**U. of Queensland Climate Denial Course - Lecture 4**

 **Climate Models and the Past**

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**1 The past tells us about the future**

John Cook - Research communication fellow

Welcome to Week 4 of Denial101x. Last week, we looked at the many human fingerprints indicating that humans are causing global warming. This week is divided into two - the past and the future. We can’t run lab experiments with our whole climate system. But what we can do is look at past climate change, throughout Earth’s history. How our climate behaved in the past provides insights into how our climate will behave in the future.

Peter Jacobs takes us into the deep past, millions of years ago when CO2 levels in the atmosphere were much higher than today. Robert Way goes medieval, looking at the medieval warm period just under 1000 years ago. Andy Skuce looks at the Little Ice Age, in the 1800s. And finally, well, it wasn’t that far back in the past but Daniel Bedford looks at what climate scientists were predicting in the 1970s.

Climate scientists make predictions using climate models, which provide a number of insights into how future climate will behave. How do they do that? Dana Nuccitelli explains how climate models are based on fundamental physical principles - that’s how they’re able to simulate how our climate behaves. He looks at how predictions based on physics tend to be a lot more accurate than predictions based on wishful thinking.

Keah Schuenemann will explain the difference between weather and climate. She’ll also examine how climate scientists have a tendency to underestimate climate impacts. Lastly, we release interviews with scientists studying the Earth’s past as well as modelling future climate.

And this week, we finally release Part 1 of our trilogy, The Climate of Middle Earth. This features an interview with Dan Lunt, a climate scientist from the University of Bristol who built a computer model simulating the climate of Middle Earth. Now this video isn’t just an opportunity for Dan and myself to geek out about Lord of the Rings - there are actually some serious scientific insights into climate models to be found in this interview. But yes, simulating the climate of Mordor is pretty cool. This week features part 1 of a three part series - we didn’t want to overwhelm you with too much Middle Earth at once. So this week is a rich set of interesting lectures and fascinating interviews - I look forward to your comments in the discussion forum.

**2 Message from the past**

Peter Jacobs - George Mason University

In February of 2010, researchers in Germany announced the formal name for a recently created element. They called it Copernicium. It’s what’s known as a synthetic element. That means that for its entire four and a half billion year history before these scientists created it in a lab, Copernicium did not exist on Earth. Copernicium is very radioactive, and unstable. It has a half life measured in seconds. But it is a powerful demonstration that humans are capable of changing the world around them. Some of these changes, like the creation of Copernicium, are fleeting. Others, like the way we’re changing the Earth’s atmosphere and climate, can shape the world far into the future.

The Earth is heating up. And human activities, mainly the burning of fossil fuels, are the cause. But how do we know we’re responsible? Any time scientists want to answer a question like this, they look at many different lines of evidence. When all of the lines of evidence point to the same conclusion, scientists can be confident about it. And this is exactly what’s happening with climate change.

First and foremost, we know humans are changing the climate through basic physical principles. Increasing greenhouse gases like CO2 leads to more energy building up in the climate system. And this causes the planet to warm in response. We have understood the \*physics\* behind this since the 1800s. But we can be even more confident. Because greenhouse warming will leave different fingerprints on the climate than other possible causes.

We have known for many decades that increasing levels of CO2 in the atmosphere will produce a unique pattern of temperature change from the surface to the upper atmosphere. The surface and lower atmosphere will warm, while the upper atmosphere will cool. By contrast, warming due to some natural factor, like more sunlight reaching Earth, would warm the upper atmosphere as well as the surface. The cooling of the upper atmosphere while the surface warms is a \*fingerprint\* of increased greenhouse warming. And it’s exactly what we can see happening now.

We can also look at the ways in which \*natural forces\* have changed the climate in the past. We can use this information to \*rule them out\* as causing the current change. We know that changes in the Earth’s position relative to the sun has caused climate changes in the past. But understanding those changes tells us that they aren’t what’s happening now. They occur far too slowly to be the present cause, and right now, they would be acting to slightly cool the climate.

We know that the sun’s intensity can change over time. But we have many instruments on the ground and on satellites monitoring solar activity. Over the past several decades, the amount of sunlight reaching the Earth has actually decreased, which would act to cool the climate. Massive, long-lasting volcanic eruptions caused by the movement of the continents are capable of heating up the planet by increasing greenhouse gases. But we’re monitoring volcanic activity, and volcanoes release a tiny fraction of greenhouse gases relative to human activity. And the greenhouse gases they do emit have a different chemical composition than gases produced by burning fossil fuels.

The chemical signature of the gases building up in the atmosphere tell us they’re from fossil fuels, not volcanoes. One by one, we can look at how natural changes could be affecting the climate, and rule them out. And we can clearly see the human fingerprint of greenhouse warming in the pattern of temperature changes in the atmosphere. All of this agrees well with our expectations from basic physical principles. Humans are responsible for climate change.

One myth ignores these lines of evidence. It claims that because the climate changed in the past naturally, it must be changing naturally now. This is perhaps the most common myth about global warming. And it’s dead wrong. This is like a defense lawyer who claims his client must be innocent of murder because humans have been dying from natural causes for 200,000 years. Meanwhile, the police caught his client at the scene of a murder, with his fingerprints all over the murder weapon. Arguing that humans have been dying from natural causes for thousands of years isn’t going to convince a jury to let a murderer off the hook. Arguing that the climate changed naturally in the past doesn’t negate the fact that humans are changing the climate now.

The idea that because something happened one way in the past, it will always happen that way, is faulty reasoning. Focusing on the way things happened before and ignoring all of the possible ways they could happen \*oversimplifies\* the issue. This oversimplification leads to \*jumping to the wrong conclusion\* that the climate is changing due to natural causes, when in fact we know humans are responsible. Human activities are responsible for the changing climate. We understand how the climate has changed in the past, and this allows us to rule out natural causes. And our fingerprints are all over the warming climate.

**3 Little ice age**

Andy Skuce - Independent research consultant

There is a lot of evidence that shows that the recent warming of the planet is caused mostly by human emissions. This evidence is so strong that an overwhelming majority of climate scientists accept that the warming seen since 1950 is mostly man made. However, there’s a certain climate-change myth that chooses to ignore all this research. The myth claims that recent warming is just a continuation of the natural processes that ended the Little Ice Age. Here, we'll see that the evidence shows that natural factors were indeed important to begin with. But, since 1950, human influences have become dominant.

The Little Ice Age. First, what was the Little Ice Age? Well, it lasted from about 1450 to 1850--although some scientists think it started as early as 1250, at the end of the Medieval Climate Anomaly, or—as some prefer to call it—the Medieval Warm Period. Just how cold was this Little Ice Age? In Europe, Central Asia and North America, the average temperatures are now one degree Celsius --about two degrees Fahrenheit -- higher than the temperatures that prevailed during the Little Ice Age. This warming might not seem like a lot, but it has been enough to cause the majority of the world’s glaciers to shrink.

Most of the rest of the world has warmed up since then as well, with the exception of a very small areas that are slightly cooler than they used to be, for example, off the southern tip of Greenland. Glaciers advanced during the Little Ice Age: not only in the Alps and Rocky Mountains, but also in New Zealand and the Southern Andes, although the exact timing of these advances varied. But after that, as the cool period ended, glaciers nearly everywhere started to retreat.

The Little Ice Age had its best-known historical impacts in Europe. Some odd weather patterns in the North Atlantic area made the already cool climate there even worse in some years. There were some bitterly cold winters and there were also some very wet years that led to crop failures and famines. Famously, the River Thames in London froze over, and “frost fairs” were held on the ice. The Frozen Thames in 1677. Despite the cold average temperatures, the hard freezing of the Thames was still a rare event. It froze over thickly enough to hold a frost fair just twenty-one times in three hundred years.

What do we know about what caused the Little Ice Age? First, small changes in the tilt of the Earth helped cause a gentle, decreasing trend in temperature over five thousand years. The rate of cooling was about one-fifth of a degree Celsius (that’s about one-third of a degree Fahrenheit) per thousand years. The Little Ice Age occurred towards the end of this long, slow decline. It ended when temperatures started to go up sharply after 1850. Second, there were at least two large lows in the output of the Sun, which we call the Spoerer and the Maunder minima. Third, there was an unusual number of really big volcanic eruptions that threw small particles high into the atmosphere. These acted like little mirrors that reflected sunlight back into space and cooled the Earth for a year or more afterwards. An example was the huge Mount Tambora eruption in 1815, which caused what came to be known as “The Year Without a Summer”.

Scientists are not completely sure about the exact size of the cooling effect that volcanoes and solar lows had on the Earth. But, even so, a range of calculations for the Northern Hemisphere shows a very good match with what the evidence suggests the temperatures were. Researchers estimate the temperatures of the past by analyzing records like tree rings, ice cores and the growth bands of stalactites in caves. In this graphic, the red and blue lines show the calculated values and the grey shading shows the range of reconstructed temperatures. The long-term trends match very well, including following the rapid upward trend into the twentieth century.

Volcanic eruptions and solar variations carried on after the Little Ice Age ended, but they were generally smaller and were dwarfed by ever-bigger human influences. More people and growing industries produced more and more greenhouse gas emissions. This graph, made with data taken from the recent IPCC report, shows the relative importance of volcanoes (in black) and the sun (in green) as well as natural variations which are shown in orange. These variations are mainly caused by fluctuations in ocean currents, like El Niño. Note that the natural factors sometimes cancel each other out and they do not show any lasting trends, unlike the steadily climbing human influence shown in red. When we add together the natural and human factors and overlay the natural variation as the faint background that jumps around, we can see that it would be hard to distinguish a clear separation between human and natural causes before the 1930’s.

Let’s compare those factors with the thermometer record. The monthly temperatures are shown here as a grey wiggly background, and a smoothed version of this is shown in black. The match is good when we look at all of the factors combined, but terrible if we exclude the human influences. Back in 1914, it would have been possible to argue that the recovery from the Little Ice Age was almost entirely natural, but now—one hundred years on—it’s clear that humans are playing the major role, and by far.

To claim that what was arguably true one hundred years ago must still be the case today is to introduce the fallacy of jumping to conclusions.. Which is to say that just because a factor was once significant, does not mean that it is still important. Times change and, over the past one hundred years, human influences on the climate have grown enormously. And they continue to grow. They are now the main factor causing the warming of the Earth.

**4 Ancient CO2 levels**

Peter Jacob - George Mason University

Imagine you’re hiking. Deep in the wilderness. You’re with a friend of yours. The one who is a lot of fun, but doesn’t always have the best judgment. As you turn a corner on the trail, you come across an enormous bear, asleep on the path ahead. You could turn around. You could walk around it. But instead to your horror, your friend says, at full volume, “HEY, LOOK AT THAT BEAR.” You whisper at him to shut up. But it’s too late. The bear opens its eyes. Looks at you and growls. “We gotta get this bear out of our way,” he says. He picks up a stick and walks towards the bear. Renowned climate scientist Wally Broecker has said: “The climate system is an angry beast, and we are poking at it with sticks.” And like our friend poking the bear, humans have been poking the climate system by adding heat trapping gases into our atmosphere.

Wally Broecker studied the climate of Earth’s past, before records were kept. This branch of science is called paleoclimatology. Paleoclimate researchers use techniques from chemistry to infer what temperatures, sea levels, and the makeup of the atmosphere were like. Not just before modern records, but before humans. Going back hundreds of thousands, and even millions of years. As far back as we can reconstruct the conditions on Earth, one thing is clear. The climate changes significantly when the amount of energy in the system changes. Like from changes in energy received from the sun. Or changes in the amount of greenhouse gases in the atmosphere. It does so because changing CO2 levels changes the energy balance of the climate system. The physics behind this have been understood for more than a century and a half, and are completely uncontroversial.

However, what we have learned more recently is that the climate system is pretty sensitive to changes in its energy balance. Reinforcing feedbacks amplify any initial change in temperature. That means that the total amount of temperature change in response to a change in energy is several times greater than what you would see if there were no reinforcing feedbacks. We now have paleoclimate reconstructions going back hundreds of thousands, to hundreds of millions of years of Earth’s history. They suggest that the Earth’s sensitivity to changes in energy- from changes in CO2 levels, for example- is similar to what our most advanced climate models predict.

Paleoclimate reconstructions also tell us that when CO2 levels changed rapidly, not only did the climate change rapidly, but this has had big impacts on life at the time. Changes in greenhouse gas levels are associated with most of the Earth’s worst mass extinction events. But it’s important to keep in mind that greenhouse gases, like CO2, are not the only factor in climate.

The sun’s energy is obviously a big player as well. You might not know it, but stars like our sun get brighter and hotter over time. In the ancient past, we received a significantly lower amount of energy from the sun, which meant CO2 levels could be higher without boiling away the ocean. We know that the position of Earth’s continents has also changed a lot over time. It turns out that this can have a significant effect on climate. On average, land is a lot more reflective to sunlight than the ocean is. And the sun is much more intense near the equator. That means if the continents are more clustered near the equator, a lot more of the sun’s energy gets reflected back out to space before it can warm the planet. And when the continents tend to be spaced away from the equator, a lot more solar energy gets absorbed by the ocean.

Other factors, like the presence or absence of plants and ice sheets, can also change how much of the sun’s energy makes its way into the climate system. When looking at the relationship between greenhouse gases like CO2 and the climate, it’s important to control for these other variables. When we look over Earth’s history, using our best available data, the relationship is clear. When greenhouse gases change, the climate changes in response.

There is one myth that argues that because CO2 levels got so high in the Earth’s past without climate becoming super-hot, then that must mean CO2 can change a lot with just a small change in climate. In other words, the myth uses past CO2 levels as evidence that the CO2 warming effect is not that strong. However, this myth uses faulty reasoning. It is, in effect, cherry picking. CO2 levels are important in shaping the climate, but other factors are as well.

We have to consider factors like the changing sun and how much sunlight gets reflected back to space. Ignoring other important factors, and ignoring the best estimates of past CO2 levels and climate changes, is an oversimplification. CO2 and climate are strongly related, but that’s not the whole story. And finally, oversimplification results in jumping to a conclusion that turns out to be wrong. Failing to consider all of the relevant factors leads to the false conclusion that pumping out CO2 won’t have much impact on the climate.

But evidence from Earth’s history shows the opposite. Our climate changes when greenhouse gas levels change. These climate changes can happen very quickly. Causing some of the largest mass extinctions in Earth’s history. And now, we have increased levels of greenhouse gases higher than they have been for more than a million years. And as best we can tell, we are increasing levels of greenhouse gases faster than at any time during Earth’s history. Faster even than during those mass extinctions.

**5 From the experts: the past**

Professor Tim Osborn - East Anglia University, Professor Michael Mann - Penn State U, Professor Katrin Meissner - New South Wales U, Professor Dan Lunt - Bristol U, Professor Isabella Velicogna - UC Irvine

Osborn: Paleoclimate is when we're trying to understand what happened to the climate

prior to the period when we have instruments, like before the invention or the widespread deployment of thermometers and rain gauges and things like that. We use indirect estimates of the climate.

Mann: These are things like tree rings and ice cores and corals and sediments, various

natural archives of physical or chemical or biological archives, that tell us something about climate conditions in the distant past, farther back than we have reliable instrumental measurements. We really only have widespread thermometer measurements around the globe for a little over a century, but we can extend these records further back in time by using these so-called proxy data.

Osborn: The ones I'm most interested in are ones with kind of finer resolution that can

tell you about individual years or decades, for example tree rings. Those tree ring records, if they're based on living trees obviously they're limited by the lifespan of a tree, which might be a few hundred years. Occasionally a thousand years or more.

Mann: Back in the late 1990s, my co-authors and I sought to reconstruct the surface temperature record back in time, hundreds of years back in time, using these proxy data. Now what actually drove the research was our interest in the underlying patterns of past temperature variation. What was the history of El Niño in the past and its large-scale influence on the climate? What was the pattern around the world of the response to some of the largest volcanic eruptions of the past thousand years?

Osborn: So from the paleoclimate data variations of climate in the last thousand years have been quite large in individual regions but not necessarily coherent so some regions are warm and other parts are cooler. If you take a large scale picture, what you see is generally warm conditions at the beginning of the last thousand years, often called the Medieval Warm Period or some name like that. Then coming down to a cooler period called the Little Ice Age, perhaps between 1450 and 1850 at its peak. After 1850 coming back up to kind of warmer conditions in the 20th century and now into the 21st century.

Mann: Now if you look at that curve, what it shows is that the modern warming spike

is unprecedented as far back as we could go, a thousand years, in our 1990s studies, but there were some temperature changes along the way, and there was a period of about a thousand years ago where temperatures over the Northern Hemisphere were relatively warm, and then temperatures cool as you slowly descend into what’s sometimes called the Little Ice Age, sort of the 1300s through the 1800s. You have this long-term cooling from the medieval climate period in the Little Ice Age of the 17th, 18th, 19th century, followed by this abrupt spike, which takes you outside of the range of any of that previous variation.

Osborn: so our best estimates for the Little Ice Age is that there was a cooling effect

in most parts of the world of a moderate level, but then superimposed on that are regional fluctuations if there's changes in atmosphere or ocean circulation they can transport heat around and make some areas even cooler and some areas less cool. The phenomenon is probably a Northern Hemisphere wide and maybe a global event.

Mann: Now, when it comes to the medieval period, it used to be widely claimed that global temperatures were warmer then than they are today. The evidence that we have now does not bear that out, but what it shows is that there are some regions where temperatures were quite a bit warmer. The pattern of warming and cooling around the globe isn’t uniform. There is a lot of redistribution of heat around the globe associated with changing ocean currents, associated with changing atmospheric wind patterns.

When you look back in time, there’s a very complex regionally diverse pattern of temperature changes, and what we find is that in certain regions in the North Atlantic and parts of Greenland, during the height of the sort of medieval climate period, may have been almost as warm as conditions today, if not even warmer, within the uncertainties, perhaps even warmer, but most of the globe was substantially cooler. When you average over the globe or over the Northern Hemisphere, what you find was that temperatures then are not nearly as high as they are today because what’s different is the coherent pattern of the warming.

The warming period we’re seeing now isn’t just a patchwork of warming in some regions interspersed with cooling in others. Essentially, the entire globe is warming up in unison, and we don’t see that in the past record. Study after study has not only reaffirmed our key conclusion about the unusual nature of the recent warming. More recent work has strengthened and extended those conclusions. The most recent report of the IPCC concluded that the recent warming is unprecedented not just in a thousand years, as we concluded a decade-and-a-half ago, but at least 1,300 years and maybe even longer. I sometimes refer to what exists now when it comes to these paleoclimate reconstructions as not a hockey stick, but a hockey league because there are dozens of these reconstructions and they don’t all agree on all of the details.

What was the coldest part of the Little Ice Age, and what was the precise pattern of the Medieval climate period? Different studies come to different conclusions because they use different kinds of data, different methods to take those data and form a climate reconstruction. The one thing they all agree on is that the recent warming has no precedent as far back as we can go.

Meissner: One of the major misconceptions right now is that people argue that the climate has changed in the past and therefore what we see now just might be part of natural variability. This is not true. The changes we see now are so fast and so enormous that that doesn't compare to anything we actually have i the records, certainly not in the last 2 million years but also if you go very far back there was maybe one event and 55 million years ago, which was associated to a big increase in CO2, but even that happened at a much slower rate than the rate we are actually changing the climate right now.

Mann: Ironically, when it comes to contrarians, climate-change deniers who will wrongly

claim that the Medieval period was warmer than today because the science seems to definitively say otherwise now, but even granting them that, if that were true, they say, “And because that’s true, it means that the warming today could be natural, too. “ Well, in fact, we have a pretty good idea of what the natural driving factors were during the Medieval period: volcanoes, changes in solar output, small changes, long-term changes in Earth orbital, or the geometry of the Earth’s orbit around the sun. If the climate really were far more sensitive to the natural factors, it would imply that it’s more sensitive to CO2 increases. It would imply just the opposite of what the skeptics or contrarians or deniers of climate want you to think.

Meissner: Looking into the past can tell us a little bit about how the system might react

if we push it, but the way we push it right now is out of context of anything we can see in our records. Lunt: If we just look at the record, the observed record, of the last 200 years the variations in CO2 are tiny and get nowhere near these high values that we're expecting by the year 2100. So basically if you look at the plots, if you just look at temperature reconstructions of CO2 plots, you see all the variability and you have ice down here and interglacials here and it goes like this and today we're up here. So we are completely out of this range of variability.

Velicogna: If you look at temperature, the plot of changes in temperature, and changes

in CO2 concentration, they go together. When temperature is high and CO2 concentration is high and when it's low, CO2 concentration is low.

Lunt: So a really good question to ask is, what was the climate like the last time CO2

was about 400 ppm and it turns out that our best estimates are that it was associated with what we call the Pliocene time period, so this was the mid Pliocene, around about 3 million years ago. What was the climate like 3 million years ago? Well, this Pliocene world one of the things we know about it is sea level, for example, was probably about 10 meters higher than it is today.

What does 10 meters mean? Well, we're talking about inundation in many of the world's major cities. We're talking about inundation of much of a lot of the crop land and for example we used to feed the population today. A lot of the modern day population lives near the coast and those are obviously the ones that are going to be the most greatly affected. A 10 meter sea level rise is serious serious news for our planet, let's make no bones about it.

**6 Medieval warm period**

Robert Way - University of Ottawa

Nearly a thousand years ago, there was a period we now call the medieval warm period. It spanned roughly 250 years from 900-1150 AD. It’s so called because it featured a warmer climate than the harsh Dark Ages before it or the cold Little Ice Age that followed. But what caused the warmth? And how does it compare to today’s temperatures?

Averaged over the entire globe, temperatures during the medieval warm period were similar to the mid-20th century, according to records collected by scientists studying past climates. However, just like today, certain regions during this time warmed more than others. For example, the North Atlantic region warmed far more than the tropics. In areas where warming was the greatest, air temperatures were similar to the late 20th century but are less than those seen over the last decade.

The warmth of the medieval warm period made northern lands easier to access. In coastal Greenland, Vikings were able to build villages that survived for many decades, before cooler conditions forced them to relocate. Although some areas became more livable, other areas became harsher. For instance, a thousand years ago mega-droughts occurred in the southwestern United States, making living in the area harder. The medieval warm period was caused by a combination of natural factors that led to a slow warming, which peaked around 1000 years ago. Likewise, the end of the medieval warm period was caused by these same natural factors acting to cool the climate and begin the Little Ice Age.

There are three main factors that scientists believe caused the warmth during the Medieval Warm Period. First, scientists estimate that solar activity was greater during the medieval warm period than in the Dark Ages beforehand or the Little Ice Age that followed. An increase in solar activity caused a warmer climate, especially in the summer. Second, during the medieval warm period there were few volcanic eruptions which inject dust into the atmosphere and reflect incoming radiation from the sun. The low volcanic activity during the medieval warm period allowed warm conditions to prevail for longer periods in between eruptions. There is strong evidence that increasing volcanic activity was a major cause of cooling at the end of the medieval warm period. Third, the earth’s orbit was different 1000 years ago then it is today. Orbital changes influence the amount of solar radiation received at the earth’s surface. Compared to the orbit today, the medieval warm period summers would have been warmer in the polar regions. Combining the three factors above is enough to explain conditions during the medieval warm period.

 Studies with climate models have shown that air and ocean temperatures during this period can be reproduced by including these three factors. Although we understand the main drivers of the climate of the medieval warm period, there is less certainty in other regards. For example, more knowledge is still needed on how the recorded regional patterns developed and on how the atmosphere and ocean reacted at that time.

There are two common myths about the medieval warm period. The first myth argues that modern global warming could have been caused by the same natural factors that caused the medieval warm period. This is an example of jumping to a conclusion. The drivers of the medieval warm period are well-understood and not the same as those driving climate change today. If we only look at the natural drivers of climate over the last 50 years, globally there should have been cooling instead of warming. The only way to account for recent global warming is to include the increase of human emissions of greenhouse gases. Natural drivers can’t have caused recent warming - in fact, they have had a cooling influence.

The most common myth about the medieval warm period is that conditions during medieval times were warmer than now. However, when scientists reconstruct temperatures averaged out over the whole planet, they find the medieval warm period was not warmer than at present. So how do people argue that the medieval warm period was warmer? By cherry picking single locations and comparing medieval temperatures to today’s temperatures at that location. One location may have been warmer in medieval times. A nearby location may have been cooler. You need to average over huge areas to compare medieval climate to today’s climate.

There is another important piece of data that also confirms that the medieval warm period was not as warm: sea levels. If it were warmer during the medieval warm period, then sea levels would have been higher and would have risen faster than now. This is for two reasons: more ice would have melted and warming oceans expand in volume. We see no evidence of sea level rise like today in reconstructions of sea level rise. This is strong evidence that the current warming exceeds that of the medieval warm period. The global temperatures being experienced now are unprecedented for at least the last 1000 years.

**7 Confused decline**

Peter Jacobs - George Mason University

The earth is a massive and complicated system. How are we so sure that the planet is warming? Well, weather stations around the world are monitoring \*surface temperatures\* and seeing them rise. We monitor \*ocean temperature\* using buoys, measurements from ships, and large networks of floats. The ocean surface is warming and \*heat\* is building up below the surface. We can also observe global warming using weather balloons and satellites. Ocean water expands as it heats up, and land ice melts and runs off into the ocean. This causes sea levels to rise, which is happening rapidly.

Glaciers around the world are shrinking. Warmer air holds more moisture, and over both land and sea, humidity has been increasing just like we’d expect in a warming world. These, and many other indicators, tell us that the planet is unquestionably heating up. Based on all of these different lines of evidence, everyone can agree that the globe is warming, right?

Unfortunately not. For example, a former United States Vice Presidential candidate wrote that leading climate ‘experts’ deliberately manipulated data to ‘hide the decline’ in global temperatures. Similarly, a past Chairman of the United States senate Committee on the Environment claimed stolen emails show “one scientist wrote of a ‘trick’ he employed to ‘hide the decline’ in global temperature trends”. These claims are classic examples of conspiracy theory. In order to fake an increase in global temperature, you have to fake all of the indicators of warming we’ve talked about: Surface thermometers. Ocean buoys. Weather balloons. Satellites. Tide gauges. Glacier lengths. And more. It would require the greatest conspiracy in the history of the world to pull such a deception off. An extraordinary claim, which requires extraordinary evidence.

But this “evidence” is just another tactic common in denialism: quote-mining. When denialists seek to refute a mainstream position, they often take phrases out of their original context and claim they mean something they do not. Sometimes this is deliberate, other times it happens because of a lack of understanding of the science they are attacking.

In the cases I mentioned, the quote-mining was being performed on emails that had been stolen from a university email server back in 2009. Given that warming of the planet is unequivocal, what “decline” was being referred to in the stolen emails? The word “decline” was \*actually\* referring to a change in the behavior of a subset of climate \*proxies\*. Let me explain what I mean by that.

Proxies are indirect ways of estimating something you’re interested in when you don’t have direct measurements of it, or if you want an extra line of evidence to solve a problem. Imagine you’re walking along a beach. It’s low tide. You want to know where you can put your stuff down so that it’ll be safe when the water reaches high tide again. You see a line of seaweed, bits of shell, driftwood, and other debris. You place your blanket and food a few feet up-shore from this, thinking that this was the point of the previous high tide. You’re using the debris as a proxy for the tide line, inferring its location even though you did not observe it directly.

When scientists study past-climate, they have to use proxies, because we can’t go back in time to get those true measurements. For example, we can use records of tree growth to estimate how hot summers have been over the entire lifetime of a tree. Around 1960, however, some temperature proxies from tree growth stopped tracking temperature. Temperatures went up, as evidenced by thermometers, weather balloons, satellites, and all those other indicators we’ve talked about. But some tree proxies went down. This is the “decline” mentioned in the email -- decline in tree proxy data, not actual temperatures.

This “divergence problem” is an area of active research in the paleoclimate community. We have good ideas about why the proxies stopped tracking temperature, but we’re still working on it. Many other proxies are not affected by the “divergence problem”. Glacier length, chemical ratios in cave deposits, borehole temperatures- none of these show a decline. So we can use these other proxies to make sure that the tree proxies showing the divergence now were still tracking temperature far back in the past. This is similar to how we treat sensors that malfunction on modern satellite platforms.

We identify the problematic data. We cross-check the earlier data against overlapping records. And we stop using the data from the malfunctioning sensor. So scientists do run into problems with data. Sometimes thermometers fail or proxies stop following reality. Still, all major lines of evidence, from satellites in space to sensors in the deep ocean, show the planet is heating up. Denialists resort to conspiracy theory and quote-mining to claim the opposite.

**8 From the experts: Decline**

Michael Mann - Penn State U, Tim Osborn - East Anglia University

Mann: In this effort to discredit climate science in the lead up to the 2009 Copenhagen

Summit, where various e-mails, including e-mails that were mine or were written to me, were stolen and then combed through to try to find words and phrases that if you took them out of context could sound a little questionable. It could be used to try to make it sound like climate scientists were engaged in something inappropriate or hiding something. That’s what climate-change deniers did. They combed through thousands of e-mails, looking for even just one little short phrase that they could use to try to attack climate scientists.

One phrase that they seized upon was an e-mail to me and some other scientists from my colleague Phil Jones of the University of East Anglia. What the critics also tried to do is to take two different phrases from the same e-mail that appear at opposite ends of a very long sentence and splice them together, so you actually heard people—there were people out there claiming that the e-mail talked about using a trick to hide the decline, using Mike’s trick to hide the decline. The e-mail doesn’t say anything of the sort. The “hide the decline” is referring to something else later in the sentence. What Phil Jones was talking about was that one particular climate reconstruction that was shown in his comparison that had been performed by Keith Briffa and colleagues with the University of East Anglia. They had used the density of the rings of trees.

Osborn: In addition to the width of the individual tree rings, the density of the wood that makes up the trees, also appears to respond to the climate, so with warmer summers we tend to get trees which are denser especially at the end of the growing season that kind of the late wood put down by the trees at the end of the growing season. The density there is linked to summer temperature even more strongly than the width of the ring widths.

Mann: You can use tree-ring-growth thickness to tell you something about climate, but it

turns out that if you look at the density of the wood that grows in any particular year, that also tells you something about temperature. They had performed a reconstruction of temperatures using exclusively these tree-ring-density measurements. For various reasons that have been explored for now nearly two decades, these particular measurements tracked temperatures very well until about 1960, and then they began to diverge.

Osborn: What tree ring divergence is is a separation in the trends of the tree data

and the temperature data in recent decades. So if you go back to the early part of the 20th century, there's quite a good cross references between the tree data and the temperatures. So that warmer summers tend to coincide with wider rings or with denser wood in those rings and colder summers with less dense wood or thinner rings.

Mann: The thermometer measurements tell us very clearly that the globe warmed substantially since then, but the tree-ring data stopped; the tree-ring densities that they used stopped reflecting that warming.

Osborn: So divergence problem is something that affects some tree rings. Often it's misconstrued as if it affect all tree rings. What it is is that for some tree rings the changes in recent decades have gone down while the temperatures recorded in some locations have gone up. Whereas if you go back to previous decades the tree rings have responded quite closely to the temperatures. So when the summers are warmer than normal the trees have tended to grow more than normal, and our view is being that the cause of it is likely to be something fairly unique to the 20th century.

In order to have this common effect on many different trees across the northern hemisphere, you need something in a large scale and affecting many regions in one time period and therefore some anthropogenic pollution related influence or maybe some climate warming related influence could be part of the explanation. A paper recently by Stine and Huybers (A. R. Stine & P. Huybers, 2014) that suggests that changes in the sunlight reaching the trees could explain the divergence. And they backed it up by looking back at the early record and identifying a change when volcanic eruptions occur, which also put aerosol and dust into the atmosphere, which can also affect the amount of sunlight reaching the trees. That seemed to be consistent with the locations where the divergence is strongest in recent decades.

Mann: Before that e-mail ever was written, they had published a year earlier a paper

in the journal “Nature” talking about this problem. It was hardly something that was hidden or nefarious. They were well aware of this problem, and they stated very clearly in that paper in 1998 that, because of this problem, you should not use the post-1960 data to depict temperature changes. What Phil Jones was talking about, that e-mail, was he was “hiding.” All he meant was not misleading the readers of this report by showing them this very misleading post-1960 tree-ring-density data because they wrongly convey what was actually happening with temperatures, and we have thermometer measurements that tell us what actually happen with temperatures.

He was literally saying, “For this simple graphic that’s supposed to convey to this lay audience what we know about temperatures over the past thousand years, let’s not show this bad data that will confuse them and mislead them.” Somehow that was parleyed once again into something nefarious, something inappropriate, by very cynical bad-faith actors who were using this misdirection and confusion really as a distraction to make sure that there were no meaningful negotiations in dealing with climate change at the upcoming Copenhagen Summit in 2009. That’s what you have. When you’re left without a legitimate argument for your case, which is what we have in the case of climate-change denial today, all you’ve got to turn to, apparently, is innuendo and obfuscation and misdirection, and this was just another example of that.

**9 Principles that models are built on**

Dan Nuccitelli - Climate blogger

Global climate models use the laws of physics to simulate our planet’s climate. They’re so sophisticated, they have to be run on some of the world’s fastest supercomputers. It can take months to run a single simulation! So how do climate models work? They’re mathematical representations of the Earth’s climate. And to simulate the climate, they divide the Earth, its ocean, and atmosphere into a three dimensional grid. Factors like temperature, wind, and rainfall are calculated at each grid point to predict their future climate changes. As computing power has improved, the size of those grids has gotten smaller and smaller. Essentially, better computers allow us to make more and more detailed models. Today’s models are so high resolution that we need supercomputers to run them.

Swedish scientist Svante Arrhenius is often credited with creating the world’s first climate model over a century ago. His computer was made up of a pencil, paper, and his brain. Arrhenius estimated that doubling of the amount of carbon dioxide in the atmosphere would result in global surface warming of about 5 to 6°C. That’s only a few degrees from the estimates we get today from our complex models and supercomputers. Not bad for pencil and paper in the 1800s! Detailed modeling of the Earth’s climate really began in the 1950s and 60s. The first climate model that combined how the oceans \*and\* atmosphere work was developed in the late 1960s.

Over the past 50 years, our understanding of the details of the Earth’s climate and our ability to simulate it have continued to improve. Today’s models include components representing the atmosphere, oceans, land surface, and sea ice. The atmospheric component simulates greenhouse gases, clouds, and aerosols. Aerosols are tiny particles released by volcanic eruptions and from the burning of fossil fuels. They both deflect sunlight and play a role in cloud formation. In climate models, the atmospheric component plays a major role in moving heat and water around the globe. The land surface component simulates characteristics of the Earth’s surface like vegetation, snow cover, soil moisture, rivers, and carbon storage.

The ocean component of climate models simulates the movement and mixing of ocean currents. This is a critical component for an accurate climate model. The ocean is the main reservoir of both heat and carbon in the Earth’s climate system. The sea ice component plays a big role in the amount of heat reflected or absorbed by the Earth. Ice is very reflective, whereas dark oceans absorb sunlight. That means it’s important to simulate changes in sea ice if we want climate models to accurately represent changes in the reflectivity of the Earth’s surface. Sea ice also plays a role in heat exchanges between the ocean and atmosphere.

In all these different parts of the climate, scientists calculate different variables like temperature or rainfall in each part of the grid, using equations based on the laws of physics. The models compute how these variables change over time, and simulate how they interact with one another. So, global climate models are based on well-understood physics. The results of individual simulations by each climate model are checked by a large community of climate modelers and researchers around the world. Climate models have been able to produce simulations of current and past climates that match observations. Models have also accurately simulated 20th century climate change, including increased warming due to human carbon emissions. They predict many other features of the climate system, like the Earth’s infrared spectrum, patterns of rainfall, and changes in warming patterns. This gives us confidence in using these models to project future climate change.

There’s a common misperception that because they’re not perfect, climate models are useless. This myth suffers from the fallacy of impossible expectations. No model can ever be perfect. By setting the bar at a level they can never reach, contrarians can always reject climate model predictions. But as the statistician George Box once wrote, " \*all\* models are wrong, but some are useful" Global climate models are certainly useful tools. They represent sophisticated simulations of the Earth’s climate. Their level of detail and resolution has improved dramatically over the past several decades. Our confidence in their ability to predict future climate change is based on their ability to reproduce past climate change - whether over the 20th Century or longer timescales - and the current climate.

**10 Success stories**

Dan Nuccetelli - Climate blogger

These days, scientists use the world’s fastest supercomputers to model the Earth’s climate. But the first numerical model of the Earth was created over 100 years ago. It was done using pen and paper, by Swedish scientist Svante Arrhenius. How good was this first attempt, made long before computers were invented? Arrhenius performed a complex calculation and estimated that if the amount of carbon dioxide in the atmosphere were to double, the planet would warm about 5 to 6 degrees celsius as a result. That result was remarkably close to estimates from today’s complex global climate models. They find that a doubling of the amount of carbon dioxide in the atmosphere will warm the planet somewhere between 2 and 4.5 °C. Arrhenius also predicted that if the amount of carbon dioxide in the atmosphere rose and warmed the planet, the atmosphere would be able to hold more water vapor. Water vapor is another greenhouse gas, so that would amplify global warming even further.

By 1967, scientists Manabe and Wetherald had created a three-dimensional model of the Earth’s atmosphere. They used that model to calculate that a doubling of the amount of carbon dioxide in the atmosphere would cause about 1.3°C warming by itself. That warming would increase the amount of water vapor in the atmosphere, which would cause another 1.1°C warming of global surface temperatures. Recent research has found that as the planet has warmed, the amount of water vapor in the atmosphere has increased as anticipated by climate models by scientists since Svante Arrhenius in the late 1800s.

Global climate models have done well in projecting global temperature changes too. In 1972, British meteorologist J.S. Sawyer projected that humans would increase the amount of carbon dioxide in the atmosphere 25% above 1850 levels by the year 2000. He estimated that the planet would warm about 0.6°C in response. Both projections were almost spot-on. In 1975, American climate scientist Wallace Broecker coined the term “global warming.” He used a global climate model to estimate that due to rising carbon dioxide levels, between 1975 and 2015, the Earth’s average surface temperature would warm by about 1°C. His estimate was about 0.3°C too high, but that’s pretty close for the simple climate model he was using 40 years ago.

In 1981, NASA climate scientist James Hansen had developed a somewhat more detailed model of the Earth’s climate. He projected that between 1981 and 2015, the planet would warm about 0.5°C. In actuality, the planet warmed about 0.6°C during that time, so Hansen’s model was remarkably close with this projection. Hansen made another global warming projection in 1988 using a newer version of his climate model. However, this newer model was more sensitive to the increased greenhouse effect than his 1981 model, and more sensitive than most of today’s global climate models. Hansen projected that between 1988 and 2015, the Earth’s average surface temperature would warm about 0.67°C, whereas it actually warmed about 0.5°C during that time.

The Intergovernmental Panel on Climate Change has also used simulations from the most advanced climate models available to project global temperature changes in each of its reports. Those reports were published in 1990, 1995, 2001, 2007, and 2014. In each one, the global warming projections made by the climate models have turned out to be remarkably accurate.

Climate models have made many more accurate predictions too. Manabe and Wetherald accurately predicted that while the lower atmosphere warmed, the upper atmosphere would cool. In 1975, they also predicted that the Arctic would warm faster than the rest of the planet, in part because of decreased reflectivity due to melting ice. In 1989, Stouffer, Manabe, and Bryan predicted that the land surface would warm faster than the ocean surface. Models have predicted the geographic pattern of global warming, the loss of Arctic sea ice, the rising of sea levels, and so on.

All of these predictions have come true, confirming that climate models are good representations of the Earth’s climate. Yet there’s a common myth that climate models are useless. This myth stems from the fallacy of impossible expectations. Many people argue that climate models must be able to make perfect short-term predictions for us to rely on them. However, climate models actually do better in predicting long-term changes. That’s because there are a lot of unpredictable factors like ocean and solar cycles that can have significant short-term influences on the climate. Sometimes they have short-term warming effects, and sometimes cooling.

Over the long-term, those effects average out, leaving the long-term effects like the increased greenhouse effect to dominate climate change. That makes the long-term changes easier for climate models to predict. As climate scientists Tom Knutson and Robert Tuleya said in 2005, “if we had observations of the future, we obviously would trust them more than models, But unfortunately, observations of the future are not available at this time”

There’s no way to predict the future without a model. Like all models, global climate models are imperfect, but they’ve made some very accurate predictions for decades. On the other hand, predictions made by climate contrarians have been way off. They’ve mostly predicted global cooling, while we’ve actually experienced global warming. That’s a poor track record, not nearly as accurate as predictions made by climate models.

**11 Weather vs Climate**

Keah Schuenemann - Metropolitan State University of Denver Meteorology professor

A common mistake people make when it comes to climate change is confusing weather with climate. So how is weather different from climate? Weather is the state of the atmosphere at a given point in time. What’s the current temperature, cloud cover, air pressure, wind direction and speed? Is it raining or snowing? Climate, on the other hand, is the average weather over a long period of time. It represents long-term factors like the average high and low temperature for a given date at a given location, the record highs and lows, precipitation amounts and types, and the seasonal variation.

As a meteorology professor who teaches and trains future weather forecasters, I sometimes get comments like, “Oh, so you get paid to be wrong?” I laugh, but then list the many reasons why weather forecasting is difficult. I’ll explain that long-term weather forecasts past five days should be taken with a grain of salt, but overall weather forecasting has gotten quite good. Short term weather forecasts are extremely accurate and have improved dramatically. On the other hand, I live in Boulder, Colorado, where the weather changes very quickly. If a forecast is just slightly off, I might unexpectedly find myself walking to the bus in a snow storm wearing a t-shirt! Why? Because the models had forecast that the temperature would be warm at that time of day. This can be frustrating! Nailing the timing of weather events for a given location can be difficult.

So the goal of a weather forecast is to tell you the temperature, precipitation, and cloud cover forecast for your exact position at an exact time in the near future. This is done using a variety of data from weather balloons, weather stations, and satellites that are put into a weather model. The weather model consists of computer code that does calculations to get the forecast. The model divides the world up into blocks and the resolution, or the size of the blocks, is extremely important. You don’t want a nearby mountain range to be represented as a few blocks on a grid. You want it to resemble a mountain range! And you also don’t want your storm forecast to be relegated to a low time resolution, like a day long. You’d rather have hourly or three-hourly forecasts to get a better idea of when the temperature will drop.

Meteorologists analyze the results from several weather models to make the short term forecast that is sent to you in the form of a webpage, television or radio broadcast, or maybe an app on your phone. Climate models, on the other hand, have \*completely\* different goals! Yes, climate models simulate weather systems and all of those useful variables that come out of a weather forecast. But the goal isn’t to tell you that the weather in Denver, Colorado on March 30 of the year 2050 will be a high of 0 degrees, a low of -5, and 10 centimeters of snow should fall between noon and 4:00. The goal is to tell you that the average weather from the year 2080 to 2100 for spring over the central United States will be an average temperature and range of such and such, this much average precipitation, and so on. This is called the climate, the average of a bunch of weather over a long period of time.

Using climate simulations, we can then say that the springtime temperatures at the end of the 21st century will be this much warmer than the last 20 years, this much wetter or drier, and have this many more droughts, for example. To get these long-range projections, climate models are built differently to weather models. The climate is influenced by processes that happen over much longer time scales and bigger areas than weather.

The climate models used in the IPCC reports, called Atmosphere-Ocean General Circulation models, include many important earth systems. They take into account cycles such as the carbon cycle. They also include feedbacks including interactions between the atmosphere, ocean, sea ice, and land that happen at a global scale. Climate models tell us that the factors that control our everyday weather will be different in the future. So that’s how weather and climate models differ.

However, one myth distorts what models are, in order to cast doubt on their usefulness. The myth goes like this: “Since modern computer models can’t predict the weather two weeks from now with any certainty, how can we rely upon computer models to predict what the Earth's climate might be like a hundred years from now?” This myth suffers from the fallacy of impossible expectations. It confuses weather with climate and tries to use the emotion of disappointment in a failed weather forecast to have you fall victim to this fallacy.

 Imagine if I asked you to predict the result of a coin flip. Heads or tails? You would have a 50/50 chance of getting it right. Now, what if I asked you to predict the results of a million coin tosses? You’d tell me about half would be heads and half tails and you would be almost 100% correct. This is a good analogy for the difference between weather and climate predictions. Although, luckily for us, your chances of predicting the weather tomorrow are usually much better than 50/50! Using your confidence in the ability to forecast the weather to then judge the validity of climate modeling just isn’t fair, because as you now know, they are two completely different challenges.

**12 Climate science in the 70’s**

Dan Bedford - Geography professor - Weber State University

Imagine you’re a climate scientist in the 1970s. At the time, global temperature hadn’t changed much for several decades. In fact, it had even cooled slightly. We’ll look at why in a moment. But what’s interesting is what climate scientists were expecting to happen next. Most research in the 1970s projecting future climate expected that global temperatures should soon start to increase. In other words, these papers predicted imminent global warming. Why? Because humans were burning huge amounts of fossil fuel. We were emitting heat-trapping greenhouse gases into the atmosphere. In fact, among climate papers published between 1965 and 1979, the number predicting global warming was accelerating. The scientific community was becoming more convinced that global warming was just around the corner.

And what happened next? Global temperatures did start to increase, just as climate scientists expected. However, a small number of papers in the 1970s speculated that under certain conditions, global cooling might happen. This is the basis for one persistent \*myth\* about climate change: that in the 1970s, the scientific community was predicting global cooling, maybe even a new ice age in the next few decades. This myth is a misrepresentation. It distorts the scientific position in the 1970s, and to understand how, we need to look at why that small number of papers was speculating about global cooling.

After World War II, the global economy was growing fast. Burning of fossil fuels, like oil and coal, grew rapidly. When we burn fossil fuels, besides releasing carbon dioxide pollution, we also release other by-products into the atmosphere. Among these by-products are tiny particles called sulfate aerosols. As fossil fuel burning increased in the mid-20th Century, we emitted more sulfate aerosols into the atmosphere. We know that carbon dioxide is a heat-trapping gas causing global warming. Sulfate aerosols have the opposite effect. They reflect sunlight, which leads to an overall cooling. With both carbon dioxide and sulfate aerosols increasing at the same time, climate scientists were faced with a challenging question.

Which would win out? The warming from carbon dioxide or the cooling from sulfate aerosols? Because humans are unpredictable, climate scientists don’t make \*predictions\*. Instead, they make \*projections\*. A projection is when we estimate what will happen as a result of a certain scenario. Each projection represents a different path that humanity could take. How much more global warming we’ll see depends on which path we choose. The same was true in the 1970s. Scientists didn't know exactly how much fuel we’d burn, or whether we’d start installing filters to reduce aerosol pollution. What happened next would determine how Earth’s temperature would change.

Like they do today, climate scientists considered different scenarios. Then, they made global temperature projections for those scenarios. In one scenario, NASA scientists considered what would happen if sulfate aerosol pollution accelerated rapidly. Specifically, they examined what would happen if sulfate aerosols in the atmosphere quadrupled due to fossil fuel burning. They calculated that this would block enough sunlight to cool global temperatures by 3.5 degrees Celsius, or 6 degrees Fahrenheit. They further concluded that if that kind of cooling continued for several years, it might even trigger a new ice age.

Despite this projection, climate scientists in the 1970s generally expected to see global warming from increased greenhouse gases. So how did a \*handful\* of papers turn into a myth about the scientific community predicting an imminent ice age? In 1974 and 1975, Time and Newsweek magazines published articles warning about a possible oncoming ice age. This was partly based on NASA’s research. But Time and Newsweek are \*news\* magazines, not scientific journals. No one is surprised when a news magazine publishes a sensationalized headline.

But in \*scientific papers\*, which take a more reasoned, evidence-based approach, the research indicated oncoming global warming. Moreover, those NASA scientists weren’t predicting global cooling or an ice age. Their paper projected that \*if\* sulfate aerosol pollution quadrupled, \*then\* we might trigger an ice age. But the opposite happened. In the 1970s, a number of countries enacted regulations to \*reduce\* sulfate aerosol pollution. One example of this legislation is the passing of the Clean Air Act in the United States. As a result, sulfate pollution began declining in the late 1970s.

The scenario where sulfate aerosol emissions quadrupled just didn’t happen. This example of sulfate pollution is instructive for today. Scientists published research explaining the effects of sulfate pollution. In response, governments enacted regulation to reduce the pollution. In the same way, we \*can\* avoid the worst impacts of global warming if we act to reduce carbon dioxide pollution today.

**13 Future ice age**

Dan Nuccetelli - Climate blogger

Scientists predict that if we continue on our current path, we'll see around 4 degrees Celsius warming by the end of this century. That's because we're burning more and more fossil fuels, and emitting heat trapping greenhouse gases into the atmosphere. Carbon dioxide is the main control knob for the Earth's climate. Other factors act like fine tuning knobs, but it's carbon that causes the big changes.

Over the last few decades, the sun has been getting cooler. What if it kept getting cooler? This \*has\* happened before. From about the year 1450 to 1850, Europe and North America went through the Little Ice Age. Around this time, there were two periods when the sun was relatively quiet. These two periods are known as the Maunder Minimum and the Dalton Minimum. The Maunder Minimum occurred from 1645 to 1715. Astronomers like Galileo and Christoph Scheiner kept records of the number of sunspots starting in the 1600s. Sunspots are a good indicator of how active and energetic the sun is at any given time. If there are lots of sunspots, there's also more sunlight reaching the Earth. During the Maunder Minimum, astronomers observed very few sunspots. The sun was quiet.

Toward the end of the Little Ice Age, there was another period between 1790 and 1830 known as the Dalton Minimum. During that time, again, there were relatively few sunspots. In other words, less energy from the sun was warming the Earth. What would happen to future global warming if the sun's output fell down to Maunder Minimum levels? Several teams of scientists have investigated this question. All of these studies agree. Even if the sun entered another quiet period like the Maunder Minimum, the drop in sunlight would only be enough to offset about one decade's worth of human-caused global warming.

In other words, a quieter sun would cause global cooling of no more than three tenths of a degree Celsius, or about half a degree Fahrenheit. To put that into perspective, global temperatures are already more than 1 degree Celsius, or about 2 degrees Fahrenheit hotter than the Little Ice Age. The planet will warm another 1 to 5 degrees Celsius this century, depending on how much more carbon pollution we put into the atmosphere. That slight cooling would also only be temporary. As soon as the sun entered another more active phase, the cooling from the solar minimum would be erased by that solar warming. Compared to greenhouse warming, the sun's role in current climate change is a minor blip.

One myth argues that rather than see global warming in the future, we're heading into an ice age. Why? The myth argues it'll happen because of the cooling sun. This myth misrepresents the role of the sun in climate change. Over the past several thousand years, changes in the sun have not been the main driver of climate change. Rather, it's been changes in carbon dioxide in the atmosphere and volcanic eruptions that have been the two main factors. Recent research suggests that the sun has played less of a role than scientists previously thought, and volcanoes a larger role.

Once, climate scientists thought the sun was a major contributor to the Little Ice Age. However, scientists have discovered that the sun is more stable than we used to think. The best recent estimates suggest that the amount of sunlight now is only about one-tenth of one percent higher than during the Little Ice Age.

So what caused the Little Ice Age? First, it's important to understand that the Little Ice Age really was little. The planet just wasn't that cold outside of Europe and North America. The average global surface temperature was only about half a degree Celsius, or 1 degree Fahrenheit cooler than the Medieval Warm Period that happened 500 years earlier. That half a degree cooling took several centuries. In comparison, human greenhouse gas emissions have caused \*more\* than a half degree Celsius global warming in just the last 40 years.

There were a lot of volcanic eruptions during the Little Ice Age. When volcanoes erupt, they send tiny particles into the atmosphere that block sunlight. During periods of high volcanic activity, this can cool the planet. Recent research has found that high volcanic activity during the Little Ice Age played a bigger role than cooling from the quiet sun. So unfortunately, the sun isn't coming to our rescue. It's up to us to prevent the worst impacts of global warming. Until we dramatically reduce our greenhouse gas emissions, they'll continue to be the main factor driving global warming.

**14 Tendency to underestimate climate impacts**

Keah Schuenemann - Metropolitan State University of Denver

The job of the Intergovernmental Panel on Climate Change, or IPCC, is to assess the science on climate change and produce summary reports. Interestingly, when we look back at their past reports, it turns out the IPCC is much more likely to \*underestimate\* than overestimate climate impacts. But before we get into that, let me give some background.

The IPCC is organized by the United Nations. Since 1990, they’ve produced five reports. Each “report” is actually a series of books, each almost 1000 pages. The books cover the physical science, the impacts adaptation and vulnerability, and the mitigation of climate change. The IPCC include climate models from more than twenty different climate laboratories around the world, each with their own supercomputers. Each lab’s model is written independently from the others. They come from China, Norway, the United States, Canada, France, Australia, Germany, Korea, Russia, Japan, and the United Kingdom!

The IPCC puts the report through a rigorous review process where each sentence is scrutinized. It produces a report that all authors agree on, and that the governments of the member countries agree on. Because of this process, the IPCC reports tend to err on the side of being conservative.

Here are three examples of the IPCC being conservative. First off, they’ve tended to underestimate how much greenhouse gases we’ll emit. In fact, the carbon dioxide concentration and emission rates measured in the last few years indicate that we are currently on the “worst case scenario” path. This suggests that the IPCC should adjust its scenarios to give a better sample of future emissions in order to imagine a worse worst-case, which it has done for the most recent report.

The second example is Arctic sea ice decline. The area of ice covering the Arctic Ocean has been getting pretty small at the end of summer these days. Whenever this bright white ice melts, it reveals a darker ocean surface underneath it. Dark ocean water absorbs more sunlight, making the system even warmer and melting even more ice. This is an amplifying feedback. If we graph the Arctic ice area at the end of summer each year, we find it’s decreasing \*much quicker\* than any climate model projected! This signifies that all of the climate models have underestimated the strength of this self-reinforcing cycle.

The last example is sea level rise. Measurements indicate that sea level rise is accelerating faster than projected by climate models. Most recently, the IPCC estimate was 60% below the observed trend. When the fourth report of the IPCC came out, scientists studying glaciers had begun to report that their flow of ice discharge to the ocean was accelerating. Some glaciers were accelerating, others were not, and we didn’t really know why. Giant meltwater lakes and drainage holes called moulins were observed on the Greenland ice sheet and fears were that the water might be getting to the ground, lubricating the ice sheet and its glaciers and causing it to accelerate its melt. Rather than include these dynamic ice melting processes in their sea level rise projections, the IPCC scientists decided they didn’t have enough information to include this effect properly. So they left it out entirely.

This is a good example of their erring on the side of caution. One study has taken a more thorough look at the IPCC projections, looking at new scientific findings after the IPCC reports came out. What they found was that new scientific findings were more than \*twenty times\* likely to be \*worse\* than what the IPCC predicted. There were a few examples where the IPCC overestimated climate impacts. But overall, the cautious approach of the IPCC means it’s been systematically underestimating climate impacts.

Why is this? Another study suggests that the IPCC and climate scientists in general tend to be conservative in their predictions because they’re erring on the side of least drama. In other words, scientists underestimate the threat of climate change because they’re worried about being accused of alarmism. However, one myth distorts the evidence for IPCC reports.

That myth is that the IPCC and the impacts projected by the climate models are alarmist, exaggerating the danger of global warming in order to cause needless worry. This myth uses the technique of conspiracy theory. Some people believe the scientists of the IPCC are conspiring to trick people about the effects of global warming. This myth also uses cherry picking. It uses isolated examples where the IPCC overestimated climate impacts. But we’ve learned that most of the data points towards the IPCC tending to underestimate climate impacts. They are the polar opposite of alarmist. In reality, the IPCC is 20 times more likely to underestimate rather than exaggerate climate impacts.

**15 From the experts: Climate models**

Professor Dan Lunt - University of Bristol, Professor Andrew Pitman - University of New South Wales, Professor Katrin Meissner - University of New South Wales

Lunt: A good question is what actually is a climate model, so a climate model is a piece

of, or the usual use of the word for climate model, is a piece of computer code, a list of instructions to a computer that encapsulate our very best understanding of the way that the atmosphere of our planet and the ocean work in a physical sense.

Pitman: The basic underpinning laws that climate models are built from includes the basic Newton's laws of motion, conservation energy, conservation mass. Basic physical principles that physicists discovered a very long time ago.

Meissner: All these models share lots of characteristics and, of course, the physics of the models are very very similar because they are all based on the fundamental same equations of fluid dynamics. It's the same equation that we knew that equation since hundreds of years.

Lunt: And actually you can write down the very fundamental equations on a single piece

of paper. Solving them is a lot harder, and that's actually what climate model does.

Pitman: All a climate model is is a million lines of computer code running on a really

really big computer system.

Lunt: The way that climate models work is that the divide the world up into a series

of boxes, so it's very like LEGO if you like.

Meissner: Basically a model is like if you would construct your world out of little LEGO

blocks, and it's basically the size of the LEGO blocks. You can buy a real expensive LEGO Star Wars ship, my son has those, very big expensive, takes the poor parents two days to build them and they have lots of detail or you can buy a little car for a 3 year old, which doesn't have that much detail but is made out of big big blocks.

Lunt: So you can imagine sort of building up LEGO in that, each one of those LEGO blocks perhaps represents a box in which the climate model has a value for temperature, has a value for the amount of air or water within that box, it has a value for how fast the air or water within that box is moving, how much moisture is contained within it, if it's the atmosphere. So you imagine you've got this kind of matrix, if you like, surrounding the world of these boxes that go up into the atmosphere, down in the ocean.

Now the model can't actually tell you anything about the climate on a scale that is smaller than one of these grid boxes. The very highest resolution models are perhaps 10s of kilometers, but most models you're talking hundred of kilometers, so there are lots of processes in the atmosphere in particular that actually occur in reality on a much smaller scale than that. For example, clouds themselves are much smaller than the size of one of these grid boxes and so we have to make approximations to have some of those processes work.

Pitman: You build parametisations or representations of processes, which need to be resolved at scales we can't explicitly model in the climate models, things like clouds, things like convection in the atmosphere, things like eddies in the ocean, things like land-surface processes.

Lunt: The first weather forecast that was carried out on a computer that I'm aware of

was carried out by a guy called Charney [Jule Gregory Charney] and actually he did a 24 hour weather forecast. It took him 24 hours to do that forecast, so it wasn't particularly useful. It turned out that if you, there is some archived photography of what that machine actually looked like, and actually it looked very similar to a modern day supercomputer. It's about the size of a room, it's got lots of leads everywhere, and it's got a few people looking around, technicians looking after it.

Actually it looks very similar to a modern day super computer, but actually if you work out, it turns out that the amount of computer power in that first supercomputer that did that first weather forecast in the 70s, your mobile phone is probably about 30,000 times more powerful than that supercomputer. A modern day supercomputer is about 30,000 times more powerful than your mobile phone, so there are many orders of magnitude. That gives you a flavour of how supercomputing has moved on from the 70s just today, just in 40 years or so.

Pitman: There's probably no parts of a climate model, of a modern climate model, that still reflect what was done in the 70s. Almost everything has been rebuilt or rewritten, I think. The resolution has increased from something around 700 by 500 kilometers to 100 by 100 kilometers. The detail in the vertical has increased dramatically. Oceans have been properly and fully coupled. The land surface has been completely revised to incorporate a whole suite of processes.

Sea ice models have improved dramatically. Cloud parametisations have improved. We've resolved most of the water vapour feedback problem. It's like asking what's the relationship between a Formula 1 Grand Prix car in 2014 compared to 1970. And the answer is there probably isn't a single widget that's shared.

Lunt: The resolution is getting higher. In other words, the boxes are getting smaller

and smaller, but the computer power is also increasing. We're able to simulate sort of the same amount of time, if you like, with one of these models.

Pitman: One of our grand challenges in climate models is to dramatically improve the spatial detail that climate models use and that's really a computational problem. We just need bigger supercomputers to really resolve the detail of those things. The things that climate models struggle to capture well would include some extreme events. They struggle with the location of the storm tracks. They struggle with the detail of cloud fields. They struggle with some major challenges we don't represent at all - the processes which might trigger abrupt climate change, so methane release or permafrost melt.

Lunt: A climate model is never going to be able to completely reproduce the weather of

the last 200 years; however, when you average together all of these weather events, what you end up with is climate. What we think is if we also run lots of climate model simulations as well as and compare the average of those with the average of many years, for example, of observed weather, we can get quite a good comparison between a climate of a model and the climate of the real world and compare those. That is a fundamental test that we can use to test our climate models.

Pitman: If you ask what do the climate models struggle to represent in terms of the simulation of whether it will warm for doubling of CO2, my answer would be nothing at all because they do that really well. If you ask what the climate models struggle to predict at the scale of a region and its response to doubling of CO2 in terms of rainfall, lots of things .They don't get the details for clouds, the convection, the rainfall processes, the detailed synoptics blocking a whole range of things because the spatial resolution that we use for climate models is probably too coarse to capture a a lot of kinds of those key phenomena.

There's a whole range of reasons why we're confident in the skill of climate models for the problems that they were designed for. First of all, they are built upon physical principles, and those physical principles are known unless of course Newton was stupid, which I don't think he was. So we have basic fundamental theory, not sourced from climate science but sourced from basic chemistry, basic physics, basic biology and applied mathematics that says the core of climate models is sound.

Secondly, of course, they're used routinely in other applications like weather forecasting, and so we effectively can evaluate a lot of our science routinely and weather forecasting is becoming increasingly accurate irrespective of what some of your listeners might think. If they actually write a diary of a 5 day forecast and check off how those 5 day forecasts evolve they'll find that they are shockingly accurate nowadays. That's the second test. Thirdly, we routinely test our models against observations over the last century and earlier and they do extremely well in that respect.

Finally, we can test our models against perturbations, so we can, for instance, simulate a volcanic eruption, for example, and check that the climate models respond appropriately to what a volcano does to the atmosphere. There are multiple lines of evidence and they all point to the climate models being reliable for what they were designed. There's a lot of myths out there on what we think or how we build our understanding of what will happen in the future.

There are many lines of evidence that are used to understand how climate might change in the future. If you could take the climate models away, we would still be just as worried about the future climate. Climate models merely inform and embellish and colour and flavour to the future of the climate, the projections of future climate, but we would be just as worried based on theory than data. Climate models are one strand of evidence for future climate change, but by no means do they underpin our concerns. What underpins our concerns are physics.

**16 Ocean modeling**

Dan Stevans - East Anglia University

Hello. My name is David Stevens. I do research in oceans and their impact to the climate system at the University of East Anglia. I guess, as a scientist, I like to control the experiments. You maybe change something and see how it responds but you need a control case. Unfortunately, we don't have a control case. We've only got the one planet, and yet we are performing an experiment. I guess, modelling is pretty much our only chance of trying to predict what would happen or understand what we are doing to the planet.

A climate model is a mathematical description of the components of the climate system: the ocean, the atmosphere, the cryosphere. We use equations to represent those components. Essentially we just solve those equations. I do find it amazing that you can set up a mathematical model of the Earth and essentially do nothing but shine the sun on it, and it produces a climate not unlike what we see if we can’t take measurements.

The fundamental equations we use, I guess, go back to Newton's second law of motion. If you consider a parcel of fluid in the atmosphere or in the ocean, then there will be forces on that parcel of fluid. Those forces will induce an acceleration. That gives that parcel of fluid a motion. We can essentially solve many, many millions of parcels of fluid all around the Earth and compute the winds in the atmosphere that comes in the ocean.

My main interests are in the ocean, and the oceans fall on the climate system. I'm very much focused on trying to improve and understand the ocean component of climate models. The four models themselves are really, really complex. Understanding them is not really a kind of thing that a single person can do in isolation. Climate modelling tends to be a team-type activity. There might be a group working on the ocean, a group working on the atmosphere, but then they'll come together and help build a single model of the entire system, and then work together in terms of analyzing the results because the components are all interacting with one another.

Let's start by just talking about why you might even study the ocean. It's really important because of its enormous capacity to store heat. One of my favorite factoids for telling people about the ocean is the top few meters of the ocean has got the same heat storage capacity as the entire atmosphere above. There's an enormous potential for storing heat, or taking heat out of the atmosphere, or releasing heat back to the atmosphere.

The ocean isn't a single monolithic slab of water. If you go to, say, the tropics, the water's surface can be around about 30 degrees Celsius. Yet if you go down to the depths of, say, 4 or 5 kilometers, the waters can be two degrees Celsius. There's an enormous differential in heat between the surface ocean and the deep ocean. That leads to possibly the question of why is the water so cold in the tropics, in the deep waters? Where does that cold water come from? It doesn't take too much for one to think that actually it must have come from somewhere cold.

There are movements in the ocean right down to the deepest parts of the water column which are transporting waters from the poles—waters tends to sink, gets very dense and sinks to the sea floor, and then spreads out throughout the world's oceans. This transfer of cold water towards the warmer regions, the equatorial regions and associated warm water flowing from the surface of the tropics towards the poles, provides the heat transport. The ocean is transferring heat from the equatorial latitudes to the polar latitudes.

This flow of warm water at the surface towards the poles and cold water at depth towards the equator produces a transfer of heat from the equator towards the poles. It's this transfer of heat that plays an important role in keeping our planet at the temperature in the regions of our planet, at the temperatures that we live in. I'm not talking at all about global warming here, just how the climate system maintains itself in a fairly equilibrium state. There are some variability on top of this, but the basic mainstay is set by some of these processes.

People have, for many years, thought about what would happen if this overturning circulation we talked about earlier, particularly within the Atlantic, shut down and transport an awful amount of heat northwards towards the high latitudes in Europe. There's been less focus on some oceans, and yet there is an overturning circulation associated with the sub-motion and the waters around Antarctica. It often seems very remote. We thought, "What would happen if that shut down? Would it have an impact? How global would the impact be felt?"

We did some similar experiments where we released significant amount of fresh water in southern oceans to mimic carving or melting of the ice sheets to look at the impact that might have on the planet as a whole. There were some surprising findings right through to impacting the northern hemisphere. The Antarctic being a long way away doesn't mean to say you can ignore it. Problems that might occur there are not our problem but they potentially might be.

I guess, probably, the key question at the moment is how will the ocean respond in a changing climate? Will it reduce the impacts of the global change we're seeing, or is it currently reducing the impacts of global change? What are the potential feedbacks? Could some regions see a faster change in climate, some regions slower? We already know that the Arctic sees a much more amplified response to global warming than, say, the tropics.

There are a number of ways of going out into the ocean and measuring the heat of the ocean, the temperature of the ocean. The traditional method was to go along in a ship and then lower an instrument from the surface down to the sea floor and make a profile measurement of temperature. That's very expensive, both in terms of people and monetary costs. Ship time is tens of thousands of UK pounds per day. Then you have to man it and have trained scientists operating the instruments.

More recently, there's been a huge increase in the number of profiles of temperature in the ocean from something called the Argo Network. Argo is a network of floats. They do seem rather odd for a float in that they sink. They start at the surface and will sink to a depth of about 2,000 meters. They move along with the ocean currents. After 10 days or so, they can pop up to the surface. When they come up to the surface again, they're measuring temperature. They speak through a satellite communications network and deliver their temperature data they've recorded, and then sink back down to the depth again and then travel on. There's about 3,000 of these in the world oceans. It's produced a real step change in the number of measurements we have of temperature profiles.

Pre-imposed Argo is really—stark contrast. The temperature data we collect from the—both ships and from the Argo program are useful to help us start off our forecasts of the climate system and in particular the ocean component. To start forecast, we need to know the state of the system at one particular time. Back in the ‘60s, we had a very few measurements of vast sways of the ocean, where there were literally no measurements had ever been taken. Whereas since about 2005, there are measurements throughout the world's oceans, pretty much everywhere. There are very few regions, possibly just the polar regions, where measurements are sparse.

We use this data to provide some starting point for our forecasts. That's called initialization. Initialized forecasts of ocean conditions have certainly got a much better chance of being more accurate now where we have all these data compared to the ‘60s. I originally trained as a mathematician. In my third year, I did a course on mathematical modelling of the oceans. It is very theoretical. It looked ay very idealized models of oceans per square basins. It is really focusing in on processes. I found that really, really interesting. I went on and did a PhD in mathematical modelling of the oceans, but the models became more complex and more realistic.

Eventually, that led me to talking to observational oceanographers. I guess, in the late ‘80s, early ‘90s, it was a time when the models of the ocean were just getting realistic enough, observational oceanographers to really start to believe them and possibly even use them in planning their observational campaigns. I started to work with one of the observational oceanographers here. I actually even went to sea a few times, which was really, well, one, exciting; but two, seeing the measurements actually collected at first hand, that really gives you a much greater insight into what's going on within the ocean and also an appreciation of what you are doing in terms of the modelling. This research cruise—they're called cruises.

They're not necessarily a holiday but it was to the Antarctic and to the southern ocean, taking measurements in the southern ocean. It's about two months long but really enjoyable and really productive. I joined the ship in the Falkland Islands. Then we sailed down to the Antarctic continent, then from there, took measurements all the way up through the Atlantic to just off of Brazil, just near Rio de Janeiro. It really was mesmerizing. It was absolutely beautiful, pristine. The wildlife is just incredible. We should make sure we shouldn't damage it either. I think it's just a case of being—trying to engage and be open and be honest. I do try and go out and engage the public by going to schools. I try and give public lectures when there's good opportunities. Most recently, I gave one to a group of old-aged pensioners in North Falkland in July. They were all really interested, really engaged, and it's good fun. I really do enjoy trying to pore over some of the science.

**17 Land modeling**

Andy Pitman - South Wales University

I'm Andy Pitman. I'm the Director of the ARC Centre of Excellence for Climate System

Science based at the University of New South Wales. My personal research is focused on terrestrial processes and their representation in climate models. The basic underpinning laws that climate models are built from includes the basic Newton's laws of motion, conservation of energy, conservation of mass—basic physical principles that physicists discovered a very long time ago. They are the basic underpinnings of the core of the climate model. Then on top of that, you build parameterizations or representations of processes which need to be resolved at scales that we can't explicitly model in the climate models: things like clouds, things like convection in the atmosphere, things like eddies in the ocean, things like land surface processes.

A lot of the challenge in modeling, the detail and the regional patterns of climate come from how we represent those parametrizations. We don't so much tune parameters in climate models. What we do is take observations, learn from those observations how processes work. Then we build mathematical representations of those basic processes into the climate models in the form of computer code. All the climate model is a million lines of computer code running on a really, really big computer system. That computer code is a suite of algorithms built from observational data where that exists, or basic physical principles where we lack the observations to understand the detail process.

When you run a climate model and you get data from it, you always reintroduce observations at that stage to evaluate the model, to check the model. We always analyze the model results to find weaknesses. There are always things that work better in climate models or worse in climate models. We use observations routinely to tease out what does and doesn't work well in the models and, of course, focus on improving those things that don't work well.

The things that climate models struggle to capture well would include some extreme events. They struggle with the location of the storm tracks. They struggle with the detail of cloud fields. They struggle with some major challenges we don't really represent at all the processes which might trigger abrupt climate change, so methane release or permafrost melt, although some people begin to work on permafrost. I think it all depends upon your perspective.

If you ask what do the climate models struggle to represent in terms of the simulation of whether it will warm for doubling of CO2, my answer would be nothing at all because they do that really well. If you ask what the climate models struggle to predict at the scale of a region and its response to doubling of CO2 in terms of rainfall, lots of things. They don't get the details of the clouds, the convection, the rainfall processes, the detailed synoptics blocking a whole range of things because the spatial resolution that we use for climate models is probably too coarse to capture a lot of those kinds of key phenomenon.

One of our grand challenges in climate models is to dramatically improve the spatial detail that climate models use, and that's really a computational problem. We just need bigger supercomputers to really resolve the detail of those things. Look, if you go to observational data sets of the global patterns of anything—pressure, rainfall, temperature—you won't be able to tell which is from a model and which is from the observations.

The climate models' large-scale simulations of the climate are outstanding, a truly phenomenal achievement over the last 20 or 30 or 40 years. At the large scales, they are outstanding. There's probably no part of a climate model, of a modern climate model, that still reflects what was done in the ‘70s. Almost everything is being rebuilt or rewritten, I think. The resolutions increased from something around 700 by 500 kilometers to 100 by 100 kilometers. The detail in the vertical has increased dramatically. Oceans have been properly and fully coupled. The land surface has been completely revised to incorporate a whole suite of processes. Sea ice models have improved dramatically. Cloud parameterizations have improved. We've resolved most of the water feedback problem.

It's like asking: what's the relationship between a Formula One grand prix car in 2014 compared to 1970? The answer is there probably isn't a single widget that's shared. Because climate models are built from the basic physics, they should be applicable to any environment. You should be able to take a climate model run for the Earth and use it for a different planet, and people do do that. Similarly because the basic physical processes in Newton's laws of motion don't change, and conservation energy and mass don't change with time, in any context that we understand it anyway, the climate model that's built for today ought to be able to do the past paleoclimates, for instance, and the future.

Indeed, they can. They're not by any stretch of the imagination perfect if we try to simulate the last glacial maximum or 30 million years ago, but they do capture an awful lot about long-term past climates. Indeed, there had been discoveries around things that happened in the long distant past, which have been hypothesized using climate models and then discovered from observational data. If the climate models do a pretty decent job of simulating the long-term past climate change and can simulate the 20th century extraordinarily well, we have considerable confidence that they can simulate the near future extremely well.

By near future, I mean after 2040, 2050. As you move forward into the future, if mechanisms begin to develop that are outside of the observational record, the observations we've used to build the model, uncertainty increases. For instance, we don't represent the processes that might trigger abrupt climate change. We suspect there are things that might evolve in the climate system that aren't in the observational record. Whether or not we will capture those nasty surprises, time will tell.

Paleoclimatic modeling is extremely useful because it tests the models for very last changes in the Earth's climate in the past. The problem is they're not necessarily good analogies with the next 50 to 100 years. Paleoclimate mostly was orbitally driven and driven my movements of continents. On the time scales of 50 to 100 years, we're not expecting massive changes in solar luminosity. If there were, we have bigger problems than global warming. We're not expecting Africa to suddenly move a thousand kilometers west. The triggers and the drivers of paleoclimatic change are profoundly different to the drivers of human-induced climate change. It's used for the test models, but it's insufficient. It's useful but insufficient; necessary but insufficient.

There's a whole range of reasons why we're confident in the scale of climate models for the problems that they were designed for. First of all, they're built upon physical principles. Those physical principles are known, unless of course, that Newton was stupid, which I don't think he was. We have basic fundamental theory, not sourced from climate science, but sourced from basic chemistry, basic physics, basic biology, and applied mathematics that says, the core of climate models is sand.

Secondly, of course, they're used routinely in other applications like weather forecasting. We effectively can evaluate a lot of our science routinely, and weather forecasting is becoming increasingly accurate irrespective of what some of your listeners might think. If they actually write a diary of a five-day forecast and then check off how those five-day forecasts evolved, they'll find that they are shockingly accurate nowadays. That's the second test.

Thirdly, we routinely test our models against observations over the last century and earlier. They do extremely well in that respect. Finally, we can test our models against perturbations. We can, for instance, simulate a volcanic eruption, for example, and check that the climate models respond appropriately to what a volcano does to the atmosphere. There are multiple lines of evidence. They all point to the climate models being reliable for what they were designed. On longer timescales, so not five years, but for periods where the initial conditions aren't critical, on timescales of decades and longer, they are very, very good.

For problems that are large spacious scales, so continental scales and above, they are, I think, extremely reliable up to 30 to 50 years into the future. As you move further into the future, I become less confident. I think they are a good and indicative guide for what the climate might be like in 2100, but I wouldn't be absolutely sure. I wouldn't be sure, not because I think they're overestimating the response, but I think they lack a suite of mechanisms that might amplify global warming. I suspect, if anything, they are underestimating the scale of change after the end of a century. The science isn't clear on that, so I'm being a bit speculative.

Secondly, spatial resolutions that say the scale of Queensland or New South Wales, the detail isn't in the models because of the computational cost. As you move down to finer and finer scales, as more and more mechanisms are interwoven to give you the regional pattern of change, I think the climate models become things that we're less confident about.

Finally, the things that are not based upon well understood physical principles. Changes in agricultural yield require a whole variety of things to be done well, ranging from—soil moisture and rainfall and temperature and lots and lots of—lots of things that interact. When you need to get dozens of things right at finer special scales and for a climate model to give you an impact, then you should treat what the climate model tells you about that impact very carefully.

There's a lot myths out there on what we think or how we build our understanding of what will happen in the future. There are many lines of evidence that are used to understand how climate might change in the future. If you could take climate models away, we would still be just as worried about the future climate. Climate models merely inform and embellish and add color and flavor to the future of the climate, the projections of future climate. We would be just as worried based on theory and data.

Climate models are one strand of evidence for future climate change, but by no means do they underpin our concerns. What underpins our concerns is physics. There's a lot of research out there that gives us insight on climate sensitivity. It ranges from some fairly sophisticated analysis of paleoclimates through to some rather simplistic approaches to understanding how much the climate may change. Climate sensitivity is how much the planet will warm in equilibrium to a doubling of CO2. The range in the last IPCC report was 1.5 to 4.5 degrees. I think the 1.5 will turn out to have been overly cautious or optimistic from the science community. I think the right number is in high 2s or low 3s. I base that upon multiple lines of evidence.

The evidence to suggest it's below 1.5 is very arguable, I think. People need to understand that there's a multiple line of approach to the peer-reviewed literature. Somebody can write a paper and get it through the peer-review process. That's the first check. The much tougher check is time and the test of time. People will publish papers that suggest climate sensitivity is 6 degrees or 1.3 degrees. Both of those are big claims needing strong evidence and critically independent reproduction. What we tend to find is, the big claims that climate sensitivity is very low or very high turnout over time when checked and reproduced and rerun and reanalyzed don't stand independent scrutiny.

That's the proper process in science. There's nothing wrong with that. If you come up with a really strong piece of evidence that the climate sensitivity is 6 degrees and you can get that published, good for you. It's then a requirement that the community do their best to destroy that. If they can't destroy it, then that's really scary in the case of 6 degrees, and really good use in the case of one degree. So far as I know, every single time somebody has come up with values very low or very high, subsequent analysis has demonstrated that they're wrong. I do like the scientific method because—a lot of people don't understand how it works. They assume that if you've published the paper, the paper is right. Obviously, everything I've published is right including the things that I have contradicted in subsequent papers. Science evolves.

The bigger the claim, the bigger the attack on the claimant. It's right that that's true. It's good that that happens. One of the really emerging challenges in climate science is the question of extremes. Weather forecasts are built to capture extreme weather or to predict extreme weather. It's really, really hard. It's particularly hard when an extreme is a combination of multiple events occurring simultaneously. Climate models cannot model or simulate the detail of extreme events. For instance, a tropical cyclone—I don't think climate models tell us very much about what will happen to tropical cyclones because they're just not built at the spatial resolution that enables us to capture the detail. Also, things like blocking where a high pressure system forms and holds the climate in place for a significant period of time commonly leads to extreme conditions, particularly heat waves and drought. Climate models just don't have the finesse, the spatial detail, to capture the mechanisms which drive those sorts of things.

There has been a huge growth in analysis of climate models and extremes, but most of it is the statistics of extremes. What would be the probability of particular events occurring in the future, not what would a specific event look like in 2030 or 2050. When you're looking at the statistics of extremes, I think climate models have some scale in showing you the sign of the changes, but I'm not overly confident they yet have the scale to give you the detail around how extremes would change. The problem is that whichever extreme you look at seems to get worse in the future, in part because of the intensification of the hydrological cycle and just the background warming that we see from CO2.

I think we have a good understanding that a lot of the extremes will get worse, but of course, some extremes will get much rarer, like extreme cold, at least in Australia. It's not necessarily true that extreme cold will get less common in higher latitudes, where you see an increase in the strength of the storm tracks and more variability, for instance bringing Arctic air down over parts of North America and Europe. Global warming doesn't mean everywhere has to warm. The relationship between global warming and the hydrological cycle is something we're beginning to understand much better.

Basically, you can start at a whole variety of points in the hydrological cycle because it's a cycle. If you start with evaporation, if there is more energy, there is more energy to drive evaporation. If you increase CO2 and you increase downwelling infrared radiation, there's more energy in what we call net radiation. It's the net radiation that's used to drive processes like the turbulent energy exchange with the land, the latent heat flux of evaporation, and the sensible heat flux which directly warms our atmosphere. If you have more energy, you drive the evaporative processes faster and you pump more energy at the base of the atmosphere in the sensible heating. That drives deeper convection, more moisture being driven up higher into the atmosphere that tends to increase the probability of rainfall and more intense rainfall, and you can see how a cycle begins to form.

Basically, it's an acceleration or an intensification of the evaporative processes. We suspect that areas already susceptible to drought will end up in drought for longer periods because you tend to see a situation where the evaporative process driven by the energy sucks the water or drives the water out of the landscape a little bit quicker. No, massively quicker. We're not thinking this process would drive a one-month drought to be a 20-year drought. If you have more energy and there's water available, that would evaporate a little bit faster. If you evaporate the water a little bit faster, you dry the landscape out a bit quicker and that tends to intensify drought. The major driver of droughts across the landscape is the large-scale synoptic patterns and the modes of variability like ENSO and La Nina and El Nino cycles. The key regional drivers of drought are the large-scale modes of variability.

What I was talking about in terms of latent heat, in a sense more heat drying out the landscape, is, if you like, the detailed brush strokes on a larger canvass. You have to look at the system in its full glory to understand the difference between a drought that's occurring becoming slightly more intense because of evaporation, as distinct from the large-scale patterns driving more frequent droughts. Those are two quite different mechanisms. If you're in an area that's already susceptible to drought, it may well be in some years enough to drive so much deficits which are problematic for agriculture or for water resources, in general beyond, the threshold such that they're problematic.

Also if you have a general drying, when it does rain, that water doesn't necessarily make a substantial difference for agriculture or for water resources. A much drier landscape where everything's in deficit, if there is rainfall, that landscape will suck up that rainfall and hold it, which is a problem for dams and water supply as we have seen in Perth, for instance. A small change in the dryness and a small change in the rainfall commonly translates into a big change in the runoff into dams, for example. There's good understanding of the mechanisms behind that now.

 When I was an undergraduate, I was offered a choice of either going to Canada to work on land service processes or France to work on cloud processes. My French is appalling, so I chose Canada. Okay. My personal area of research is terrestrial processes. There are huge number of opportunities for bright students to contribute in this area. There's a whole variety of interesting questions. It depends where you sit.

One is, how do we parameterize or represent urban landscapes in climate models? Urban environments appear to amplify some extremes. Those aren't represented in the climate models because they are too fine a special scale. We're now moving down to those scales that we need to resolve those landscapes properly and how to represent urban landscapes in a climate model so we get the right moderation or amplification, but global warming signal is very important.

Another one is: how do we represent agricultural systems in climate models? They act quite differently to natural landscapes. For instance, they're harvested. They have quite a different phenology in terms of the way that they interact with the atmosphere. How to do that is a real problem. Next is something around soil carbon. Soils store a vast amount of carbon. There's good evidence to suggest they'll store less carbon in the future because microbial activity will break down that carbon more quickly and recycle it back to the atmosphere. That's a six-million dollar or six-billion dollar question, because if the soils lose their carbon as a consequence of global warming, it's a massive positive feedback. If the soils hold on to their carbon, as well as they currently do or even increase their ability to store carbon, that's a negative feedback on global warming. While we're pretty sure now we have a positive feedback, we're not sure of the scale of that feedback. It's extremely messy and complex to represent those processes. It's something we have to do much more skillfully.

The last is the whole issue of human modification in the system. Things like irrigation, damming of rivers, how those flow into the oceans, because that impacts on the ocean's circulation, that whole issue of how humans interact with the energy carbon and water cycles is a massive challenge that we're only beginning to chip away at. Most of us who work in the field think that using soils to store carbon, if we did it really well and really actively and on very large scales, might enable a country to retain its current levels of soil carbon. By default, we'll lose soil carbon. We're losing it by erosion because massive amounts of soil are eroded annually across the Australian landscape because of farming practices and land clearance and a whole range of other things. The default is we lose soil carbon over the next 30 to 50 years at a significant level. If we really actively work on that system, we may be able to hold the current soil carbon in place.

The notion of using soils as a carbon sink to offset global warming is optimistic. Traditionally, I would have a conversation with them. I started—it depends who they are, but I've started saying, "Look, everyone's entitled to their own opinions but not their own facts. If you happen to want a conversation around why the science is now clear and robust, I'm happy to have that conversation with you. If you've already decided that we're a bunch of global conspirators who've managed to orchestrate a complete conspiracy that has convinced most of the world's governments of a problem that doesn't exists, I probably can't do much for you."

Climate scientists are trained in math, physics, computer science, biology, chemistry. As most people know, people trained in those fields have ordinary communication skills typically. Our definition of success is our ability to write code or do a chemistry experiment or whatever it is. I recently spent some time assessing graduate students for what's called The Monash Foundation. A number of the students who come in to be interviewed for scholarships are from law. They have spent lots of time mooting and debating. Their ability to communicate, to succinctly summarize their interests, their desires, their vision is phenomenal, because they're practiced.

One of the things we're trying to do is get our graduate students into a much more personalized program where they do talk more frequently. We're trying to build opportunities for them to be trained a bit more in science communication because I think it's critical. The answer to the question is practice and understand that the first time and the 15th time and the 50th time, you'll probably do it not very well, but in the end, you'll develop some skills. I also think we have to read more broadly. I do not believe that we can all go and do a second degree in science communication or in psychology. Climate denial is increasingly understood by the psychology community. There are some fairly accessible books ranging from things like Naomi Oreskes' book on "Merchants of Doubt," which gives you a really good insight on some of the problems. There's also books in psychology. There's even great posters which show you this psychological trick that someone trying to deny climate change is using and why it's falsifiable. It's worth knowing about those things so you can see the techniques being used against you. It does require a little bit of a broadening of the training that we all have.

We have to be very careful with that because what we really need are really committed, bright students doing climate science not trying to be everything to everyone. It's a balance, but at least engage in some of the basic background to why people have these scientifically invalid views is a useful thing to do. I think I'd simply say that if we're emitting ten billion tons of carbon dioxide in the atmosphere per year, and you don't think that can have an impact, you need to look around you and look to see what happens in a city like Beijing when a fraction of that level of pollution is put into the atmosphere, people can't breathe in the summer. We can look around us. If you open your eyes, you will see changes going on around you that are clearly demonstrable evidence of climate change and the consequences. If you choose not to look, there isn't probably very much I can do for you.