**U. of Queensland Climate Denial Course - Lecture 2**

 **Global Warming Indicators**

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**1 Overview - Is warming happening?**

John Cook - Communications Research Fellow

Last week, we briefly looked at the many lines of evidence that humans are \*causing\* global warming. We also looked at how all this evidence has resulted in an overwhelming scientific consensus. However, a small minority don’t even accept that global warming is \*happening\*. So this week, we’re going back to basics. We’ll examine the many different indicators that our planet is warming. We’ll look at the heat building up in our climate system and how that affects heat records and sea level rise. We’ll look at a growing contributor to sea level rise: melting ice. We’ll talk about the challenges of putting together a global temperature record. And we’ll even look at what’s been causing some recent intense winters in the Northern Hemisphere.

I’m here at the University of Ottawa, where one of our presenters is researching the cryosphere. Standing in the snow, it might seem a little weird talking about global warming. But remember global warming is about the temperature averaged over the whole planet. Even while the planet continues to build up heat, some places will still experience cold, even record cold, at times. So let’s look at some of the myths casting doubt on the basic reality of global warming.

**2 Heat build-up**

Kevin Cowtan - University of York

Over the past century, we’ve released huge quantities of heat trapping gases into the atmosphere. This has caused the earth to warm on a global scale. If you were to look at a short time period or a single place, you would find it hard to see the overall picture. Let’s see how taking a narrow view can lead to a misunderstanding.

Here is a temperature history for Sao Paulo, covering the 20th Century. 1900 is on the left and 2010 is on the right. Temperature runs from bottom to top. We can see that it has warmed in Sao Paulo over the course of the century. Here's another temperature history, for Louisville. This one doesn't show any obvious warming. Here's another one, for San Diego. This shows warming, but a different pattern to Sao Paulo. If we look at weather records for different places around the world, they all show different things. That's because weather varies from place to place.

But there is a pattern: most show some kind of warming. If we combine weather records from many locations around the world, we get an estimate of global temperature change. And now the warming pattern is clear. It's hard to see what is going on if you look at just one place. But if we look at the whole planet, we see a clear pattern of warming. One myth says that global warming stopped in 1998. This misunderstanding occurs because 1998 was a hot year compared to many in the last two decades. But we can see other examples of exceptionally hot or cold years in the record. Both 2005 and 2010 are hotter. There has been a slowdown in the rate of atmospheric warming over the past decade and a half, but this is exaggerated by picking 1998 as the start of that period.

When we see this slowdown, are we looking at the whole climate system? Actually, we're not. So far we've only looked at the air temperatures at ground level - which is where we live. What about the rest of the planet? Climate is driven by heat from the sun. Climate changes when there is a change in how much of the sun's heat is captured by the Earth. The extra heat causes global warming. Most of the Earth is covered by water. Water can hold a lot more heat than air. In fact, more than 90% of the extra heat trapped by the Earth goes into warming the oceans. Some of what's left warms the land, or melts ice. Only about 2% of the extra heat ends up in the atmosphere.

If we look at the heat in the whole climate system including the oceans, we can see that the heat in the system has continued to increase since 1998. There's a good reason for this. The changes we've made to the atmosphere cause it to trap more heat. The warming of the atmosphere is one symptom of that extra heat, but not the only one. We saw that looking at just a part of the climate system - one city - gave misleading results. But when we looked at the whole globe, the pattern of warming was clear. This is an example of cherry picking. The atmosphere is also only one part of the climate system, and not the largest part. If you get to choose one part of the planet to look for warming, you can prove whatever you want.

By looking at the whole planet, we don't get to choose our answer. Looking at the warming since 1998 is also a cherry pick. 1998 was a hot year, although not the hottest. Picking it as a start date makes the hot years since seem less exceptional. When you see a claim based on data from just one country, or one or two decades, ask yourself "why did they chose that data"? What happens if you look at the bigger picture? There is evidence that the pattern of global warming has changed in the last decade, with more heat going into the oceans and less into the atmosphere. There are also other factors which affect global temperature. However, they are temporary and none of them affect the big picture. The heat trapping gases we have released are continuing to warm the planet.

**3 Hot records**

Kevin Cowtan - University of York

In this lecture, we're going to look at the difference between weather and climate. Weather changes all the time. Climate only changes when something makes it change. Global warming doesn't stop weather from happening. It doesn't even stop \*cold\* weather from happening. To understand the difference between weather and climate, let’s visit a weather station. This is a historical weather station in England. Weather stations like this have been used to measure temperature for over a century. There are more than ten thousand weather stations around the world. The equipment has changed a bit over time, but the job they do is the same. We’re mostly interested in temperature, which is measured here.

This is a Stevenson's screen. Inside are two thermometers, measuring minimum and maximum daily temperatures. The screen keeps the sun and wind off of the thermometer, so that it provides a reliable measure of air temperature. What do weather station records tell us? People tend to remember record breaking weather, so we can look for records in the temperature data. We can count record breaking hot days and record breaking cold days - days which were either hotter or colder than any other day before that date. But once a record is set, a new record needs to be even more extreme. So as our weather history has grown, new records have become rarer. Just counting records is misleading.

Instead we can compare the number hot and cold records in any decade. If the number of hot and cold records is about equal, then the weather is not changing. If we see more hot records than cold records, then it is getting warmer, and vice-versa. Here is a comparison of the number of hot and cold records, counting 2000 weather stations in the United States. The number of records is given for each decade from 1950 to the present. For the \*first\* few decades, the number of hot and cold records are about equal. Over the \*last\* few decades, the proportion has changed, with almost twice as many hot records as cold records. That suggests that the United States has been getting warmer.

Here is a similar comparison for Australia, counting record hot or cold months. Records have been counted for both daytime and night time temperatures. Again, we see that the proportion of hot records has increased. This is a very simple way of analysing historical weather data. In practice, scientists have better ways of detecting warming. But even these \*simple\* comparisons strongly suggest that it has been getting warmer.

We call this global warming, or climate change. What is climate? Climate is how likely you are to get different kinds of weather. Different parts of the planet have different climates - they are colder or warmer, wetter or drier. But there is normally a mix of weather that is likely to happen in one place. Alaska is cold. Arizona is hot. New Zealand is wet. Egypt is dry. Each place has its own climate. If the \*climate\* changes, different kinds of weather happen more or less frequently. If the climate gets \*warmer\*, you are \*more\* likely to get exceptionally hot days, and \*less\* likely to get cold days. You still \*get\* cold days. Some places will \*even\* set cold records. But they happen less often.

Here's an illustration. I’ve got some dice with weather symbols. If I roll them, I get different kinds of weather. Sometimes I get three suns - a very hot day. Sometimes, I get three snow clouds - a very cold day. Now suppose I were to rig the dice, so that they roll suns more often than snow. I’ll still get the occasional very cold day, but less often than before. But I’ll get \*more\* hot days. Global warming is like rigging the climate dice.

People naturally find this confusing. What we \*experience\* is weather. You need a long memory and the right lifestyle - for example, someone who lives off the land - to notice climate change. Most of us experience \*weather\* on a day to day basis, whereas \*climate\* change happens over the course of decades. Unless you live off the land, you probably won’t notice the changing climate. But a small change in global climate \*can\* affect us, through the water cycle, through extreme weather, and through agriculture.

 A common misconception is confusing weather and climate. You've probably heard someone say something like 'It's cold outside. Whatever happened to global warming?' But cold weather doesn't disprove global warming. What is the fallacy here? It's a fallacy of false expectations. Global warming is a change in the \*climate\*. It doesn’t mean that we'll never get cold days. But warm days will become more common and cold days will become less common. More importantly, climate change is gradual. The most noticeable impacts are going to be indirect - for example, through effects on water supply, extreme weather and agriculture.

**4 Sea level rise**

Keah Schuenemann - Meteorology Professor

One of the most concerning consequences, and an indicator of global warming is sea level rise. Sea level rise has the potential to displace coastal populations throughout the globe and consequently allows storm surges from tropical storm systems to penetrate further inland, This causes damage to places previously untouched by the sea. Sea level rise is not uniform and some areas will see significantly more rise than others.

One reason sea level is rising is from the thermal expansion of seawater as the oceans warm. When water gets warmer, it expands. As a result, warmer water takes up more space than colder water. This effect alone has been responsible for a lot of the sea level rise we have observed so far. Thermal expansion is pretty straightforward, just basic physics.

Another reason sea levels are rising is due to the melting of ice that sits on land, such as glaciers and the two ice sheets: Greenland and Antarctica. When sea ice melts, it doesn’t add to sea level rise - just like melting ice cubes in a cup don’t make the water level go up. So as far as sea level rise is concerned, it’s melting land ice that matters. We have some awesome satellite technology and other observations to keep track of ice loss, but predicting future ice loss is what gives our model projections of sea level rise the most uncertainty. This rate of melt of glaciers and ice sheets is complex and change is happening quite quickly.

What sea level rise have we observed in the past? Well, by stitching together the tide gauge record with the recent satellite record, we have found sea levels have already risen about 20 cm since 1880. We have also observed that the rate of sea level rise is increasing. In other words, sea level is rising more quickly now than we’ve seen over the past century. We expect global temperatures to continue to warm, so we expect thermal expansion’s contribution to sea level rise to continue. This also means we expect land ice to continue to melt. It’s very likely that the rate of sea level rise will increase more and more over the 21st century, although how quickly sea level rise speeds up depends on how much carbon dioxide we emit.

For a middle of the road emissions scenario, the IPCC report projects a rise of about a half a meter, or one and a half feet, by the end of the century. Other studies predict as much sea level rise as twice that amount. The answer will depend on how much ice melt takes place on the ice sheets. So that is what we know about sea level rise, but some myths distort the observations of sea level rise. One myth related to sea level rise is that sea level rise is exaggerated, and it is actually slowing down. This myth uses the technique of cherry picking. This means it picks out a short term change in sea level and exploits it while ignoring the long term trend.

For example, look at this graph of sea level rise. Notice the dip around 2010 when sea level actually went down temporarily. One of the reasons for the dip was an incredible amount of rainfall and flooding that year in Australia and South America. You might remember hearing about the devastating Queensland flooding that year. If the water cycle produces flooding rains over land, and the water doesn’t drain back into the ocean right away, this can temporarily affect sea levels. But eventually, the water did drain back into the ocean. Sea level rebounded and continued increasing along the trend line as expected. So, in summary, we’ve seen that all scenarios point to continued increasing sea level rise. We expect more sea level rise in the 21st century than we did in the 20th century, despite the myth that distorts the science of sea level rise.

**5 Heatwaves**

Sarah Perkins - Climate change research center

My name is Sarah Perkins. I'm a research fellow at the Climate Change Research Centre, and my field of research is heatwaves. I look at heatwaves. I currently have a research grant to analyse how they've changed, why they've changed, what drives heatwaves, how those drivers interact with each other and the human contribution behind those changes. Heatwaves are very complex, as I'm discovering. I guess the term heatwave is very anecdotal. You hear it in the press. Oh, there's a heatwave. What does that mean? Oh, it's a bit hot.

So that's what kind of got me into my research with what exactly is a heatwave, what does it mean? And how do we measure them? And it turns out there are lots of ways of measuring them. It depends on what you're interested in. If you're interested in human health, you might measure it differently to someone who's interested in flying foxes or fruit bats. You might include different variables, like relative humidity. You might just want to look at temperature. You might want to look at night time temperature. There's literally a plethora of ways.

But the way we're trying to break it down in the climate community is looking at their intensity (so how hot the hottest part of a heatwave is, the hottest day, I guess), their duration (how long heatwaves go for), their frequency both in terms of the number of heatwave days you may get in a season and also the overall number of discrete heatwave events, their spatial extent (so how big is a singular event, what area does it cover) and their timing (how early does heatwave season start). I haven't looked at this myself, but also how late does a heatwave season end. So is it broadening? Is it shrinking? Etcetera.

 So there are lots of different ways that we look at heatwaves. You can also look at the average magnitude. The average intensity of an event. You can do other things like combine all the indices together to get one magical heatwave index, which I don't think works very well personally. Those sorts of, all those characteristics of heatwaves are potentially affected differently by different physical mechanisms. And that's what we're trying to nut out. What drives heatwave intensity? is it different to what drives heatwave timing? Does that also affect heatwave duration? If not, what drives those sorts of different things?

Heat waves have occurred in the natural climate record before. I'm not going to deny that, particularly in summer. It's hot. Occasionally you'll get 3 or 4 days that line up and form a hot event. However, they are changing. They are increasing in their intensity, frequency, duration and also how early they occur in the season. That's what we're concerned about. If we didn't exist, yes, heatwaves would still occur, but they wouldn't occur as often. And they wouldn't be occurring as higher intensity or as early. That's what we're concerned about.

Different locations are exhibiting different changes of different magnitudes. But generally overall all those sorts of characteristics of heatwaves are increasing. It depends how long the observational record is. Over Australia we can look back in some locations as far back as 1910. Over the globe really the best data set that we can use only goes back to 1950 with any sort of reliability. In terms of observed at or looked at heatwaves in Australia, over Australia and globally as well, at the moment I have almost 3 Ph.D. students looking at Australian events, but my research in terms of projections, what's changing them and the human contributions behind those changes, I'm trying to do that on a global scale as well.

There's a few methods that you can use to work out the human contribution. I'm at the moment using a methodology called the fraction of attributable risk. It's working out what fraction, what's the percentage behind a particular event in terms of its likelihood of occurring. It's the same kind of analysis that doctors use for studying the risks of cancer in smokers versus non-smokers, or cases like that. We look at an event, say the hottest year on record last year or the number of heatwaves we had last year, compare that in a model to conditions where we don't have climate change, where it's just the climate as if we didn't exist and work out how often that particular event occurred in both of those cases. Then we compare them, and it's just a matter of comparing two probabilities or two percentages, and then you get that attributable risk factor.

We're seeing a much larger contribution from humans in the heatwave frequency. If we look at a heatwave that occurs once every 20 years on average, that event now compared to say 50 years ago or 30 years ago now occurs 16 times more often, so it's almost once a year now.

The heatwave metrics I'm looking at is certainly indicating that for heatwave frequency we're seeing 16 times more likely, but for heatwave intensity it's a bit less, it's about 9 or 10 times more likely. It depends what we're looking at, how you're defining heatwaves, I'm seeing larger signals when I look at Australia as a continent averaged. If I look at south east Australia, so that's like Victoria or New South Wales, it's a lot less because we've got natural variability or internal variability, which average out on the continental scale. It depends, if I did that globally, I would get an even stronger signal again.

Europe actually is showing a lot of changes, so are other regions where we saw the Russian heatwave, the 2003 heatwave. Parts of eastern Asia are showing increases. South eastern Australia, that's where we're seeing most increases in heatwave intensity. We don't have enough data unfortunately for Africa, basically all of Africa, or India or the Arctic or Antarctic, so I can't say what's going on there. South America we've only got a little bit of data, and I'm not sure how good it is.

Actually in America, the western parts of America are showing increases, but there is the warming hole, as it's called, in the central eastern parts though. That's actually in a lot of the temperature records, that area hasn't warmed as much or if at all. A lot of that's actually put down to land cover change. So there's a reason for that, but perhaps if that didn't happen then it would be equally as warm as the continent. The models don't pick it up because they haven't incorporated that sort of land cover change into the model itself.

America and us are the highest emitters per capita, but it's the people in the developing regions that will be affected the most. Poor old Kirabati is already having saltwater intrusion inundation and sea level rise. And they're not putting any greenhouse gas emissions into the atmosphere. Those that are low lying, those that don't have access to things like air conditioning or good public health infrastructure. If you get a heat wave in those sorts of areas, people get sick or the elderly generally get really sick after a heatwave if they don't have the public infrastructure to cope with that more people will unfortunately be killed. In any society the people who are most affected by heatwaves are generally the elderly and the very sick.

There's a lot of work going on at looking at flying foxes at the moment, particularly in Queensland. Unfortunately they tend to literally drop out of the trees at 42 degrees Celsius - lactating mothers and their babies. I think yesterday or the other day a colony of 5000 in Queensland. And that's not the only one that's happened. It's happened here in Sydney. It's happened I think further south. I know certainly of that one. That's an example of an animal that has a finite threshold.

For us, I'm not entirely sure what our threshold is. We can adapt at least to different climates. We have the benefit of being able to walk into an air conditioned building. But different animals would have their own thresholds and they may or may not be particularly sensitive to that threshold.

The lack of soil moisture is a big driver of heatwaves, we know that, by how much we're not sure, but we know it definitely affects heatwaves and hot days. It affects the latent and sensible heat fluxes. Generally if something's wet or you've got lots of vegetation or lots of soil moisture. Any sort of extra energy that's put into the system. So say a hot day would go into evaporating the moisture. Take the moisture out of the system and all it's got to do is in the sensible heat flux it will just simply heat up the area. So that would have contributed to Brisbane having hot days as well.

But saying whether or not climate change caused this event outright, we can't answer that because we don't know. That heatwave could have occurred sure, but maybe the intensity wouldn't have been as strong or maybe it wouldn't have lasted as long. But we just don't know. Particularly in summer months. Say for example that Australian Open heatwave, it was summer, so getting a heatwave at that time of year probably could have happened anyway, but in my mind it was more the intensity that was the issue. We likely would have seen it but perhaps it would have been a couple degrees cooler.

We can technically have heatwaves in winter, too. We actually had one in May last year because it was hot relatively at that time of year.

**6 Shrinking glaciers**

Robert Way - University of Ottawa

The word ‘glacier’ is familiar to most people. But do you really know what a glacier is? You might of think as a big rigid piece of ice. However, under pressure, glaciers act like a soft plastic. They can bend and flow downhill like slow-motion rivers of ice. Most people also picture glaciers on mountains. However, ice caps, ice sheets and really any masses of ice which remain year round are also considered glaciers. Even the most basic fact, that warmer temperatures will melt glaciers, has an interesting exception. We’ll come back to that later.

Overall, glaciers are shrinking in our warming climate. This has been measured by satellites that feel gravity getting weaker over glaciers as they melt. Overall, excluding the polar icesheets, glaciers are losing about 150 billion tonnes of ice each year. In some areas this is concerning because glaciers act like water towers for cities downriver. They store water in winter and release it during the summer months. Most glaciers expanded until the late 19th century and began retreating afterwards.

Their retreat has accelerated over the past two decades, particularly in the Polar Regions. In some areas, rapid warming has completely disintegrated some small glaciers. Many of the smallest mountain glaciers in the European Alps and other mid-latitude locations will eventually disappear, as well. In the Canadian Arctic, for instance, sample cores taken from ice show recent melt is the greatest in 4,000 years. Researchers have also found that ancient vegetation preserved under ice is now thawing out. Dating these frozen plants shows that they have been covered by ice for thousands of years. This tells us that some glaciers are now smaller than during anytime in the past several thousand years.

The same thing has been found in western Canada and on Baffin Island. Over the past decade, the rate of glacier loss in the Arctic was similar to thousands of years ago when the earth received more sunlight in the summer because of a different orbit. Current global warming is melting most glaciers, and will continue to do so. But one myth says the opposite. It gives a few examples of growing glaciers. There are over 100,000 glaciers in the world, so even though most are shrinking, it’s possible to find examples that aren’t. This myth relies on a cherry pick.

The observation that a small fraction of glaciers are growing is actually an interesting scientific question. In order to explain it fully, let’s take a bit of time to understand how glaciers form. For a typical glacier, snowfall builds up on its surface. Over time, all the layers of snow press down on the layers beneath, compacting the snow crystals into ice. This ice forms the main body of the glacier. Glaciers gain ice from snowfall. They lose ice through surface melting, melting from beneath, and, in some cases, by gradually flowing into lakes or oceans and breaking off into icebergs. In winter, new snow weighs down on the glacier, pushing it downward towards an ocean, lake, or the end of a valley. In summer, ice melts and can cause the glacier to recede.

The difference between the total gains and losses of an ice mass measured over a year is called its annual mass balance. Because of the seasonal back-and-forth between advancing and retreating ice, the size of a glacier is typically measured at the end of summer when ice covers its smallest extent. As glaciers advance, they often push up ridges of sediment called moraines. You can see these ridges with your own eyes and they remain long after a glacier has retreated up a valley. Moraines are useful to estimate how big a glacier used to be.

We are currently studying the rate of change in many glaciers. What have we learned? Glaciers are very sensitive to climate. They can only form in regions with low summer air temperatures and high winter snowfall. Changes in summer air temperatures or winter snowfall can, therefore, change the yearly mass balance of a glacier. So how will a warmer climate affect glaciers? It seems obvious that warmer air will cause them to melt faster. But it’s a bit more complicated than that.

Warmer winter air can also increase snowfall. This is because warmer air holds more moisture. If temperatures warm from very low below freezing to a little below freezing, then you can get more snow. This means that each individual glacier will react differently to changes in climate, depending on whether its particular mass balance is more controlled by temperature or by snowfall. Usually the warmer summers are enough to melt the extra winter snowfall. It is possible for increases in snowfall to balance out, or even beat out, the effect of warming summers.

So, even though it seems strange, some glaciers will actually get larger in a warming climate. If you ever hear someone use the argument that seeing a glacier grow disproves global warming, now you know why that is false. Hand-picking a few growing glaciers is cherry picking the data because it ignores the bigger picture. A slightly warmer regional climate might cause some glaciers to temporarily grow. But overall, almost all glaciers worldwide are now shrinking. This will continue as it warms over this century.

**7 Greenland ice loss**

Robert Way - University of Ottowa

The Greenland ice sheet is losing ice. How much? Currently, it’s losing over 300 billion tonnes of ice every year. That’s more than the entire weight of Mount Everest. How can an ice sheet lose that much ice? You have to understand that ice sheets are big. They’re among the largest physical features on Earth, rising kilometres up into the air. Our planet has three major ice sheets - in Greenland, East Antarctica and West Antarctica. If all three ice sheets were to melt, they’d raise global sea levels by nearly 80 metres.

The Greenland Ice Sheet is the smallest of the three ice sheets. Even so, its melting would still cause sea level rise of over 6 metres. When we look into the Earth’s past, we can see that the Greenland Ice Sheet is very sensitive to climate change. Around 400,000 years ago, when global temperatures were about 3 degrees Celsius warmer than now, the Greenland Ice sheet melted enough to raise global sea levels by four and a half meters.

Greenland loses ice in a few ways. First, Icebergs break off the end of glaciers. Ice also melts at the surface, then runs off into the ocean. Some of this melt water drains into deep channels in the ice called “moulins”. If the water reaches the bottom of the ice sheet, this can serve as a lubricant at the base. This speeds up the flow of glaciers into the ocean. Also, the floating ice found along the edges of ice sheets can act as a cork, holding back the ice sheet and preventing glaciers from falling or melting into the ocean. Warming air and ocean temperatures are melting these ice shelves and sea ice along the coast. This is effectively popping the cork and letting the outlet glaciers flow faster into the ocean.

However, the Greenland Ice Sheet is also gaining ice in its interior. This happens in winter, when snow falls or when summer meltwater refreezes. Whether Greenland is causing sea levels to rise or fall depends on whether the total mass of Greenland’s ice is increasing or decreasing. Air temperatures in Greenland have increased by nearly 2 degrees Celsius over the past century and a half. Satellites have found that the surface area of ice melt on the Greenland Ice Sheet has doubled over the past decade. Satellite data also show that most of Greenland’s largest outlet glaciers are speeding up and losing more ice to the ocean. As a result, Greenland has been losing ice at an accelerating rate.

So when you look at the whole picture, the Greenland Ice Sheet is now the largest individual contributor to global sea level rise. However, there is a misunderstanding about what’s happening on Greenland, because of a cherry pick looking only at the ice build up in its interior. Not considering the rest of Greenland created the myth that Greenland is gaining ice. The Greenland Ice Sheet was relatively stable throughout the 1990s. It was losing more ice along its coastlines. But at the same time, it was gaining more ice in its interior due to more winter snowfall. The increase in snowfall was caused by warming temperatures, which led to more moisture in the atmosphere. More moisture in the air results in more precipitation, which in Greenland means more snowfall. So in the 1990s, losses around the coast were balanced by gains in the interior. But since the early 2000s, the amount of ice being lost in coastal areas began to exceed ice gains in the interior. And now this process is accelerating.

Over the last few decades, the Greenland Ice Sheet has gone from being in near balance to losing about 300 cubic kilometres of ice each year. Again, this is more than the entire mass of Mount Everest! While this is a startling statistic, even more startling is that ice loss from Greenland is on the increase. This means Greenland is contributing more to sea level rise over time. And if the lessons from the past are any indication it's that Greenland is highly sensitive to warmer temperatures and can contribute significantly to sea level rise.

**8 Antarctica land ice vs sea ice loss**

Robert Way - University of Ottawa

The continent of Antarctica is a beautiful land made almost entirely of snow and ice - unique on planet Earth. But what makes it beautiful also makes it sensitive to human influences. Our changing climate is causing rapid changes in the Antarctic. The West Antarctic Ice Sheet, in particular, is losing over a hundred billion tonnes of ice each year. West Antarctica contains about 18% more ice than Greenland. If it all melted, it would cause over 7 metres of global sea level rise.

But West Antarctica has a much bigger brother - East Antarctica. The East Antarctic Ice Sheet is the largest ice mass in the world. It covers an area roughly the size of the United States. The East Antarctic Ice Sheet has been around for nearly 32 million years. The West Antarctic Ice Sheet formed millions of years later and has partially melted several times. If both of these ice sheets were to melt, global sea levels would rise 72 metres.

At first, scientists thought Antarctica wouldn’t respond strongly to global warming. Regional warming was expected to increase both ice melt and snowfall which would balance each other out. However, recent studies have found that the West Antarctic Ice Sheet is more sensitive to climate change, and in particular warming oceans, than previously thought. Satellite measurements have shown that both the Antarctic Peninsula and West Antarctic Ice Sheet are now losing ice. For both regions, ice losses began in the 1990s and have since accelerated. The best available knowledge today points to the West Antarctic Ice Sheet being a large contributor to current and future global sea level rise over the next century. The East Antarctic Ice Sheet, by contrast, has remained relatively stable since the late 1990s. In this case, ice losses in coastal areas \*have\* been balanced by greater snowfall in the interior. For now, the East Antarctic Ice sheet is stable.

There is of course another type of ice in Antarctica which has undergone some changes. Antarctic sea ice has reacted to a changing climate very differently, and arguably more interestingly, than land ice. Antarctic sea ice forms in the ocean waters around the continent each winter, during the polar night from July to August. During the 24 hours of daylight in the Antarctic summer, December to February, it nearly completely melts. This means that Antarctic sea ice is mostly seasonal and does not influence the global climate as much as Arctic sea ice. The area of sea ice around Antarctica has actually been increasing over the last few decades, especially during winter. This is despite data showing that the Southern Ocean around Antarctica is warming.

This raises an interesting scientific question. How can sea ice increase when the oceans are warming? One possible contributor is wind. The winds which flow off the Antarctic continent down onto the surrounding ocean have been increasing. This carries more cold air to the ocean where sea ice forms. It also blows sea ice away from the coastline spreading it out further. That extra open water allows more sea ice to form and expand outward. Another potential factor is increasing melt water from the Antarctic ice sheets. Freshwater is easier to freeze than saltwater, so an increase in ice melt, say from coastal glaciers, can make the waters surrounding Antarctica easier to freeze. Finally, Antarctica’s changing climate may play an important role. Snowfall has increased over the continent and surrounding oceans. This can lead to a thicker sea ice cover. Even though Antarctica as a whole has warmed, there are also regional differences with some areas cooling while other areas have warmed. Combined together, all these factors are the best available explanations for the recent increase in Antarctic sea ice.

The differences in the reaction of land ice and sea ice to a changing climate feeds a very common myth that Antarctica is gaining ice. This myth relies on an error of omission and it ignores the difference between land ice and sea ice. It’s also an example of cherry picking. By focusing on one small part of the Antarctic cryosphere it ignores the full picture of how the Antarctic ice is changing. Although sea ice in Antarctica has increased in recent years, land ice in Antarctica is currently declining. Scientists are confident that both changes in sea ice and land ice are linked to a changing climate. They are both also examples of unexpected impacts of climate change. Although increasing Antarctic sea ice may have local impacts, the unexpectedly quick decrease of Antarctic land ice could have huge global implications through sea level rise.

**9 From the Experts - Cryosphere**

Professor Jonathan Bamber, Professor Isabella Velicogna, Professor Eric Rignot, Professor Mauri Pelto, Professor Richard Alley, Professor Luke Copland, and Professor Lonnie Thompson

Bamber: So cryosphere means the cold environment, the cold component, the frozen component of the Earth. That includes seasonal snow cover which mainly covers quite a large part of the northern hemisphere seasonally in winter. It includes sea ice which I mentioned earlier, glaciers, ice caps, ice sheets, and permafrost.

Veligocna: Now we have different measurements that are very complimentary. They all are more sensitive to different processes and we can get a good picture.

Bamber: I mean the technology is quite complex. Some of the principles are really simple but the satellites, I mean, it is truly rocket science. This stuff is pretty pretty sophisticated technology.

Rignot: With satellite data they have completely revolutionised the way we look at polar regions. They make the whole place accessible.

Bamber: The other really incredible piece technology approach that is used for measuring how the ice mass evolving is by looking at changes in the gravity field of the earth. As mass goes from the land into the ocean, the gravity field locally on the surface of the earth changes and with incredibly sensitive satellite technology you can actually measure those small very changes in the gravity field. And that tells you what, where the mass is going.

Pelto: And operation ice bridge and those using altimetry to figure out the surface

of the ice sheet.

Bamber: Altimeters measure the elevation of the surface very accurately and there are two types that have been flown: a laser and radar altimeter. They can measure changes in elevation to a few millimetres a year. And they're flying at altitudes of 600 miles, 1000 kilometres above the surface and measuring one or two milimetres change a year is pretty impressive technology. One of the great things about both satellite technologies I've talked about, that's the altimetry and the gravity measurements, is that they can make observations over the whole ice sheet. Over the whole of Greenland and almost all of Antartica now. There's a little hole in the pole in Antartica, but all of Greenland for sure. What we see in Greenland is that there's big elevation changes, lowering of the elevation around the margins and a very, very small increase in the interior, which is what you'd expect in a warming climate.

Velicogna: Greenland is losing mass faster. If you look over the last 10 years I’m just

going to use an estimate from GRACE since I have it off the top of my head. From 2002 to now, you have a mass loss of about 270 gigaton per year.

Pelto: There's 210 or so outlet glaciers in Greenland, marine terminating. Wow. 99 percent of them are retreating. 90 percent of them have accelerated, so we're seeing the details may be different but the overall pattern is the same.

Rignot: We get a report of the collapse of an ice shelf and the formation of a new

type of glacier in northeast Greenland. Way up there at 79 north, which most of us did not think we would see that happening maybe in our lifetime.

Velicogna: The ice shelf works a little like if you have a cork in a bottle of champagne, stopping the champagne. You break the ice shelf and the thing comes out. The glacier has been observed so that once the ice shelf collapses and it breaks up in pieces the build ups are flowing faster in the ocean.

Bamber: In the 1990s the mass loss in West Antarctica seemed to be quite, quite small,

close to the detection limit in the early 1990s and its increased continuously until the present day.

Velicogna: For Antarctica we're seeing the mass loss is increasing and we're seeing for

sure West Antarctica the mass loss is accelerating with time.

Bamber: So in Antarctica the ice is up to 5 kilometres thick. That's 3 and a half miles

thick. And if you melt that, it goes into the ocean and it changes the mass of the ocean. And, therefore, the ocean level goes up.

Alley: And there has been a paper a good colleague of mine, a very good scientist, that said we may have already committed to more than 3 metres of sea level rise from West Antarctica. If we haven't we're pretty close to it and the scholarship's strong on that.

Bamber: Geometry of West Antarctica suggest it's in what we believe is a potential unstable configuration. And what that means is, if you just change the forcing a little bit, warm ocean temperatures a little bit, that instability could trigger a rapid mass loss from the ice sheet.

Rignot: It might retreat faster if climate warming continues at this pace. It might retreat

slower. We don't know that absolutely for sure, but the fuse is already blown.

Bamber: There are some fairly recent results that both from observations and from a numerical modeling study that suggests that we've actually passed this threshold of stability. Part of West Antarctica is going into an unstable regime where it's going to lose an increasing amount of mass. And that cannot be easily reversed.

Rignot: All the observations we've collected in the past decades is actually pointing towards shorter time scales than what the models are able to replicate. To foresee ice decay the models are not able to replicate that. It's true for the decay of the glaciers and ice sheets. They're going on a pace faster than what the models projected, faster than even the present day models are able to replicate.

Bamber: The changes in sea ice that we have seen during a satellite aerial, which have

made observations, which is a bit longer than the ice sheets, it goes back to about the mid 1970s. Almost a 40 year record. A pretty continuous decline in what's called multi-year ice in the Arctic. And this trend, very dramatic trend, in reduced sea ice area in the Arctic. Some people have pointed to it as the poster child of climate change research because it's a bit signal. It's unequivocal: sea ice are getting smaller and smaller. A very important component of the global energy balance. Something slightly different seems to be happening in the southern ocean. In the Antarctic. Because the sea ice that doesn't seem to have gotten smaller if anything larger, although it's a very small signal it's about two percent per decade. It's sort of moving around a bit. But if anything it looks like it's getting slightly larger.

Copland: There's been an increase in wind away from the continent, so that wind kind

of does two things. One is pushes the ice further away from the continent so it makes it extend further north than it ever did in the past. And the second thing that it does is when it pushes ice away from the continent in the winter then areas of cold water, which are adjacent to the continent become ice factories essentially. More new ice is being produced all the time as the winds are increasing.

Pelto: For 24 consecutive years alpine glaciers around the world, every continent, have lost mass. One year maybe one glacier on one continent has a good year, but overall globally glacier mass balance is declining. For most of my students, they weren't even alive the last time glaciers had a good year, a positive balance.

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

Thompson: Glaciers are kind of like an insurance policy, that they accumulate snow during wet seasons and wet periods, and then they melt and release that during droughts and dry seasons, but they're getting smaller, so their ability to do that becomes less and less. This has tremendous implications for people who live in areas that depend on those water resources.

Copland: I think the biggest impact is on agriculture because if you think of the prairies

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

Pelto: We're most concerned about the sea level rise aspect, which is not useful.

Bamber: The sea level rise around about a metre it's suggested would displace potentially up to 200 million people. We are very very vulnerable as a species to relatively small changes in sea level. There are countries like Bangladesh, The Netherlands and all the atolls in the South Pacific, which would be absolutely devastated from a sea level rise of more than a metre.

**10 Building a robust temperature record**

Kevin Cowtan - University of York

How do we measure global warming? Thermometer records, which are maintained and checked by a number of groups, tell us that the planet is warming. We also know it is warming from satellites, tree-rings and ice cores. In this lecture, we will investigate how we know the thermometer record is accurate enough to detect human-caused warming. We can never measure anything exactly. So whenever we measure something, we also try to estimate how \*accurate\* that measurement is. We know that our estimate is only approximate, so we also estimate how far off it might be. Scientists call this the \*uncertainty\* in the measurement.

What they’re talking about is the range of possible values. When scientists estimate global temperature, they also work out the \*accuracy\* of those estimates. Accuracy is often represented on a graph by error bars, or by shading. They indicate how close we think our measurement is to the truth. How do scientists determine the accuracy in their global surface temperature estimates?

Let's look at one very simple method. Consider two weather station records - we'll colour them red and blue. The stations are close together, so they should show similar temperatures. If the thermometer measurements are accurate, then the records from the two stations will look quite similar. However, if the thermometers are inaccurate, the station records will look quite different. The data themselves can give us a measure of their accuracy.

Do we have enough weather stations to estimate global surface temperature? Again, we can compare neighbouring stations. As the stations get farther apart, they will experience different weather, and the records will start to differ. Again, the data can tell us if we have enough stations. But we don't have just two weather station records. We have thousands. How do we check \*all\* of them to get a measure of the accuracy of the global mean temperature?

There is a very simple extension of our two station test. Here are the actual weather stations listed in the Global Historical Climate Network. Let’s randomly divide the thousands of stations into two groups: red and blue. We'll calculate a global temperature record from the average of just the red stations. Then we'll calculate another global temperature record from just the blue stations. If the two records agree, it tells us that the stations are reliable, and that we have enough of them. As you can see, the red and blue temperature records are not identical, but they are very similar. The difference between the two records is an estimate of the accuracy of the temperature record. The differences are small compared to the warming signal we are trying to observe. This is just one simple way to look at accuracy of the temperature record.

This approach and others like it are used across many fields of science. And the data themselves tell us that the record is reliable. That's not the only way we know the temperature record is reliable. There are a lot of different sources of temperature information we can compare. Firstly, here are versions of the thermometer record calculated by different groups around the world. But scientists can also calculate global temperature without using the weather station thermometers.

Weather forecasting software can be used to estimate air temperatures using ship data and air \*pressure\* observations. Satellites also measure air temperature from the radio noise coming from different layers of the atmosphere. Finally, there are various natural thermometers, like tree rings and ice cores. All of these confirm that the planet has warmed over recent decades. The natural thermometers can also give us temperature records over much longer periods. These tell us that the recent warming is very different from natural climate change.

Despite all this evidence, there is a myth that the thermometer record is unreliable. One claim is that early thermometer readings are not sufficiently accurate to detect a change of about one degree Celsius over the course of a century. Another claim is that there aren't enough weather stations to produce an accurate estimate of global land temperature. But scientists have included both of these when estimating the accuracy of the global temperature. So what is the fallacy here? If someone says our measurements aren't perfect, so much of the warming could be due to measurement errors, they are jumping to conclusions. When we estimate the measurement errors, they are much smaller than the warming that we see. We know that the thermometer record is reliable, both because the data themselves tell us so, and because they agree with other sources of temperature data.

**11 Heat in the city - data collection**

Kevin Cowtan - University of York

Data collection is fundamental to every branch of science. In order to construct a reliable record of climate spanning a century or more, we need to understand how the observations are influenced by non-climate factors, such as changes in the instruments and their environment. For example, on hot summer days, urban areas are noticeably warmer than rural areas, or even city parks. This is called the Urban Heat Island effect, and it's a real effect. Urbanization creates darker surfaces which absorb sunlight rather than reflecting it back to space. Urban areas also have less moisture to cool the air. A number of other factors, including waste heat from human activity, also play a role.

We've built a lot of cities over the last century. When rural weather stations are surrounded by urban sprawl, that can lead to an increase in the observed temperatures at that station. But does this significantly affect our measure of climate change? As an initial check, let’s look at a map of global temperature trend over the 20th Century, from the Berkeley Earth project. Red areas are warming, and blue areas cooling. We can see that some areas have warmed more than others. We can get a good estimate of human development from satellite images of the Earth at night, showing light pollution from our cities. Let’s compare that to the warming map. The areas which show the fastest warming are often areas with very little development - for example, the [American] Arctic, the Amazon basin and Mongolia. Some areas with a lot of development show little warming, like China and the south-eastern United States.

There is also warming in the oceans. The oceans dominate the surface of the planet, but we don’t build cities in the oceans. NASA has done a detailed analysis in which they adjust urban stations to match the nearest rural stations. Here is what the global temperature record looks like using different methods to identify urban stations. The results are almost identical. Another study by the UK Met Office compared temperature trends for still and windy days. The urban heat island effect has most impact on still nights. They found no significant effect on global mean temperatures. These studies and other evidence all tell us that urban heat islands have a minimal effect on the global warming trend.

Even so, there is a myth that urbanization, and not the greenhouse effect, is responsible for a significant part of the 20th Century warming. So what is the fallacy in this case? It is the fallacy of jumping to conclusions. Just because localized urban warming could affect the temperature record, does not mean that it does. To determine whether 20th Century warming is due to Urban Heat Islands, we actually have to look at the data. And the data tell us that the effect is small compared to the total warming over the last century.

Another point of confusion arises from the fact that scientists make corrections to the weather station data. Why do we need to correct the weather station records? The result of any observation is determined by a combination of what is being observed and the instrument which is being used. If there is a change in the instrument, this will affect subsequent observations. Scientists apply adjustments to observations to address changes in station location, instrumentation and operating practices. They do this by reconciling temperatures before or after the change with observations from other nearby stations.

For example, if a weather station is moved up a hill, it may record cooler temperatures than before the move. We need to adjust for that so that the data before the move is comparable to the data after move. Otherwise, we create a false cooling effect that does not correspond to reality. Even though the adjustments are justified, we can check whether they are significantly affecting the global temperature record. Here is a comparison of the temperature record with and without adjustments. We can see that the adjustments do make a difference, but that the difference is small. So adjustments are necessary to maintain a true record of temperature changes.

However, one myth claims that these corrections are responsible for a significant amount of the warming over the 20th Century. This is another fallacy of jumping to conclusions. Scientists do adjust the observations. But only when there is a good scientific reason to do so. And the adjustments only make a small difference to the global mean temperature. We've looked at a couple of myths involving possible problems in the temperature record. In both cases, the effect is much smaller than the warming signal.

**12 Wavy jet stream**

Keah Schuenemann - Metropolitan State U of Denver

Prior to 1952, if you wanted to fly from Tokyo to Honolulu, it took you around 18 hours. But in 1952, airlines figured out a way to make the same flight in just 11 hours. How did they do it? Did they discover a new type of fuel or develop a sleeker jet? No, they simply used something that had been there all along: the jet stream! The jet stream is a narrow band of strong winds near the top of the troposphere, about 10 kilometers above the Earth’s surface. It’s like a fast moving river of air.

The wavy shape and the location of the jet stream changes constantly with the weather. Under the ridges formed by the jet stream are warm, dry conditions. Sometimes the ridges can take on such a shape that it opens the door to the poles and allows for cold Arctic air to blow down through the trough. It’s like leaving the refrigerator door open, letting cold air leak into the kitchen. This cold air streams down from the pole and pools in the area north of the trough. This weather pattern, sometimes called a blocking pattern, is usually slow to move so the cold air persists in what we call a cold air outbreak.

Something to note is that this cold air was previously sitting comfortably over the traditionally cold areas, the poles. The weather pattern brings the cold air down to lower latitudes, which usually means the poles get unusually warm. In other words, when we experience cold temperatures at low latitudes, it’s a bit like a balancing act. The warm air doesn’t just disappear, it just moves to other places. So that’s how the jet stream and cold air outbreaks work.

However, one myth distorts the science of global warming, and I’m sure this is one you’ve heard quite a few times. Every time winter conditions set in, people say, “It’s cold out, so much for global warming!” implying that record cold winters disprove global warming. This uses the technique of cherry picking a weather event in a local region instead of looking at the global picture. When cold air leaks down from the poles to your region, it doesn’t change the fact that global warming is happening. It usually means your area has just exchanged air masses with another place on Earth. It’s important to remember that the definition for \*global\* warming is the \*global\* average temperature change, not the temperature you feel at your local area.

One of the hot topics in climate science right now asks the question, “Is climate change causing these events to take place more often?” Scientists are digging into the observations as well as computer simulations of our future climate to try to find the answer to this question. One hypothesis is that climate change is creating the conditions for a slower, wavier jet stream. Here’s why: The strength of the jet stream is based on a force called the pressure gradient force. This force’s strength depends on the difference in temperature across the polar front, the area of tight contrast between the warm tropical air, and the cold polar air.

One of the most interesting pieces to the global warming story is that not everywhere on Earth is warming at the same rate. The Arctic is warming faster than any other region on Earth! We call this Arctic Amplification. There are several reasons for it. The biggest contributor is a positive feedback or self-reinforcing cycle involving the melting of Arctic snow and ice. Global warming has caused less snow and ice cover in the Arctic. This replaces white, reflective surfaces with dark, absorptive surfaces that absorb more sunlight and get warmer. This melts even \*more\* snow and ice, causing \*more\* absorption, and causing even \*further\* warming! This cycle has caused the Arctic to warm up twice as fast as the global average.

Because the Arctic is warming faster, the cold side of the jet stream is a few degrees warmer than usual, while the warm side hasn’t warmed up as much. This means the strength of the \*difference\* in temperature becomes smaller, weakening the pressure gradient force. Therefore, the winds up in the jet stream could become slower. Occasionally, a consequence of this slowing is that the jet stream takes on a really large amplitude wave pattern, which can lead to more of these blocking patterns, or so the theory goes!

Now, it is worth noting that these cold events can take place with or without Arctic amplification and global warming. But climate scientists are exploring whether we might have more of these blocking events leading to cold air outbreaks than before. In time, the answer might become more obvious, time will tell! The winter of 2013-14 in the United States was a great example of a blocking pattern in the jet stream! The eastern half of the United States experienced one of the harshest, coldest winters on record. At the same time, the western US experienced one of the warmest and driest on record, leading to an extensive drought in the California region. It’s a great example of that balancing act, with one region cooler while another region is warmer.

Meanwhile, looking at the whole planet, we set the record for warmest year on record in 2014! This can be confusing for people in the eastern US who had weeks of school cancelled due to low wind-chill values as that door to the Arctic refrigerator stayed open for weeks. But we have to remember the big picture, the global picture, when we think about global warming. A cold winter in one region doesn’t disprove global warming, you have to look at the big picture!

**13 Climate change vs global warming**

Peter Jacobs - George Mason University

A clip from a comedy talk show has gone viral. Which isn’t all that surprising. But what might be surprising is that the subject matter doesn’t sound particularly funny. The video is asking people about health care reform in the United States. The premise of hearing people on the street say they prefer one plan to reform health care over another doesn’t exactly scream “comedy”. But the genius of the clip is this:. While people are describing how they love one plan and hate the other, they don’t realise they’re talking about the same plan. The interviewer asked about the Affordable Care Act, the name of the plan in the legislature. And also asked about Obamacare, the name associated with the President. But the plans were the same. But peoples’ preferences turned out to be different. Sometimes, it seems, labels matter a lot more than you’d expect.

A lot of professional fields have their own jargon which can seem confusing or redundant at first. But often, words that might seem to be interchangeable actually have important distinctions. The terminology dealing with changes to the Earth’s environment is no exception. “Global warming”, “climate change”, and “global environmental change” can all refer to the present human-caused warming of the planet. But each can also refer to specific aspects of environmental change that the others may not.

It is possible to have climate change that isn't global or isn't warming, such as a regional drought. It’s also possible to have global warming that is not man-made. The Jurassic got hotter due to greenhouse gases from widespread, long-lasting volcanic activity. Or it’s possible to have man-made global environmental change that is neither warming nor climatic. The world-wide loss of wildlife due to hunting and habitat destruction by humans, for example. Maybe this sounds a little complex, but it’s a lot simpler than the terminology of the British Isles. I’m still trying to figure that one out.

Basically, global warming means an increase in the average surface temperature of a planet. Climate change refers to a change in the statistics of a climatic variable over a given area. The variable doesn’t have to be surface temperature. It could be precipitation, or wind speed. The statistical property doesn’t have to be an average. It could be a change in how often an extreme value is reached. The area doesn’t have to be an entire planet. It could be a hemisphere, or even a region. So global warming is a kind of climatic change, but not all climate changes have to do with global warming.

When you look at the usage of these terms over time in the scientific literature, you see that climate change has been used for a much longer time than global warming. Climate change’s usage goes back to the 1920s. And “climatic change” goes back even further- to the 1850s. Global warming is a more recent term. The modern usage of global warming is often attributed to Wally Broecker, from a 1975 paper in the journal Science. However, it was actually used a little earlier, going back to the 1960s.

Climate change has been used much more often than global warming. While it might be tempting to think that climate change is used more frequently overall, but global warming has been used more often in association with our present warming, that’s not actually the case. The international negotiating system set up to deal with our emissions of greenhouse gases was established in 1992. It is called the UNFCCC, or United Nations Framework Convention on Climate Change. Similarly, the scientific group responsible for summarizing the scientific research on the issue is the IPCC, or Intergovernmental Panel on Climate Change. It was established back in 1988. Climate change is the term used most by the scientific community. Even though both climate change and global warming describe human’s increasing greenhouse warming.

Climate- science denialists tell themselves a different story. They claim that scientists used to prefer the phrase global warming. But then they conspired to stop using global warming and instead use climate change. Climate- science denialists typically claim that scientists did this because the Earth stopped warming up or even cooled. The problem for their narrative, of course, is that the Earth has continued to heat up. Heat in the ocean continues to build up. Glaciers are on the decline. Ice sheets are melting and raising sea levels. And despite short term ups and downs caused by natural variability, the global average surface temperature continues to increase.

If the climate science denialists were right, you’d expect to see the phrase global warming used by scientists more often than the phrase climate change, and that this preference would reverse if temperatures went down. In fact, climate change has almost always been used more often. And there is no correlation between a preference for the term global warming during times of hotter temperatures. In fact, when temperature was increasing at its fastest rate in recent decades, global warming was used less often. Not more. The claim by climate science denialists is a classic example of conspiracy theory. In their telling, scientists almost always have a nefarious hidden agenda, and they will say whatever they can to advance it.

Climate -science denialists allege that If mother nature doesn’t cooperate with the scientists’ claims, they’ll just change their terminology definitions to keep their plot going. Such a conspiracy theory depends on its believers not being able or capable of looking at what scientists have actually said all along. This conspiracy theory is successful because it oversimplifies a complex reality into a simple falsehood. Believing something that is incorrect because it’s easier to understand than a more complex reality is another common characteristic of science denial. The terms climate change and global warming both describe human’s increasing impacts from greenhouse gas emissions. Climate change has been used longer, and more often, by scientists. And they didn’t switch terms based on the weather.

**14 Global temperature record**

Phil Jones - Research Director of the Climatic Research Unit (CRU) and a Professor in the School of Environmental Sciences at the University of East Anglia

I’m Phil Jones. I’m in the Climatic Research Unit at the University of East Anglia in Norwich in the United Kingdom. I did a first degree in Environmental Sciences and then did a masters and PhD in Hydrology.

In 1976 we’d been in contact with several people at NCAR in Boulder, Colorado, and learnt that someone in the US digitized something called “World Weather Records,” which is masses of volumes of just temperature data and rainfall data from stations around the world. The first time we produced the land global temperature record was just interpolating the station data. There was no check on the homogeneity of the data, the station, or the quality. We were just using the available data. We wrote up the work for a paper in journal of “Monthly Weather Review” then. We just did the northern hemisphere. We just did the land. One simple way of displaying the results was to produce a large-scale average for the northern hemisphere land areas, but the whole aim was to produce a gridded data set to look at the patterns of change and relate those to patterns and other variables.

Later we moved on to the southern hemisphere, land again, and in the middle of the 1980s, we knew we’d not done anything but the marine data, so we added that in jointly with some colleagues at the Met Office. That was then the first sort of truly global temperature record combining both hemispheres and the marine parts of the world. Now people had done this before. I mean, at the same time, unbeknownst to us, Jim Hansen was doing something similar at GISS. It was land-only, though. There was a Russian data set at the time. There was a guy called Maury Mitchell in the United States have done some work on this in the 1960s. There was even earlier work in the late 1930s—someone called Guy Stewart Callendar produced the data set, and he also looked at carbon dioxide measurements before the record at Mauna Loa started. If you go way back, you find that a guy called Wladimir Köppen, who also developed the Köppen classification of climate, had produced a series in the 1880s.

In some more recent work, we’ve actually gone back and digitized some of the earlier series when people were clearly just working by hand. I think Maury Mitchell in the ‘60s probably had some sort of computer calculator doing it, but Callendar did it all by hand and Köppen certainly did. We digitized their data, and they agree amazingly well. I had a little paper out with Ed Hawkins a few years or so ago because it was 75 years since Callendar’s paper in 1938 last year, and it was an amazing agreement with what Callendar did. Callendar was using just the northern hemisphere or the land areas from about 400 or 500 stations around the world, and he just had annual averages. We had sort of 5,000 stations, and we were getting pretty much the same results.

If we look into the future and how global temperatures might go and the whole idea of climate change and the influence of humans on the climate system—when we started the work in the early 1980s, the temperature series then that we produced, finished in 1981 has actually showed cooling from the sort of late 1950s, so the 1960s and early ‘70s were quite a cool period. There was some initial warmth in a couple of years in the early ‘80s, but we didn’t really capture that in that data set. When we started doing it, we didn’t start it to look at longer-term change. We were trying to look at the reasons why you were getting some warm years and some cold years and the patterns of change around the world, and could we relate those to the circulation.

Obviously, having looked at the data a lot more now, you found that obviously the very warm years are often, almost always El Niño years, and the very cold years are often La Niña years or—and the really cold summers in the northern hemisphere are volcanic years when we’re responding to big eruptions like Pinatubo. From the mid ‘80s onwards, the science moved to more climate change, global warming, and climate models, but you always need the observations to provide some way of checking the models. It wasn’t just the models in isolation. You had the observations checking how they’re doing, and then that moved into detection and attribution.

I realized, in doing the original work, that when we updated it, we got some different extra stations. There were people digitizing stations, even the 1980s, getting access to more data, putting more stations in. We realized that if you just addressed the global average, there had to be a finite number of series that you could use and get away with. We were always interested in the gridded product, and if you wanted to improve that, then you’ve got to improve the number of stations everywhere. There were always a lot of stations in Europe and parts of the United States and parts of Australia and Japan and places, but obviously there was never that good coverage in parts of Africa, South America, and some parts of Asia, so we’ve always concentrated on trying to get more stations for the less well-covered areas of the world.

In ‘97, I did some work with Tim Osborn where we tried to quantify what the number was that you needed and I came up with this concept of the effective number of spatial degrees of freedom. This is how many you need to actually produce an answer that’s within the statistical error, and really, for the land, it’s probably less than a hundred stations well situated around the world.

In the latest data set, in terms of combining with the marine data, we had taken this concept a stage further. We are using this bit of statistical theory to produce a hundred realizations of the gridded data set and the hemispheric and global averages. Where you’ve got very few stations, those realizations will differ more from each other. Over Europe and North America, those realizations are almost the same because they are really robust. It’s a way of quantifying the error in the data sets spatially as well, and that’s really useful for some of the people working on detection attribution issues so that they can then compare with the climate model output.

They’ve both got multiple models, so they are used to using multiple realizations of climate simulations, and they got multiple realizations of the observations as well to work with, and so they can use that way of displaying the error structure of the data. In terms of those realizations, the data set is a gridded product on a five-degree latitude-longitude grid. Now if you have sort of—in some parts of Europe and North America, you’ve got 20 or 30 or more stations in a box, so that average is very well constrained, so there will be a value. Everything is done in terms of anomalies from 1961 to ‘90 so issues of elevation and distance from coast, et cetera, sort of disappear. The more stations you have, the smaller the error will be.

When you got fewer stations, the error is larger, obviously. You’ve got one station in the box, you’ve only got one measure. That’s a large area, an individual box. What you do is you know for that box the standard deviation, so you can draw samples from that which are the realizations about how temperature might have varied in the past, and you know that those—how you draw them is just basically random because there’s very little autocorrelation from one month to the next in most parts of the world. I mean, most people who now collect the data just collect what they might think of as the best estimate, which is the 50th percentile of those realizations, but it’s very useful for the climate modelers to compare those observations with because they know they have a range of possibilities of how temperatures have varied in the past. They can use that concept that we’ve added to the data set in their analyses.

Well, we don’t do any of the measurements ourselves. All the measurements are made by mostly the Met Services of the world or there are other organizations that do it in some countries, and we get access to that data. Now there are number of issues with the land stations. The marine data is far more interesting and more important, but the land stations—there are two main issues with the land stations, and most of these differ from station to station, so they’re not consistent problems from site to site. At one particular site, you may have several moves of that site from different places in the town, but they will be different from other places nearby. Also, sometimes the observations times at stations change, and they might also be different from place to place.

What you need to do is you need to take into account these issues of site changes and observation time changes because they can make important effects on the data. For example, if you’ll be measuring temperatures and you’ll be measuring them three times a day, which was a common way of doing it in the 19th century—the common thing was to start reading at sunrise, some time at lunchtime, about one or two o’clock in the afternoon, and at sunset. You have three observations. This was the common practice in Europe in the 18th, early 19th century. There are a lot of other issues related to that because Europe was not on—no place was on common time until the railways came in the—we didn’t get common time in Britain until about the 1830s when you needed to have common time when you had a railway timetable. You didn’t need it before then. Solo time—you’re on solo time everywhere. Places were some way—in the larger countries, places were some way out from measuring on a common time schedule.

Just think of measuring it at sunrise, one o’clock, and sunset. It’s clearly going to vary during the year—you got the seasonal cycle—but if you then suddenly switched from doing that to moving to measuring it as daily maximum and minimum temperatures when that thermometer became available in the middle of the 19th century, you probably have a one- or two-degree difference, which might differ from month to month. There will probably a seasonal cycle to the difference. You got to take into account these different observations schedules, and some of them are much more complicated than the simple example I’ve given you. There can be ones where you’ve got measurements every three hours, and then suddenly they decide that in that country that they’ve got this maximum and minimum time because they want to use those, and they just measure that once a day. They just need the observer to go out once a day rather than every—than eight times every three hours. That’s the sort of observation time, one.

The other problem is that over the years, a lot of sites have moved to outside of towns, often to airports now. A lot of their reading is taken at airports. You’ve got potential jumps in records when sites have moved from city-center sites to airports, and you got to take that into account. Well, we call the process of making sure we’ve got just the impact of climate and weather on the observations—we don’t want the effects of human change in the schedule of measurements, or where we’ve taken the measurements, or even the screens that have been built around the thermometers—we call that homogenization, and there’s a well-known definition by a pair of climatologists in the 1940s called Conrad and Pollack who said, “A climate series is homogeneous if it’s only affected by the vagaries of the weather and climate.” We’re actually—by analyses, we’re making sure that these records are homogeneous.

One or two people have this belief that there’s somehow this master data set of temperature data or precipitation data out there which we draw on. Well, there isn’t. We have accessed the data initially from weather records, as I was saying at the beginning. We have then searched in archives, particularly the Met Office archives because they had a lot of archives from the British Empire over the years and measurements taken in many distant lands, so we’ve got those. Then we’ve had contacts with other scientists and Met Services to try and get additional data. There was a big impetuous of getting extra data in 1950, after the Second World War, so the coverage improved a lot then, but there’s still a lot more data out there that could be digitized in the 19th century and the first part of the 20th century, which is coming along.

There’s been a big emphasis recently to try and get some more data digitized at the daily time scale and sub-daily time scale, particularly the pressure data, so that it can feed into new reanalysis products. That also has helped in getting some of the daily temperatures and rainfall also digitized. Okay, so the different groups have got different data sets. We have exchanged our data in the past with NCDC in Nashville, and that is the main American group in terms of—there are three American groups: NCDC in Nashville, and GISS, part of NASA in New York, and this new one called BEST, with the somewhat contrived acronym, Berkley Earth Surface Temperature. Now GISS, as far as I understand from reading the papers, uses the same station data that NCDC uses, and they apply an additional adjustment for organization, but essentially the data set is the same as what NCDC produces. BEST take a number of data sets from NCDC. Now, having got the basic data together, they then, NCDC and BEST, do some homogeneity assessment of that quality of the data and provide adjustments to the station data.

We’re a bit different. We did some work on that in the 1980s, and we realized that the best people to do that were the Met Services themselves, so we’ve encouraged Met Services to do it, and more and more of them are doing it. It’s more the developed nations that do it than the developing nations, so hardly any countries in Africa do it, for example. Once you got basic data, the other difference is how you combine that into a grid or hemispheric average, and GISS use one method; NCDC use another method, which is similar to ours now; and BEST uses a statistical interpolation scheme involving Kriging. I don’t think they make—that aspect doesn’t make much difference at all. I mean, GISS and BEST managed to do it without having to have a base period for the station. They somehow get over the problem with stations being of different elevations and also measuring temperature in different ways.

We use anomalies, so we have to have data. Each station has to have data, enough data, from the 1961 to ‘90 period. If we have a station that’s only got 30 years in the 19th century, then we don’t use it because it hasn’t got the 1961 to ‘90 base period. The other techniques can. You seem to be able to use that data, but I don’t think there’s much of that data. The biggest issue with the global temperature series—I’m talking here of the global temperature, with the land and ocean—is from the marine data. If you go through the answers I’ve given you so far in terms of the land, a lot of these issues are different from station to station, so they’re not common from station to station. An organization may be a slight factor in some regions of the world, but we think that’s relatively small, and so if you average enough stations together, and they are reasonably reliable, the land record will agree quite well. The land is always going to be much more noisier as well than the marine part.

With the work the Met Office had done on the marine data, there are a number of key changes to the way temperatures were measured at sea in the past. First of all, the land data is all air temperatures, measured one-and-a-half to two meters above the ground, and so to measure air temperatures, it’s measured by ships. The Met Office found that the ship—the data during the daytime was just not very reliable. It was affected by the heating up of the ship, particularly when you had sort of modern ships from the—well, steam ships from the late 19th century onwards. They removed the daytime data, and so that’s half the data set to start with, so you only got the nighttime ones. What we’ve always done is try to go to the sea temperature data, and the reason for that is that sea temperatures—sea doesn’t change much from day to day. In a given square of the ocean, you don’t need too many observations.

On a land station, you need observations twice a day at least to pick up the diurnal cycle. You need observations every day because it varies a lot from day to day in most parts of the world. In the marine part of the world, you can probably get away with three or four observations in a month. It will give you the average sea surface temperature for that bit of the ocean because it doesn’t change much from day to day. You’re not measuring the immediate skin temperature of the ocean. You’re measuring it some way about anywhere from the surface down to about five or six meters, so the top layer, that top layer of the ocean, doesn’t change too much.

What started at the Second World War and continued since is measurements of sea temperature taken with engine intakes, so steamships take on—or powered ships in some way take on water to cool the engines slightly a bit analogous to how a car takes on air. By putting some thermometers at the intake, at the sea intake pipe, then you can have those measuring directly on the ship’s bridge, and it’s much easier to do. The captain or the mate can fill in the logbook without having to go and take a real sample of seawater.

Prior to the Second World War, most countries weren’t doing that, and the measurements were taken with a bucket. There were buckets of various designs obviously with a rope attached to them, and you throw the rope over the ship’s side and with the bucket on, and you brought up some water, and you put a thermometer in, and you measured the temperature. The recommendations were that you left that thermometer in the bucket for a few minutes for the thermometer to equilibrate with the water. Well, depending on the bucket design, that water is going to cool because normally the air temperature is cooler than the seawater that’s being sampled over most of the ocean. It’s not everywhere, but it is in many places. There was a cooling—the bucket temperatures tended to be somewhere between about 0.3 and 0.7 degrees Celsius cooler, and that jumped—that change took place around 1940, ‘41. There’s a massive jump in the sea temperatures if you don’t adjust them for that homogeneity problem. In the sailing ship period in the 19th century, they were using buckets as well, and they tend to be wooden buckets, and they’re better insulators, so they have slightly less of an evaporative cooling that came with steamships.

If you took the marine data and put it all together without doing these adjustments, you’d find that there was a massive temperature increase because the bucket data in the—from about 1890 to 1940 is about 0.5 degrees Celsius colder than it should be, and it’s slightly warmer by a few tenths in the late 19th century. Then you got the modern stuff, which is nearer the true temperature. If you didn’t make that adjustment, you will have a massive warming, much greater than you see over the land in the marine data. The biggest adjustments to any of the components of the global temperature data is the sea temperature adjustments around the beginning of World War Two. If those adjustments were not made, then the air/sea temperature differences would just be totally—will be fine after World War Two and then completely wrong before World War Two. You cannot use unadjusted data.

I put it in another context. There’s been a lot of—I’ve read things about the New Zealand temperature record and people claiming that the New Zealand MetService, NIWA, have made adjustments to data going back into the 19th century. Well, this is to account for the site changes. You end up with a record in New Zealand which shows relative warming throughout much of the 20th century, and that agrees with sea temperature measurements from the adjusted sea temperature data set around the coast of New Zealand. If you didn’t make adjustments to the land data, the land data would have no warming. If you didn’t make the adjustments to the marine data, the sea temperature would have about twice the warming it currently has. Everything in New Zealand before the Second World War would just be completely ridiculous because you’d have air and sea temperature differences that’s totally wrong compared to the period after the Second World War roughly because of the big adjustments to marine data.

Really, the really important change, the biggest change to any of the components of the global temperature record is in the marine data for the change of from buckets to intakes. This is really important also—the marine data changes are more important also in recent times, too, because the numbers of ships taking measurements around the world has reduced slightly. There are a number of reasons for that. Some shipping companies no longer want to do it. There’s always been issues with the fishing fleets not wanting their competitors to know where they are. The other thing is that some companies think that sending out the data with the ship’s call sign tells pirates off Somalia where they are. In order to improve, though—before that, in order to improve weather forecasting in the southern hemisphere and parts of northern hemisphere, people realize that improvements to sea temperatures were really vital.

Since the late 1970s, a lot buoys have been deployed around the world, particularly in the southern hemisphere and the tropics, these buoys provide measurements of air temperature, sea temperature, and pressure. It turns out that these buoy data—the Americans call them “bü-e”—tend to record temperatures slightly cooler than the ships of somewhere in the range of one- to two-tenths of a degree Celsius when they’ve compared collocated measurements. Since about 1990—we’ve gone from marine measurements coming almost entirely from ships to one where about 80 percent of them are coming from these buoys. They’re now allowing for that in the data sets because you’ve got to take into account that the buoys have a slightly different absolute temperature, which is probably nearer the true one than the ships. It may be that the ship intake measurements are probably about one- to two-tenths of a degree Celsius warmer than they should be, which is what a lot of people have said in the past. It doesn’t make any difference.

This slight difference in absolute temperatures don’t really make too much difference to us because we’re using temperature anomalies. It’s only if you want to try and go back to the absolute measurements in terms of real degree Celsius rather than just temperature anomalies. Yes. We did some work on this sort of—the 1940s has always been an interesting period in terms of the course of temperature change in a global basis. What you’ve got to bear in mind is that the first part of the 1940s was the Second World War, and the number of observations was markedly reduced from what was available during the 1930s and certainly what was available in the ‘50s or even in modern decades as well. The marine data has a greater error range, and in our realizations of global temperatures or gridded temperatures that I talked about earlier, that is encompassed. That greater uncertainty of the marine data, is encompassed within that.

It doesn’t help also with the—there was a major El Niño event in 1940, ‘41, ‘42, which we would like to know a bit more about, but we’ve tried the Met Office, and others have tried really hard in trying to digitize as many ship observations that we can find, ship logbook observations. Almost all of the extra British ships during the Second World War have been digitized in the last 10 years or so. They have improved coverage, but mainly in the Atlantic and the Indian Ocean. There weren’t too many British ships in the Pacific. Although we did notice one intriguing thing with the British ships, that at the start of the Second World War, Churchill made a deal with Roosevelt in that—giving the Americans leases on bases around the world, we got a number of old American ships. We haven’t got the parts for a lot of these ships, so when they needed repairs suddenly you see these British ships in the South Indian Ocean suddenly shoot off to San Francisco or Seattle for repairs, and you can see this in the logbooks. There is some British data in the tropical Pacific, but very little. It’s just when they had to go off running repairs during the Second World War. In terms of interesting questions, it’s probably—for me, it’s nothing much to do with the global temperature record.

We have produced another data set, which—people say that the CRU data set has gaps where there’s no stations—that’s true—but there’s another data set we have that a lot of people don’t know about, which is an infill data set where we do this infilling, and we also do that for temperature on a few other variables, too. That data set gets widely used by many people, particularly the climate modelers to assess how their climate models are doing in an absolute sense because we put that back to absolute degree Celsius, too, and rainfall in millimeters, so they compare how well their model is doing both over time and things on a seasonal cycle and many other aspects of the agreement between temperature and rainfall and pressure to see if the model reproduces the same sort of patterns that the real world has. If I’m giving a talk in town X, it would be useful to know what the temperature record for town X looks like. That question is always asked.

Then there must always be the question about urbanization, and people think urbanization causes much of the warming. Urbanization doesn’t cause warming of the marine data, and the trends are pretty similar between land and marine data. Another question people always asked about, the issue we’ve already talked about, is how many stations you need to produce reliable records. Now the fact that I said that you could get away with about a hundred stations, that’s at the monthly time scale. The number you need is dependent on the time scale. If you’re looking at daily data for temperature, then you will need many more stations to do it reliably.

Precipitation is a different variable entirely. It’s much less spatially conforming—it’s more spatially variable—so you need more stations. As you go further back in time to the pre-instrumental period when you start using proxy data from ice cores, corals, trees, et cetera, if that number was significantly more than a hundred, then you wouldn’t be able to produce these reconstructions in the past. Obviously as we go further back in time on longer time scales onto the thousand year and 10,000-year time scales that we think about with ice ages, then it seems people are quite happy to accept one record from Greenland and one record from Antarctica about the cause of ice ages over the last million years. They’re not worried about what happens elsewhere.

The actual time scale dependence of a number of these metrics, and particularly this number of stations you need, is crucial. I think that’s one of my best papers that I’ve ever done in ‘97 with Tim on that issue, and it’s not been—the other groups do not—they’re aware of that, but they’ve never really incorporated the error component in their data. The best people have, but I think their errors are too small.

The climate is going to continue to warm, but it’s not going to warm year on year because it hasn’t done that in the past. There have been periods when it’s warm. There’s been periods when it’s cooled slightly. There’s large changes from year to year. The climate change component from greenhouse gases are really under decadal and longer time scales. You shouldn’t see it on the individual years.

What’s really influenced the individual years is the circulation, which is where we started, and it’s really the tropical circulation, the El Niños, La Niñas—that’s the dominant one. In different parts of the world, you’ve got other components from the North Atlantic oscillation in Europe and North America, and you’ve got the sudden annular mode in the high latitudes of the Southern Hemisphere. How that circulation changes is a big component on the temperatures on the inter-annual time scale. That’s just year to year. We wouldn’t expect the El Niño events and La Niña events to contrive to produce a long-term warming. That really has to be down to greenhouse gases because we know that the sun has varied, but the variations in solar output are relatively small. They should have caused the world to cool slightly since the late 1950s, but in fact that hasn’t happened.