wouldn't be disappearing from hot places and they are.

Veron: I can't see a grain of evidence to tell me that we are not launching into the

6th mass extinction. There's never been an increase in carbon dioxide like we've seen. Kerr: So observed extinction rates around the world right now have reached what, I think most biologists would call a mass extinction level, so we are about, I mean the exact rates are not precisely known, so we normally speak about extinction rates in terms of orders of magnitude relative to what would happen in the absence of human activity. What the geological record indicates is a normal baseline rate of extinctions. Right now we are at about one thousand times the natural rate of extinction, which puts us more or less in the middle of the end of the age of the dinosaurs in terms of how fast species are disappearing from the world.

Attenborough: The increasing, the time passing, increasing those figures lead to disaster unless something is done. There are those who say that there's nothing that can be done except, and my response to that is that it will be worse if we do nothing. There's not an excuse for doing nothing saying you can't stem it - you can slow it down, that's for sure. It will be really culpable if we don't.

**12 Overall Impacts**

Dana Nuccitelli - Climate blogger

The more global warming humans cause, the greater the chance that we’ll trigger some really damaging consequences. Scientists don’t know at exactly what point various impacts will be triggered. However, based on past climate changes and what we’ve seen in recent years, they can estimate what we’ll see in the coming decades.

So far the Earth’s average surface temperature has warmed almost 1°C since the Industrial Revolution. Some significant adverse impacts are expected by the time we reach 1.5°C surface warming above pre-industrial temperatures. For example, that amount of global warming will worsen the problem of widespread coral mortality that we’re already beginning to see. Hundreds of millions of people will be at risk of increased water stress, and more damage from droughts, heat waves and floods. There will continue to be increased species extinction rates. However, by and large these are impacts that we should be able to adapt to, at a cost, but without disastrous consequences.

Once we surpass 2°C, those impacts will become even worse, and some new impacts will occur and be triggered. Coastal flooding will impact millions of people. Coral bleaching will be widespread, and exacerbated by ocean acidification. Most coral reefs may not survive. Global food crop production will decline, with the possibility of major famines. Sea levels will rise by close to 1 meter by 2100. Up to 30% of global species will be at risk of extinction. 2°C is used in international climate negotiations as the ‘danger limit.’ It’s a guardrail that we don’t want to pass because it represents such dangerous potential consequences.

At 3 to 4°C warming, corals are basically toast. The damage to aquatic ecosystems will deplete our fisheries too. If global warming reaches this level, 40 to 70% of global species will be at risk of extinction. We’ll be far down the path toward the Earth's sixth mass extinction at that point. Glacier retreats will threaten water supplies in Central Asia and South America. The possibility of significant releases of carbon dioxide and methane from ocean hydrates and permafrost could amplify global warming even further beyond our control. At this level of warming, sea level rise of 1 meter or more would be expected by 2100, and much more in the following centuries.

The destabilization of the Greenland and West Antarctic ice sheets will become a major risk. If these ice sheets collapse into the ocean, it would cause much more sea level rise and flooding of coastal communities and farm land. Many of these impacts will lead to societal problems. For example, food and water scarcity and flooding can lead to economic damages, mass migrations, and violent conflicts.

Once people move beyond denying the reality the planet is warming and humans are causing it, the next stage of denial is belief that climate change isn’t bad. They’ll often cherrypick a few beneficial climate change impacts, ignoring the many dangerous and damaging consequences that I just discussed.

There is uncertainty about just how soon these damaging climate impacts will hit. However, if we continue on our current path, pumping billions of tons of carbon pollution into the atmosphere every year, we know we’ll trigger these harmful climate consequences eventually. Climate change is ultimately a risk management issue. It’s very much like smoking in that respect. The more cigarettes you smoke, the more you increase your risk of getting cancer. Most people value their health enough that they mitigate that risk by choosing not to smoke.

We face the same choice with climate change. The more carbon pollution we pump into the atmosphere, the more we increase the risk of triggering dangerous and damaging climate changes. For example, coral reef loss, widespread species extinctions, more damaging extreme weather, and loss of coastal property to sea level rise. We only have one Earth and one climate.

Although it makes for good science fiction, we’re unlikely to have interstellar travel available within the next century. We won’t be able to solve the problem by ditching the Earth and moving to a new planet. To mitigate the risks associated with climate change, the solution is to consume less fossil fuels and pump less carbon pollution into the atmosphere. Just as with smoking, the more we reduce the consumption that’s causing the problem, the better our chances of avoiding its dangerous consequences.

**13 Carbon dioxide is a pollutant**

Sarah Green - Michigan Technological U

A pollutant is any substance that has harmful or poisonous effects. We usually think of pollutants as being chemicals like DDT that are both harmful and poisonous. However, a substance that isn't a poison can still be very harmful. A common example is phosphorous, which is an essential plant fertilizer. A person would have to eat about a kilogram of phosphate to be poisoned, so it's not considered a poison. However, excess phosphate is very harmful in rivers and lakes, so it’s considered a pollutant.

Plastic isn't toxic, otherwise we wouldn't eat with plastic forks. But it's still harmful in the environment. That's why we have rules against littering and dumping plastic trash into the ocean. CO2 is a naturally occurring gas. It is not a poison. However, we have overwhelming evidence that CO2 is harmful. It is heating the Earth, acidifying the oceans, and raising sea level. These effects will displace millions of people, disrupt global ecosystems, and threaten our food supply. And, unlike arsenic in your local drinking water, the harm caused by CO2 extends far beyond your neighborhood and covers the whole planet.

One way that some people detract from the real problem of climate change caused by carbon dioxide is to claim "CO2 is not a pollutant".This is an example of the Red Herring fallacy. In 2007, the U.S. Supreme Court agreed that carbon dioxide fits the definition of a pollutant. And the U.S. Environmental Protection Agency decided that CO2 should be regulated as a pollutant because its climate effects pose a clear danger to public health and welfare. In fact, carbon dioxide stays in the atmosphere for about a thousand years, continuing to cause dangerous climate change for centuries. Most of the other substances that we consider to be pollutants don’t last nearly that long.

Quibbling about the technical definition of the word "pollutant" demonstrates the Red Herring fallacy. It’s an irrelevant point that detracts from the real discussion. A red herring is a smelly, smoked fish that was used to distract tracking dogs from the scent they were following. That's probably a myth about the origin of that phrase, but that doesn't change it's usefulness. Wouldn’t it be great if I could divert this whole discussion to a debate about why this fallacy is called a red herring?

We could go on and on about the redness of herrings, the noses of dogs, and the smelliness of fish. Then we’d stop talking about the fact that carbon dioxide is changing our climate. The fact that carbon dioxide is changing our climate should be the focus of the discussion, not how we name harmful substances.

**14 Agricultural Impacts**

Sarah Green - Michigan Technological U

Plants need four key things to grow: light, water, carbon dioxide, and fertilizer. Anyone who has a farm, garden, or house plant knows that plants need the right balance of all of these things. No amount of fertilizer will help a plant that has no water. Scientists studying the impacts of climate change on agriculture look at all aspects of the system. Of those four factors, light will change the least.

But water is a big concern. Changing the climate changes where and when rain falls. Some areas become more wet and other areas become more dry. Rain might come too early or too late for crops. Hotter air holds more water, so when it rains, it pours. Floods wash away seeds and plants. Climate change can cause problems for fertilizer because heavy rain washes it out of the fields and down rivers.

A common myth ignores that fact and claims that "CO2 is a plant food." This is an oversimplification. It chooses a single piece of a complicated problem and ignores the other parts. It's like saying "humans need calcium so all you need to live on is ice cream". Carbon dioxide makes plants grow faster when they are in an ideal environment, like inside a greenhouse, where they have the right amount of water and fertilizer. But for the basic needs of plants, we need to consider carbon dioxide AND water.

It's not enough to have the basic necessities of life. Plants also have to be safe from danger. One big danger for plants is hot temperatures. Our major agricultural crops have ideal temperature ranges. As the temperature goes up, crop yields go down. Plants are especially sensitive to extremely hot days. Some other creatures love hot weather.

Unfortunately, many of them are pests like the Colorado potato beetle, the European grapevine moth, and a nasty wheat blight called FHB or fusarium head blight. Some pests, like FHB, even prefer the taste of crops that have grown with more CO2 and grow faster. Many pests are migrating north as the climate warms, into areas where they’ve never been seen before. The overwhelming consensus among agricultural scientists is that the negative impacts of climate change on crops far outweigh the small benefit that plants gain from extra CO2.

**15 Experts: Impacts on society**

Professor Katharine Hayhoe - Texas Tech U, Dr Sarah Perkins - New South Wales U, Professor Jonathan Bamber - Bristol U, Professor Eric Rignot - UC Irvine, Associate Professor Lisa Alexander - New South Wales U,  Matthew England - New South Wales U, Professor Richard Alley - Penn State U, Professor Lonnie Thompson - Ohio State U, Professor Luke Copland - Ottawa U, Professor Jeremy Kerr - Ottawa U, Professor Ove Hoegh-Guldberg - Queensland U.

Hayhoe: I loved the “Years of Living Dangerously” because they tackled one of the main myths about climate change head-on. One of the main myths is that climate change is a distant issue. It’s distant in space. It’s only about the polar bear and not about us. It’s distant in time. It’s only about future generations and not about us. This is a myth that isn’t just among people who don’t think climate change is real—even many people who do view it as, “Oh, it’s just—we’ll deal with it in the future.” The “Years of Living Dangerously” said, “No, we are dealing with it right now, whether you like it or not, and let us show you the faces of the people around the world who are dealing with it.”

Perkins: So we're not talking like we were 50 years ago or 40 years ago, oh, this will

be a problem. It is a problem.

Bamber: All the systems we have in place, agriculture, urban environment, everything

we've set up has all been predicated on this very very stable climate, which we're now starting to tinker with, fiddling with the dials in an uncontrolled way.

Rignot: The science is looking at the impact on the climate, the impact on humans, sea

level, impact on precipitation, it's going to be an impact on food production. It's going to be an impact on the way people live. Pretty serious impacts. Impact on biodiversity, which, in my opinion, is bigger than sea level rise right there - the decay of species.

Perkins: Unfortunately it's not the people who are causing the problems that will be

most affected. America and us are the highest emitters per capita, but it's the people in the developing regions that will be affected the most. Poor old Kirabati is already having saltwater intrusion inundation and sea level rise. And they're not putting any greenhouse gas emissions into the atmosphere.

Alexander: You can imagine if you are on a low lying Pacific island, well actually a

small amount of sea level makes a massive difference to your livelihood. Combine that with a high tide or a storm surge and then we get regions of the world that are very vulnerable to these combined events.

Bamber: We are very very vulnerable as a species to relatively small changes in sea level.There are countries like Bangladesh, The Netherlands and all the atolls in the South Pacific, which would be absolutely devastated from a sea level rise of more than a metre.

England: Millions and millions of people are set to be displaced with our low end projections of sea level rise. If we start tracking at higher ends because of these rapid melting of the land ice over Greenland and Antarctica regions, you could have even more rapid displacement of populations.

Bamber: The sea level rise around about a metre it's suggested would displace potentially up to 200 million people.

Alley: It's very clear that if you push slowly on the climate a lot of the things that we

have built hit sudden thresholds. Either the city is hiding behind the levy and the water stays just below the levy during the storm or just above. And that little change can make a huge difference to weather your city is livable or not the next few weeks.

Thompson: I think in the tropics, this is where you're going to see the first real impacts

on people because people are living right downstream below the glaciers and there are large numbers of people living downstream, so what's happening to those glaciers become extremely important.

Copland: What glaciers do is they act as sponges basically, so in the winter they hold that snow that falls and then they release that snow in the dry time of the year, which is typically the summer. What glaciers do is they tend to even out the annual precipitation that falls and essentially allow areas to carry on to have agriculture in the summer when otherwise there would be areas that are very very dry.

Thompson: If you go to a country like Peru—70 percent of the tropical glaciers on Earth

are in Peru, in the Andes of Peru. Here you have a country of 34 million people. Over 50 percent live in the desert, on the west coast of Peru, depending on rivers that originate in the glaciers up in the Andes. Seventy-six percent of their electricity comes from hydropower, the water coming from those glaciers. If you're working in Tibet, there are 46,000 glaciers there. You take a river like the Indus River, it flows through China, through Pakistan, and through India, all nuclear-powered counties. All depend on that river for water supplies. These are places—geopolitical hotpots in the future.

Copland: I think perhaps the biggest impact is on agriculture because the prairies, the

stretch east of the Rockies, there's huge areas that are fed by the rivers that flow from the Rockies.

Alexander: So you can imagine if we are trying to feed a global population and there are

crops like wheat, for example, which don't have a high tolerance to certain high threshold, then we could be in serious trouble.

Perkins: Those that don't have access to things like air conditioning or good public health infrastructure. If you get a heat wave in those sorts of areas, people get sick or the elderly generally get really sick after a heatwave if they don't have the public infrastructure to cope with that more people will unfortunately be killed.

Alexander: So when you look at health and when you look at morbidity and mortality rates, they increase substantially during heat wave events and, in fact, Europe in 2003 there was somewhere around about 35,000 to 50,000 excess deaths due to the heat wave.

Kerr: Some of my research is in east Africa. We are seeing climate change impacts in those places and they are scary. You see what happens to people when the distributions of malaria carrying mosquitoes expands. It kills them. It's not an academic issue for me. This is a deeply, ethically based issue.

Alley: Climate change in the short term is expensive but not hugely so, and as the climate change gets bigger, as we look farther into the future, the price goes up. The damages go up. Very crudely, each degree of warming costs more than the previous degree. The first degree was almost in the noise of what we're used to. It's not very expensive, but we've used that one. And the second degree will cost a little more. It's moving outside of your experience that's starting to stress things and we've committed to that one very broadly. The third degree costs more than the second and by the fourth and the fifth now sea level rise is going to get huge.

We have real problems with crops, which may be bumping up against biochemical limits and the ability to feed ourselves get s a little worrisome. By the time you start running to the third, the fourth, the fifth degree the costs of damages and dangers go way up. What we're arguing now about the third degree because we've basically warmed up almost all of the first one and we really have committed to the second one.

Kerr: There are consequences in terms of human life for this. There are consequences in terms of extinction rates for this. There are consequences in terms of ecosystem services. Every single day that goes by that we don't begin to address these problems, the problem gets worse, more expensive, more immediate and, in some parts of the world, has a toll in terms of people dying and for me this is just fundamental, we don't have time to muck about with this. This is not an ivory tower argument. This is is one where the consequences are real.

Hoegh-Guldberg: We have to really try and wake people up to realise that this is happening. It's very very serious. But we can solve it. And we have to do so not because it's going to cut the economy but because it's the planet we live on and it's the people we love that are going to be affected.

**16 Extreme weather**

Keah Schuenemann - Metropolitan State U of Denver

Since heat is a type of energy, the simplest way to think of global warming is to say that we are \*adding energy\* to our climate system. This creates a warmer, moister atmosphere. All weather will be affected in some way by the new, more energetic, climate that we are creating.

Even though we know the climate is changing we cannot answer the question “was this specific weather event \*caused\* by climate change?” In the same way, if you are tired and forget your wallet at home, you cannot say for sure that you forgot the wallet \*because\* you were tired. You might have forgotten it anyways. What you \*can\* say is that your overall performance throughout the day will be affected by your lack of sleep, just like it is with global warming and the climate system.

We should be asking the question “are weather events being \*affected\* by climate change?” The answer is, global warming \*amplifies\* the risk of extreme weather in several ways. It is causing warmer ocean temperatures, which can feed heat and moisture to storms, or change where they develop. A warmer atmosphere can also hold more moisture. This means rain and snow are likely to fall more heavily. Moisture is also the key to some extreme precipitation events, such as flash flooding from a big rain storm.

How can moisture power storms? Let’s use the formation of a thunderstorm as an example. As warm air rises it cools and water vapor condenses into liquid cloud droplets. When water condenses, it releases heat. This causes the air to rise even further, creating a nice, pronounced updraft in the storm. When you watch a thunderstorm form it can seem explosive. The heat released when the water condenses feeds more energy into the storm. The warmer the atmosphere, the more water vapor to feed this explosion. As a result, we’re experiencing more heavy rainfall events.

So while we can’t say if global warming caused a specific storm to form, we \*can\* predict some overall changes that we expect global warming will cause. For example, we’ll expect more rain and snow at mid to high latitudes of the Northern Hemisphere. That’s right – in some regions that are cold enough, we’re seeing \*more\* snow because of the extra moisture in the air. We also see that wet areas are getting wetter and dry areas are getting drier. So at the same time that we’re seeing more drought in some regions, we’re also seeing increased monsoon rainfall in other regions.

And the type of precipitation that leads to floods is getting more intense in the US, Europe, and other regions. This is projected to increase by 5-20% this century for some regions. So global warming is affecting all weather. But that doesn’t mean every time an extreme event happens, we can say global warming CAUSED that specific event. It’s important to be careful in how we speak about this.

While scientists are pretty careful, the news media sometimes makes questionable claims about the causes of extreme weather events because, well, connecting a destructive weather event with global warming can make a provocative headline! Extreme events have always happened, and detecting new trends takes time. Weather is highly variable, so detecting a trend from global warming involves separating the human influence from the natural variability. But we \*have\* observed more frequent occurrences of certain types of extreme weather and there is more and more evidence that some of these changes are caused by global warming.

When human caused climate change and a natural extreme occur together by chance, that’s usually when records are broken. One of the many techniques that attribute events to natural or human causes is to determine the likelihood of an event in the absence of global warming. Sometimes this involves using statistics and computer simulations. If there’s a really unlikely event, like a 100 year flood, that we see happening more and more often, then it’s easier to say global warming has increased the risk of those types of events.

For example, in June of 2013, parts of India experienced a heavy precipitation event that caused landslides, debris flows, and extensive flooding that sadly killed more than 5,800 people. Scientists found that events like this are happening more often now than they did 100 years ago, pointing to global warming playing a larger role.

However, one myth says that climate change isn’t connected to extreme weather. Typically, the argument goes that extreme weather has happened in the past, without human-caused global warming, so any extreme events we see today must be natural, just like they’ve always been. This argument is jumping to false conclusions.

Just because extreme weather has happened in the past, before humans, doesn’t mean that humans can’t affect weather conditions now. Extreme weather has always happened, but now, in the warmer, moister climate that we are creating, they are likely to be more severe and happen more often than they did in the past. Ironically, fossil fuels are fuel for extreme weather.

17 Heat waves

Keah Schuenemann - Metropolitan State U of Denver

In this lecture, we’ll look at \*why\* heat waves are happening more often. Spoiler alert, it’s because of global warming. Europe, Asia, and Australia are already seeing more frequent heat waves. Heat waves can cause droughts, which can lead to wildfires and crop failures, and they can be extremely deadly! Did you know that the heat wave in Europe in 2003 killed more than 50,000 people? A study found that human-induced greenhouse emissions made it approximately four times more likely that a summer like Europe had in 2003 would occur. Okay, so heat waves are already more common.

But how do heat waves relate to global warming? This bell curve is showing us the odds of getting cold, average, or hot weather. The curve shows that in a normal climate, there are good odds for average weather, that’s why it’s the average! The chances of getting cold or hot weather are pretty low, making up the wings of the bell curve. Now, if the global average temperatures go up due to human-caused global warming, the average temperature will go up, shifting the whole bell curve towards the hot end! This increases our chances for more \*hot\* weather, and the \*record\* hot weather now pokes out into dangerously warm territory.

Think of global warming as the earth on steroids. If a baseball player takes steroids, I bet he’ll hit a lot more home runs! This means a warmer world is a weirder world with more extremes. Our chances of getting home-runs, or extreme temperatures, just got bigger. This graph is showing that by increasing the range of temperatures, or making the weather weirder, we’ve created a world where we get average weather less often, but we get weirder weather more often! The wings of the bell curve got a little thicker.

When we combine the effects of the increase in average temperature with the increase in weirdness, we get a lot more record hot weather! The dark orange area shows that we expect heat waves to be hotter AND happen more often. It’s likely that human influence on the climate has ALREADY more than doubled the probability of occurrence of heat waves in some locations! It’s virtually certain that there will be more frequent hot temperature extremes over most land areas in the future. It’s also very likely that heat waves will occur more often and last longer in the future.

Another contributing factor is that we have also observed that nights are warming faster than days. This is a human fingerprint of global warming because it implicates the greenhouse effect. With a stronger greenhouse effect, less of the Earth’s heat can escape to space at night. If you’ve ever spent a hot summer in a place without air conditioning, night time is our only chance to open the windows and cool things down! If nights are hot, this is one more ingredient for a nasty heat wave in the making!

Finally, heat waves in a global warming world will put more heat stress on people in some regions, making heat waves more deadly. This is because a warmer world, on average, is a more humid world. We know that the heat index, or what the temperature FEELS like outside, depends on how humid the air is. When the air is nice and dry, the beads of sweat on my forehead can evaporate easily, cooling me down. When it’s humid outside, my beads of sweat don’t evaporate, leaving me hot and sweaty. Yuck! This adds to human discomfort and make heat waves even more deadly, especially in places without air conditioning.

So that’s how heat waves are related to global warming. However, one myth distorts the evidence for increasing heat waves. The myth is that heat waves have happened before, so you can’t say that today’s heat waves are caused by global warming. This myth uses the technique of a logical fallacy called a non sequitur, which is Latin for “it does not follow.” It means the myth is simply jumping to conclusions. It’s kind of like saying “Well, humans were dying of cancer long before cigarettes were invented, it therefore follows that smoking does not cause cancer.”

Clearly this isn’t good logic, just like saying because there were heat waves in the past, today’s increasing heat waves can’t be related to global warming. Remember, we are already observing more heat waves in some regions and we expect to see more, longer heat waves in the near future, and now you know the science behind why!

**18 Hurricanes**

Peter Jacobs - George mason U

40 years ago in the United States, Kerry Emanuel became a registered Republican. As an undergraduate at MIT in the 1970s, his classmates’ far left, pro-communist views horrified him. Today, politically, not much has changed for him. He still thinks highly of conservative icons, like Ronald Reagan. He still mostly votes Republican. But Dr. Emanuel also happens to be the Cecil & Ida Green Professor of Atmospheric Science at MIT. He is a leading expert in the field of hurricane research.

And he now gets email threats from other conservatives. Because Emanuel doesn’t just study hurricanes. He studies the ways in which human-caused global warming can make hurricanes more destructive in a warmer world. How did a conservative undergraduate end up as the face of global warming’s impact on hurricanes? By following the science.

The science of hurricanes tells us rising sea levels, heavier rains, stronger winds, and warmer ocean water will cause hurricanes to grow stronger as we warm the planet. One of the most damaging effects of hurricanes is their storm surge. Hurricanes’ powerful winds pile up enormous volumes of water. The low pressure of the center of hurricanes lets the ocean level rise higher. Together, they create a towering supply of water. Waves ride on top of this surge. In a world without climate change, hurricanes still produce storm surges. But as we continue to heat up the planet, we cause sea levels to rise. This increase in the underlying sea level makes the storm surge from hurricanes even larger in a warming world. That means storm surges can do more damage over the same area, and reach areas even further inland than before.

A recent report by Lloyd’s of London, an insurance firm, looked at the effect of sea level rise and Hurricane Sandy. They estimate that the relatively small amount of sea level rise we’ve had increased Sandy’s damages by 30%. Or around $8 billion USD in New York alone.

In addition to storm surge, hurricanes produce torrential rains. The warm, moist air they pull up from the ocean cools and condenses as it rises, causing massive rainfall. As we warm the planet, the heavy rains from hurricanes are expected become even heavier. These rains drench coastal areas, which combines with the storm surge to cause massive flooding. Hurricanes are also destructive because of their fierce winds. As we continue to warm the planet, the maximum wind speeds of hurricanes are expected to get even faster.

Hurricanes form in the tropics for a reason. They depend on hot ocean temperatures relative to the coolness of the air above. As we warm the climate, this can provide more fuel for hurricanes, making them more powerful. Studies looking at this question using many different methods have begun to converge on agreement about this. A warmer world will have stronger but fewer storms.

Not all of the changes to hurricanes in a warming world may make them worse. If ocean temperatures are hurricane fuel, wind shear is hurricane kryptonite. Wind shear is just the difference in wind speed at different heights in the atmosphere. When wind speed is pretty much the same down low as it is higher up, hurricanes can grow strong. When wind shear is high, that is, when wind speeds are different, hurricanes get ripped apart. As humans warm the planet, some places where hurricanes form may see an increase in wind shear. That means that for those areas, hurricanes may grow more intense, but also break up more often as they try to form. So we may see somewhat fewer, but more powerful storms overall.

Hurricanes are also pushed around the ocean by prevailing winds. These steering winds might also change as we heat the planet. For some areas, that might mean more storms get pushed away from land. For other areas, that might mean more storms make landfall. But this too remains an area of active research.

But climate skeptics reject even the most solid links between climate change and hurricanes. They say that hurricanes have always happened. They point to devastating storms that occurred in the past, when human influence on the climate was smaller than it is today. They point to short periods without major hurricane strikes as evidence that nothing is changing. They are sure- there is no link between global warming and hurricanes.

A closer look at skeptics’ claims reveals that they don’t actual challenge the scientific links between warming and hurricanes at all. Rather, their claims rely on a number of fallacies common to science denial. One of the most pervasive is oversimplification. Of course hurricanes, even terrifically powerful ones, have happened in the past. And sure, they’ve happened when greenhouse gas levels were much lower than they are today. But that’s not the whole story.

We know that hurricanes are affected by a number of environmental factors. One of the strongest being is hot ocean temperature. Looking back over hundreds of years, we can see that hurricanes have gotten stronger in response to natural increases in ocean temperature. That strengthens our confidence that hurricanes will get stronger as humans warm the ocean relative to the atmosphere. It doesn’t weaken it.

Climate skeptics are fond of pointing to periods with low hurricane activity to deny a link with warming, while ignoring the bigger picture. This is a common science denial tactic called cherry-picking. They point out that in recent years the North Atlantic has not had as many dramatic storms as the mid-2000s. However, the overall picture since we’ve had accurate observations points to an increase in hurricane activity. And that this increase is strongly tied to warming ocean temperatures.

When we reconstruct storm activity over hundreds of years, we see a similarly close relationship. Based on such flawed reasoning, climate skeptics jump to a faulty conclusion. They draw the wrong lessons from what observations and history tell us about hurricane behavior. During his research, Kerry Emanuel has flown into the eye of a real world hurricane. And although his findings have put him in the middle of political storm, the science doesn’t care about politics.

How hurricanes will change in a warming climate is an area of active research, but some links to warming have become clear. As humans warm the planet, rising sea levels, heavier rains, stronger winds, and warmer ocean water will increase the destructive potential of these massive storms.

**19 Making sense of the slowdown**

Kevin Cowtan - York U

The Earth’s climate is controlled by the energy balance at the top of the atmosphere. If more heat enters the atmosphere than leaves, then the planet warms. Adding heat trapping gases changes the balance, which in turn causes warming. Ocean heat measurements show that the planet is indeed absorbing heat. Despite this fact, it is often claimed that the global warming has stopped. This claim is inspired by evidence that warming of the atmosphere has been slower over the past one and a half decades. This slowdown is sometimes called the hiatus.

However, there are other factors which affect the atmosphere over shorter periods. These can cause faster or slower warming of the atmosphere. To understand the slowdown in warming, we need to understand some of these factors. If we look at the global surface temperature over the past 3 decades, there are big changes in temperature from year to year. We know the cause of some of these variations.

One of the biggest is the El Nino cycle. El Nino is a phenomena in which heat is stored up in the western Pacific Ocean, and then released to the atmosphere in the eastern Pacific. This happens over the course of a few years. El Nino is not predictable, but we can track it in retrospect through sea surface temperature measurements. If we compare past El Nino cycles with temperature changes over the past three decades, we can see that there is a strong relationship between the two. El Nino years tend to be hot years. Recent years have been dominated by the cool phase of the cycle. This is responsible for some of the slowdown in warming.

However, El Nino doesn't explain everything. There are cooler periods in the early eighties and nineties which don't fit the El Nino cycle. These were caused by two major volcanic eruptions, El Chichon and Pinatubo. Dust from the volcanoes spread in the upper atmosphere, cooling the surface. Smaller eruptions happen all the time, but can also affect temperatures. There has been an increase in the number of small eruptions over the past few years, offsetting a bit of the greenhouse warming.

Another factor is the solar cycle. Satellites tell us that the sun varies in brightness with the sunspot cycle. The last cycle has been particularly weak. A dim sun also offsets a little bit of warming.

Yet another factor is pollution. Rapid industrialisation in Asia has led to more particulate pollution in the atmosphere, which also has a cooling effect.

The final factor is in the observations themselves. Two of the major temperature data providers, the UK Met Office and NOAA, don't include the Arctic in their global temperature calculation, because there are no weather stations there. But the Arctic has been warming faster than anywhere else on the planet. Missing it out leads to an underestimation of the rate of warming.

To recap, greenhouse gases have continued to grow over the last one and a half decades. But over the same period, volcanoes, the weak sun and pollution have had a cooling effect, and the rate of warming has been underestimated as well. Two recent studies have put all of these together. If we ignore the short term influences, climate models predict faster warming than we have observed. However, if we use global temperature estimates, and add the influence of El Nino, volcanoes, the weak sun and pollution into the models, then the agreement is good.

What can we conclude from this? When we put everything we know into the models, the answers match what we observe. So the slowdown in warming makes sense in retrospect, and doesn’t give us a reason to doubt the models. However, we couldn't have predicted it in advance, because we can't predict volcanoes, pollution or the sun.

The slowdown in warming has created a whole family of myths with different levels of sophistication. At one extreme, it is possible to argue that the hiatus should reduce our estimates of climate sensitivity. This is a genuine scientific argument, although the analysis we have just seen suggests that no reduction is required.

At the other extreme, it is sometimes claimed that the hiatus disproves the role of CO2 in global warming. They claim that CO2 has increased, but the world hasn't warmed. This is an example of a strawman, and a complex cause fallacy. Climate science doesn't claim that CO2 is the only factor which affects temperature. This is why the hiatus is so hard to deal with. The myths may be wrong, but they are simple and convincing.

The complex cause fallacy exists because people like things to be simple, but explaining the complex drivers of climate is hard. But in the end, all the hiatus myths revolve around drawing attention away from the big picture. When we look at the big picture, the hiatus does not change our understanding of human caused global warming.

**20 Tree growth and warming**

An anomalous reduction in forest growth indices and temperature sensitivity has been detected in tree-ring width and density records from many circumpolar northern latitude sites since around the middle 20th century. This phenomenon, also known as the "divergence problem", is expressed as an offset between warmer instrumental temperatures and their underestimation in reconstruction models based on tree rings.

The divergence problem has potentially significant implications for large-scale patterns of forest growth, the development of paleoclimatic reconstructions based on tree-ring records from northern forests, and the global carbon cycle. Herein we review the current literature published on the divergence problem to date, and assess its possible causes and implications.

The causes, however, are not well understood and are difficult to test due to the existence of a number of covarying environmental factors that may potentially impact recent tree growth. These possible causes include temperature-induced drought stress, nonlinear thresholds or time-dependent responses to recent warming, delayed snowmelt and related changes in seasonality, and differential growth/climate relationships inferred for maximum, minimum and mean temperatures.

Another possible cause of the divergence described briefly herein is 'global dimming', a phenomenon that has appeared, in recent decades, to decrease the amount of solar radiation available for photosynthesis and plant growth on a large scale. It is theorized that the dimming phenomenon should have a relatively greater impact on tree growth at higher northern latitudes, consistent with what has been observed from the tree-ring record.

Additional potential causes include "end effects" and other methodological issues that can emerge in standardization and chronology development, and biases in instrumental target data and its modeling. Although limited evidence suggests that the divergence may be anthropogenic in nature and restricted to the recent decades of the 20th century, more research is needed to confirm these observations. © 2007 Elsevier B.V. All rights reserved.

**21 Water in the Atmosphere**

Keah Schuenemann

Supplemental material on water vapor, humidity, clouds, precipitation, and extreme weather . First, let’s fix a common misconception. Clouds are made of billions of tiny ***liquid*** cloud droplets suspended in the air, and many clouds also have ***ice particles*** in them as well. In other words, they are ***NOT vapor clouds*** . Clouds are liquids and solids, NOT water vapor. Water vapor is invisible. Open your mouth and breathe out! You just emitted water vapor. Did you see it? Not if it was at a temperature where it was allowed to stay a vapor. We can see clouds and fog because they are liquid and solid, not vapor.

Therefore, in my “Water vapor amplifies warming” video, I’m only referring to the vapor, gaseous form of water as a greenhouse gas. Greenhouse gases are unique in that shortwave visible light from the sun goes right through them because they are invisible, but the earth’s outgoing longwave infrared radiation gets absorbed by greenhouse gases. This differentiates them from clouds. Clouds are visible and have a high albedo, or reflectivity. This means sunlight can’t go through them. They still can absorb outgoing longwave radiation from the earth, though. In this sense, liquid and ice clouds are not greenhouse *gases* , but do play a role in absorbing the earth’s infrared radiation, so in that sense they are playing a role in the greenhouse effect. As we learned in Peter Jacob’s video, high, thin clouds let the sunlight through, but absorb the outgoing radiation from the earth, while thicker clouds simply reflect the sunlight, cooling the areas underneath the cloud, shaded by the sun. Of course those thick clouds also absorb outgoing radiation from the earth. So all clouds have this blanketing effect, but thin clouds let sun in AND have a blanketing effect, warming the climate.

How is a cloud formed? For the sake of simplicity, let’s stick to liquid clouds, not ice or mixed clouds, but keep in mind most clouds are mixed ice and water. A liquid cloud is formed when water vapor condenses onto cloud condensation nuclei (CCN), forming tiny droplets. CCN are suspended particles like dust, salt from sea spray, pollution from combustion, volcanoes, or forest fires. Not all CCN are from natural sources, so clouds in polluted areas may have more CCN to work with than cleaner environments. This affects clouds’ optical thickness and ability to precipitate!

If cloud condensation nuclei are available, the only other ingredient to form a cloud droplet is condensation. When the air becomes saturated , or the relative humidity is 100%, condensation takes place, forming cloud droplets. There are two ways to reach 100% relative humidity and saturation.

1. One is to add more water vapor to the system. The best sources for water vapor are warm oceans or seas. This doesn’t mean the sea has to be close by, the wind can advect moisture into an area. In fact, much of the moisture in the central United States where I live, comes from southerly winds bringing moisture from the Gulf of Mexico when large cyclonic systems go by. Wet ground or transpiration from plants can also be good moisture sources.

2. The other way to reach 100% humidity is to cool the air. This can be done in a variety of ways. The wind can blow in cooler air. Air can be lifted by convection, fronts, low pressure systems, or orographic lift in mountainous regions. Air expands and cools as it is lifted, so upward vertical motion is conducive to cloud creation.

Here’s why those are the two ways to get to 100% relative humidity, or saturation.

Relative Humidity equals how much water vapor is in the air divided by how much water vapor the air can “hold” at a given temperature. More technically, relative humidity equals the ratio of vapor pressure to saturation vapor pressure .

Relative Humidity= how much water vapor is in the air / how much water vapor the air can "hold". Relative humidity = Vapor pressure / Saturation Vapor Pressure.

Vapor pressure is the weight (technically force per unit area, pressure) of only the vapor molecules in the air. I think of this as the weight of just the H 2 O’s, not the N 2 ’s or O 2 ’s in a column of air.

Saturation vapor pressure is the pressure that water vapor molecules would exert if the air were saturated at a given temperature. This temperature dependence is known as the ClausiusClaperyon relationship. In order to get the relative humidity ratio high enough for saturation, we can increase the top part of the fraction by adding more water vapor to the region, or we can decrease the bottom part of the fraction by making the temperature colder.

Turns out, it’s pretty hard to separate the water vapor molecules from all of those nitrogen and oxygen molecules floating around in the air to measure vapor pressure. Instead we measure humidity in a variety of other ways. One of the more intuitive ones is we can take a blob of air and simply cool it until dew (a droplet) forms. This gives us the dew point temperature , the temperature air would have to drop to in order for dew to form. In this case, if the temperature was 30 degrees and the dew point was 30 degrees, the air would be saturated and the relative humidity is 100%. Unfortunately you can’t calculate the relative humidity from temperature and dew point, besides the 100% example I just gave, you’d have to use an equation or a lookuptable to get them into the vapor pressure units of millibars. Still, the proximity of the dew point to the temperature gives us an idea of how saturated the air is.

What you can’t see in my water vapor amplifies warming video is that “holds” is in quotes. This is because the statement, “Warm air can hold more water vapor than cold air” is an oversimplification that I chose to use because it will not lead you astray in this context. The proper way to say it is, warm air has a higher saturation vapor pressure than cold air. Here’s the truth, most of air is just empty space between molecules, so making it seem like the air gets “full” of water vapor at a certain point and then squeezes it out into a liquid droplet is misleading. When the relative humidity is 100%, that means the air is saturated and there is more condensation than evaporation. This is when dew, fog, or cloud droplets form. Even the word “saturated” and “capacity” makes us think of the word “hold,” which is why I continue to use it to simplify a complex topic.

Remember, relative humidity tells us how close the atmosphere is to saturation, which is one way to talk about humidity. Relative humidity can change throughout the day as the temperature rises and falls without changing the amount of water vapor in the air. In the morning when temperatures are low, the saturation vapor pressure is low and dew is likely to form. In the afternoon when it is warm out, the relative humidity goes down. Another way to talk about humidity is the specific humidity (vapor pressure, dew point temperature). This tells us how much water vapor is in the air regardless of temperature or saturation vapor pressure. It just tells us how much water vapor there is. This is just the top part of the relative humidity fraction.

Now that we understand humidity, how will it change with global warming? Global warming increases the amount of water vapor in the air. The main reason we have a more water vapor molecules in a warmer global climate is because evaporation increases with temperature. Picture a warm, tropical ocean versus a cold, polar ocean. The warm, tropical ocean has more energetic water molecules and the air above it has more energetic molecules than over the cold, polar ocean. Therefore, evaporation rates increase, putting more water vapor molecules into the air. We have found that there is more water vapor in the air with the warming we have already achieved. This makes the greenhouse effect stronger because water vapor is a greenhouse gas. (Note that there are many levels of the atmosphere and even within the lowest layer, these variables are not always the same with height.

Global warming increases the saturation vapor pressure of the air

If the temperature of the atmosphere is also rising, then the saturation vapor pressure, the amount of water vapor the atmosphere can “hold” will get larger. It turns out the ratio of the two, or the relative humidity, could stay about the same, but depends on which level in the atmosphere we measure it at. Refer to the IPCC report for these observations and projections.

More water vapor and higher temperatures could lead to the same relative humidity we have today. This result also will affect cloudiness. Will we have more high, thin clouds in a warmer world? More low, thick clouds? How will changes in aerosol pollution change these clouds? This is extremely complex and one of the areas contributing to the ranges of uncertainty in model projections of the future. Some great scientists are using a variety of satellites and instrumentation to study clouds in order to lessen our uncertainty going forward.

Latent Heat

One of the awesome things about water is that it exists in all three phases, gas, liquid, and solid, in the earth’s atmosphere. It is the change in phase of water that is responsible for latent heat absorption or release.

Evaporation (liquid to vapor) cools the environment around it as heat is absorbed. This is why our bodies sweat, in an attempt to cool us down by encouraging evaporation. As we learned in the heat wave video, if the relative humidity is too high, the air is near saturation and evaporation might not take place, leaving us wet from our sweat, and hot. Dogs pant and stick out their wet tongues when they are warm to cool down via evaporation. Pigs roll in wet mud to cool down by evaporation.

In the opposite sense, condensation (vapor to liquid) warms the environment around it through latent heat release during this phase change. This is how liquid clouds are formed. This heat release helps enhance upward vertical motion, creating large storms if atmospheric stability allows. If the actual amount of water vapor in the atmosphere goes up as evaporation off of the oceans increases, then these storms have more water vapor molecules to work with, meaning more phase changes and more latent heat release. This is one piece of the theory behind extreme weather increasing with global warming.

Precipitation

Once the cloud has formed, again assuming liquid clouds for the sake of simplicity, cloud droplets within the cloud grow and run into each other within the turbulent cloud. As they collide, they coalesce, or stick to each other. These droplets grow larger and larger until they are heavy enough to fall from the cloud as rain. Again, with more available water in the atmosphere, rainfall rates may become heavier than in a cooler world. However, if the air is polluted with too many aerosols from dirty coal burning, the clouds may have too many small cloud droplets. If there are too many small droplets, the cloud will take more time to get big enough cloud droplets to precipitate. Polluted clouds may last longer and precipitate less. You can see why cloud physics with climate change is complex!

Keep in mind that moisture changes will be regionally different. Some places may become drier and be more likely to lead to drought while other places will have more moisture available and heavier rainfall.