Some eclectic thoughts on the history and future of the Earth's Climate

I begin this talk 4,600 million years ago when planet Earth was at its hottest ever period. The Earth's temperature then is estimated to have been about 2,000 ^{o}C so, arguably, our worries about 2 ^{o}C of warming in the Earth's temperature seem to be a pretty small issue in the history of the planet. What is thought to have happened all those millions of years ago was that a Mars sized object collided with the Earth probably created the moon and vaporized most of the rock at the surface. A lake of molten brimstone, by comparison, is pretty small beer at just 446 ^{o}C. It will come as no surprise that this period is called the Hadean period and the Hades of Greek legend would have had to dig deep to get to the cooler solid rock in their under world.

All those millions of years are pretty hard to think about compared to the times we usually think about: days, hours, minutes, seconds so I am going to imagine that the history of the Earth took place in just one 24 hour day which I will call a Geo day. The Hadean period corresponds to the beginning of the Geo day and today corresponds to the end of the Geo day (a Geo day time of a little after 11:59 pm). Let's move forward in real time by about four and half Giga years to the Jurassic period. It is now between about 11:00 pm and 11:15 pm in the evening of the Geo day. Back then it is estimated that there were some real millions of years when there were polar ice caps and some when the polar ice caps had all melted. How hot did it get to melt those polar ice caps? The answer is a mean surface temperature of about 16.5 ^{o}C, about 3 ^{o}C above the modern level. Remember that the 26th UN Climate Change Conference (COP26) in Glasgow, just finished in chilly Scotland, was discussing at length an additional 1.5 ^{o}C due to greenhouse gas emissions - more on greenhouse gases later. OK, so this is pretty bad news. If the Jurassic period is anything to go by, no polar caps and not in a few tens of million years but in just a few human generations.

You might be asking why did I pick the Jurassic period of Earth's history? The first reason is that I grew up within sight of some particularly nice Jurassic period mountains near Geneva Lake in Switzerland so I can remember collecting the fossils of Jurassic life. Living on earth in the Jurassic period were reptiles and the first birds. Plants were ferns, conifers and early seed bearing plants. There were no mammals and especially no humans. The second reason is that Jurassic

period was another "hot spell" in Earth's history with similar, if a tad hotter, temperatures to 2021, that is, 3 ^{o}C hotter than now. The third reason is rather a curious one in the light of the push at COP 26 for the world drastically to reduce the consumption of fossil fuels, especially coal. Although most of the coal formation had already happened in the Carboniferous period and the Permian Period (between about 10:07 pm and 10:48 pm of the Geo day), there was still quite a lot forming during the Jurassic period. It is likely, therefore that in a world 3 ^{o}C hotter than now coal will start to form again but before we say, "aha, surely that's the answer to all our problems?" remember that we have taken a good chunk of the fossil coal out in just the last 200 years (the last 3.7 micro seconds of the Geo day) and the creation of new coal, if all goes badly enough for humanity, would take place over about 100 million years (a little over half an hour of the Geo day) – a bit too slow to be of much use in "saving the planet."

Humans are thought to have first arrived on the planet about 40,000 real years ago (in the last second of the Geo day, the time taken for a blink of an eyelid). For about 39,800 of those 40,000 real years the Earth coped very well with human beings, at least in the sense that the world's average temperature didn't change much although it moved up and down over the years leading to cold spells and hot spells. Then, from the mid-18th century to about 1830, came the First Industrial Revolution fueled largely by coal and luckily confimed just to Britain. It wasn't long before the rest of Europe, North America and Japan jumped on the coal wagon and so began the Second Industrial Revolution. In the mid and late 1900s the rest of the world jumped on the coal wagon and natural gas became increasingly part of the mix. Burning all that coal and natural gas pumped a lot of extra Carbon dioxide into the Earth's atmosphere and the proportion remaining there has gradually increased over time. Nobody is arguing with that statement.

The Industrial Revolutions also led to the development of ever more sophisticated and deadly means of warfare. Today, as I am sure you are aware, is Remembrance Sunday where we remember all of the people that have fought and died in all of the terrible wars from the First World War 1914—1918 to the Second World War 1939—1945 and those who have fought and died in other more recent conflict. Such is one dark side of human "progress."

Now I would like to briefly talk about the greenhouse effect and greenhouse gases. My apologies to those scientists here that already know about this effect. The greenhouse effect is a metaphor for what happens in the atmosphere because of the presence of water (humidity), carbon dioxide, methane, and some other gases. Here's roughly how it works. One of the ways a greenhouse keeps the plants inside warmer than the outside temperature results from what happens when light passess into and out of the greenhouse through the glass. Light from the sun passes easily through the glass and a lot of it is absorbed by surfaces and plants inside the greenhouse. Some light is reemitted in the form of heat but light at the heat end of the spectrum cannot easily pass through the glass of the greenhouse so the heat gets trapped inside. Net effect, the greenhouse becomes a bit warmer than its surroundings.

A very similar thing happens in the atmosphere. When it is cloudy weather, the light that comes through the water vapour in clouds is absorbed and reemitted as heat and gets trapped underneath or reflected back to to the surface of the the Earth and isn't able to radiate back out to cold outer space. So, on a cloudy winter's day it stays warmer on average than on a clear sky winter's day and there's much less chance of frost in Britain in mid winter when it's cloudy. Carbon dioxide and Methane are also "greenhouse gases" and trap heat near the ground, so more of them in the atmosphere means that the layers near the ground become a bit warmer. This is why the increasing amounts of carbon dioxide and methane in the atmosphere cause global warming. It's fair to say that without some greenhouse gases the earth would be a pretty bleak place with typical surface temperatures of about -18 ^{o}C so we need enough of them but not too much – what one might call the "Goldilocks" amount so it's not too hot and not too cold like Goldilocks' porridge.

Let's move forward to sixty one years ago. There was not much impact on climate at the time, that was when I was born but I am (un) happy to say that about 2 tonnes of oil are burnt each year in my central heating boiler and a scary amount of petrol and diesel is burnt in my cars and motorcycles. Another scary amount of fuel is burnt extracting the iron ore, making the plastics, producing the rubber and all the other things that go into building a car for me every ten years or so. Just because I am a typical citizen of a prosperous country, during my life I have probably burnt the equivalent of a chapel full of coal. And so do millions of other citizens in Britain. It all adds up.

In 1992, by something of an accident I started work in atmospheric science 30 years ago at Cambridge University. My four year old daughter, when asked by her class mates what Daddy did at that time said "my Daddy looks at frozen dirt using a computer." The importance of frozen dirt, by the way, is that there is a lot of a lot of a lot of it in Northen Canada, Alaska and a number of other landmasses at high latitudes. When frozen dirt thaws the carbon in it that came from plants (usually in the form of peat) gradually breaks down leading to carbon dioxide and methane emission. So no frozen dirt equals lots of green house gases.

That same year the the Intergovernmental Panel on Climate Change, established by the United Nations Environment Programme and the World Meteorological Organization in 1988, published their first Assessment Report including a section for Policymakers which said that it was "certain" that

- There was a natural green house effect which already keeps the Earth warmer than it otherwise would be (good job because otherwise it would be about -18 ^{o}C as I just said)
- Human activities were substantially increasing atmospheric concentrations of the greenhouse gases CO2, CH4, CFCs and NOX. The result is extra warming of the Earth's surface
- There would probably be more of the main green house gas, water vapour as time went on
- Emissions at 1988 rates would lead to increased concentrations for centuries ahead and humans would need to reduce emissions by over 60% to keep concentrations at 1988 levels. Carrying on as we were, "business as usual," would be likely to lead to a rise in global mean temperature of about 1 ^{o}C by 2025 and 3 ^{o}C by 2100.

In the event, global temperatures have now increased by about 1.2 ^{o}C, a bit more, and by 2021, a bit earlier, so it was a case of "even more business than usual." The real difficulty back in 1992 was that the size of the observed warming at that time was of the same magnitude as natural climate variability so it was impossible to be sure whether there really was human produced warming or not. They were honest enough to say, rather pompously, that "unequivocal detection of enhanced green house effect from observations is not

likely for a decade or more" or, in plain English, that we wouldn't be sure that there really was human produced warming until 1998 at the earliest.

They were also honest enough to point to lots of issues in climate modelling. We didn't understand enough about sources and sinks of greenhouse gases (frozen dirt and me), clouds (a really big issue since models were - and frankly still are - rather crude here), oceans (amazing given that 71% of the earth's surface is covered in water) and polar ice sheets which affect predictions of sea-level rise.

I won't say anything about the long term effects of global warming that IPCC described except to point out that you will find pretty much the same list in many newspaper reports in the last couple of weeks while the 26th UN Climate Change Conference (COP26) has been going on in Glasgow. Nothing has changed, and in this case that's probably a good thing. Oh, perhaps I will mention one thing, the melting of that "frozen dirt" was on the list as a major issue!

In 1997 there was conference in Kyoto at which The Kyoto Protocol was created, an international treaty which commited state parties to reduce greenhouse gas emissions. It took nearly ten years before the Kyoto Protocol came into force and at that time 41 countries plus the European Union agreed to reduce the emission of six greenhouse gases to below 1990 levels by the year 2012. It was widely hailed as the most significant environmental treaty ever negotiated. By a weird coincidence I was also at a climate conference in Kyoto in 1997 but not the big one – I was able to wear the borrowed feathers for a while...

In the following 15 years we climate scientists really struggled to be heard in the face of lobbying from industrialists and fossil fuel companies. To be fair, it was also a pretty good route to academic research funding to be working in climate science in 1997 so we undoubtedly had a vested interest in predicting possible disasters.

However, a more serious worry to me was the quality of atmospheric climate models – my area of research at the time. For example, one of the most obvious things that happens to the wind in the stratosphere (about 10 km above the Earth's surface) at tropical latitudes is that it changes direction every 24 to 28

months, the so called quasi biennial oscillation or QBO. Not one of the 1997 climate models were able to produce a QBO. Fortunately by the year 2000, thanks in part to gravity wave parametrizations such as the one I worked on with Prof Michael McIntre, we were able to add enough forcing to climate models from (simulated) breaking gravity waves to allow them to produce a QBO.

I thought you might be interested to see an example of a gravity wave so I brought one with me this evening in this jar. There are two liquids in the jar: oil and vinegar, and oil is lighter than vinegar so it sits on top of the vinegar. Look at what happens when I gently move the jar from side to side – there is a wave that ripples on the layer where the oil meets the vinegar which moves up and down more slowly than a wave on a pond would move up and down. This is called a gravity wave and is caused by the change in density that happens going from vinegar to oil. Although we can't see them in the atmosphere the atmosphere is also filled with gravity waves because it too gets less and less dense as you go higher and higher – it's like there are a whole load of layers of different liquids with decreasing densities as you get higher and higher. Where gravity waves break a lot of energy and momentum is deposited in a similar way to the crashing of water waves in the surf zone of an ocean beach and the deposited momentum is one of things that causes the QBO.

Another example of quality of climate modelling and measurements relates to size of a typical climate model grid square and of the typical number of, for example, sea temperature measuring devices per square km. Many people think that climate models and actual measurements are able to resolve, that is to say, make a reasonably good picture of, things such as clouds. The reality is rather different.

Let's consider consider measurements of sea surface temperature (pretty fundamental in judging how hot the world actually is). To measure sea surface temperature, scientists deploy temperature sensors on satellites, buoys, ships, and ocean reference stations. In 1992 in one "state of the art" experiment in the Pacific Ocean there was about one buoy per 124,000 km^2 of ocean or roughly one per area of England. Pretty shocking resolution, eh?

Twenty years later in 2012 typical climate models used grid squares with areas of about three Englands and now in the 2020s a typical coupled ocean and

atmosphere climate model uses grid squares that are typically about half the area of England but can go down to about the area of what used to be called Middlesex. One can count a lot of a lot of a lot of clouds in an area half the size of England on a typical day.

So what has this to do with the 26th UN Climate Change Conference (COP26) in Glasgow in the last few weeks? It seems to me that, at last, the politicians and scientists are speaking the same language (if only for a week or two). That, in itself is a remarkable achievement and has resulted in a lot of intended measures being agreed and carefully described using the ambiguous language of politicians and the sensationalist language of journalists. It looks as if my petrol turbo performance car will probably be my last such car – I love my car so I try not to feel guilty about it. On the other hand, It looks as if my much loved compost heap can continue to be a garden feature and that soon I will be able to celebrate it with a fifty years of composting party!

Let me return to where I started, to Hades. A relevant Proverb from John Ray's Collection of English Proverbs in 1670 says "Hell is full of good meanings and wishes" or, as we would now put it, "the way to Hell is paved with good intentions." The good intentions are there in plenty, so now it's just a matter of making the huge social changes – and they really are huge – that are needed to keep global warming under control. Some people think of this as a war against climate change – it's a very different type of war from the ones whose dead we remember today, but, if we don't get it right, there will most probably be further, and perhaps even more deadly wars to come.

In short, if we return to a climate similar to the Jurassic period, human beings will be in trouble... but Nature will be just fine and lakes of molten brimstone won't be an issue either for Nature or for human beings.