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Climate Change: A Defining Challenge for the 21st Century

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In 1896, Svante Arrhenius, the Nobel Prize winning physicist, made the first calculations of the influence of carbon dioxide on the Earth's surface temperature. This was based on John Tyndall's demonstration that the Earth's atmosphere must have a Greenhouse Effect to explain its warm surface temperature, and that this was due to the presence of greenhouse gases, particularly water vapour, but also carbon dioxide. In 1908, Arrhenius went on to publish a book entitled '*Worlds in the Making*' in which he noted that '........*any doubling of the percentage of carbon dioxide in the air would raise the temperature of the earth's surface by 4°Celsius; and if the carbon dioxide were increased fourfold, the temperature would rise by 8°Celsius.*' So, the fundamental physics of global warming has been known for more than a century, and this early climate change projection still lies within the range of current projections, although at the upper end.

It is interesting, though, to see how Arrhenius viewed human-induced climate change and its impacts. In 1908, he went on to write *'The enormous combustion of coal by our industrial establishments suffices to increase the percentage of carbon dioxide in the air to a perceptible degree… By the influence of the increasing percentage of carbonic acid in the atmosphere, we may hope to enjoy ages with more equable and better climates, especially as regards the colder regions of the earth, ages when the earth will bring forth much more abundant crops than at present, for the benefit of rapidly propagating mankind.'* Now a century later, when we understand so much more about climate change and its implications, it is hard to be so optimistic!

But to begin, let's look at the two words - climate and change. The word climate describes a long-term average - typically over thirty years or longer - of things like wind, temperature and rainfall, which we might regard as stable. It's what we expect year by year and season by season. Many societies and economies are now finely tuned to the current state of the climate - India is a good example where the regular return of the monsoon rains is essential for water, food and energy security, and any delay or failure of the monsoon can have a huge impact on India's economy. But as the well-known saying goes - '*Climate is what you expect, weather is what you get*'[1] - so when we think about climate we also need to think about the range of weather that makes up our climate, and especially more extreme weather, how often it occurs and what its impacts on us are likely to be. In fact, we expect the most profound impacts of climate change to be associated with weather extremes – windstorms, floods, wildfires, storm surges and heatwaves.

The word 'change' implies something that is different from the norm - but how to define the norm? Our weather and climate vary continuously on all sorts of timescales from hours to decades, and that variability is part of defining the climate. One way to define change is when the climate we experience falls outside the

[1] Sometimes attributed to Mark Twain, but most likely coined by Andrew John Herbertson, a British geographer and Professor at Oxford

margins that we, as a modern civilization, have become used to; this is essentially how scientists have arrived at the statement that evidence for climate change is 'unequivocal'[2].

It's clear though, when we look back in history, that the Earth's climate has always changed, for example in and out of recent Ice Ages, to the deeper past when the Earth was warmer and carbon dioxide much more abundant than it is today. So why do we worry now?

There are three reasons that set current climate change apart from past changes. The first is the source of the change. Today our climate is changing because the concentrations of greenhouse gases in the atmosphere, especially carbon dioxide, are rising – and rising fast. We are taking ancient carbon that was bound up over millions of years as coal, oil and gas, and releasing it into the atmosphere through combustion in just a few decades, to satisfy our insatiable appetite for energy to support our industries and lifestyles. And we are changing the way that the Earth's biosphere balances the carbon budget by clearing forests and making the oceans more acidic. Because carbon dioxide is a greenhouse gas then this un-natural and rapid increase is causing the Earth's temperature to rise with all the associated impacts on our weather and the natural environment. When we look at past changes we can see that these were driven by the slow variation in the Earth's orbit around the Sun. This first affects the temperature, which then drives a response by natural ecosystems that control the amount of carbon dioxide in the atmosphere. So, past changes were driven by very different forcing agents, and although we can learn from them, they are not analogues of what we are experiencing today.

The second difference is the pace of climate change - around ten times faster than anything in the past. Carbon dioxide levels are now over 30% higher than they were just over 100 years ago - and indeed over 30% higher than anything the Earth has experienced for at least 800,000 years. The Earth's surface temperature has so far risen by 1°C since pre-industrial times, and is on course to reach 2°C by 2050 and potentially as much as 6^{0}C by 2100, unless we take serious action. These numbers may sound small, but we should recall that the change in Earth's temperature coming out of the last Ice Age was only 8°C. By rapidly releasing ancient carbon we are also effectively cutting many of the natural feedback loops that allow ecosystems to evolve through a period of climate change. We can see this happening already in the loss of natural habitats and in the changes to the seasons that affect the lifecycle of many species. The pace of change is too fast for many plants and animals to migrate or adapt. It seems likely that this disruption of our climate could have far-reaching consequences for sustainability of many natural ecosystems in the coming decades. At the same time, we are plundering the aquifers of ancient water and we are extracting water from our major rivers to such an extent that sometimes they no longer reach the ocean. In other words, we are disrupting the major cycles of the planet - the water and carbon cycles - and taking the Earth into uncharted territory.

The third difference is the scale of the human enterprise in which this current period of climate change is operating. Our planet's population is increasing; our cities are growing rapidly, often along coastlines; our world is increasingly and intricately interdependent – relying on global telecommunications, efficient transport systems and resilient provision of food, energy and water. All these systems are already vulnerable to adverse weather and climate conditions; the additional pressure of climate change creates a new set of circumstances and poses new challenges about how secure we will be in the future. More than ever before, the weather and climate has considerable direct and indirect impacts on us – our livelihoods, property, well-being and prosperity.

So, we have every cause for concern and little time to act. As the former Prime Minister Margaret Thatcher said in 1990: *"We can now say that we have the Surveyor's Report and it shows that there are faults and that the repair work needs to start without delay. …… We would be taking a great risk with future generations if, having received this early warning, we did nothing about it or just took the attitude: "Well! It will see me out! ...... The problems do not lie in the future – they are here and*

[2] IPCC Fifth Assessment Report, 2013

now – and it is our children and grandchildren, who are already growing up, who will be affected." Nothing that has happened in the last 25 years, including the increasing weight of scientific evidence, has detracted from the urgency of her message. Global average surface temperature has now risen by over 1.0°C since pre-industrial times; Arctic sea ice extent has declined by 4% every decade since records began in 1979 – and doing so faster in summer; sea levels have been rising by about 3 mm a year since the early 1990s; each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850.

Over the last few decades we have learnt an immense amount about our climate, how it varies and changes, through a vast array of observations, especially from satellite instruments. We have been able to define the global flow of energy through the climate system with sufficient accuracy to know that the planet has been accumulating energy due to increasing atmospheric concentrations of greenhouse gases; and we know that around 90% of this additional energy is taken up by the oceans. We know that excess heat accumulated in the Tropics is transported polewards, predominantly by the atmosphere in weather systems but also by the ocean's overturning circulation, and that phase changes of water, from evaporation (cooling) at the Earth's surface to condensation (heating) in the atmosphere, as clouds and precipitation form, is a fundamental part of Earth's energy cycle. This understanding of how the climate system works has allowed us to recognise that the Earth's climate is changing in many ways.

However, the Earth's climate is immensely complex and although we can detect many changes in the climate from observations, these observations cannot tell us <u>why</u> the climate system works in the way it does, <u>how</u> different components interact and drive the variability we observe, and <u>why</u> the climate is changing. For that we need to use numerical models of the climate system.

With the advent of computers in the 1950's, the first climate models began to be developed alongside numerical weather prediction systems. These were based on simulating the weather, and thereby the climate, from first principles using fundamental physical laws, such as Newton's Laws of Motion, radiative transfer theory and moist thermodynamics. These fundamental physical equations have to be solved using sophisticated numerical techniques on a computer, by dividing the Earth's atmosphere and oceans into millions of volumes, and integrating these forward in time to produce a simulation of the evolution of the weather and climate over the coming days and decades. The main challenge for weather and climate models has always been how best to represent processes, such as cloud formation and cumulus convection, which occur on scales that are finer than the grid of the model. Great progress has been made over the years in refining our understanding of these processes and improving their representation in numerical models, through the innovative fusion of theory, observations, field experiments and model simulation, but these processes are still sources of some of the uncertainties in climate change projections.

Ever since their inception, climate models have been very compute-intensive and the availability of computing power has dictated the level of sophistication and the type of experiments that can therefore be performed. There are few sciences where progress can be so closely linked to the increases in supercomputing power. It has enabled increases in resolution so that the models capture more faithfully the weather systems and ocean eddies that constitute the climate; it has allowed the introduction of more components of the climate system, such as interactive sea ice, and the transformation to Earth system models through the introduction of bio-geochemical cycles, such as the carbon cycle; and it has delivered the capability to perform a large number of simulations to test for robustness. Today numerical weather and climate models represent some of the most complex applications of supercomputing, and the codes that produce our weather and climate predictions typically run to well over a million lines of code.

The climate models of today are now effectively simulators of the real physical world. They are able to produce realistic simulations of the weather, monsoons, El Niño and its impacts, the Atlantic Thermohaline Circulation and the Gulf Stream to name but a few. These properties of the simulated climate system emerge fundamentally as a result of only three fundamental constraints – the energy input from the sun, the rotation rate of the planet and the Earth's geography. Even the composition of the atmosphere, such as water vapour, is determined from the moist processes, and from emissions of greenhouse gases and aerosols and their chemical reactions.

For a climate scientist, the climate model is our laboratory. We cannot perform experiments on the real system to test hypotheses formed from theory and observations as one might in physics or chemistry. Instead we need to use the model to pick apart feedbacks and interactions within the climate system so that we can understand how it works and why it varies and changes. The most striking example of this are the 'what if' simulations of the past century that explore the climate that would have been, without human emissions of greenhouse gases. These show that recent observed trends, in an increasing range of climate metrics, cannot be reproduced in the absence of human emissions. This is the fundamental attribution of climate change to human activities, which underpins all the global debates on climate change mitigation.

These models also allow us to 'look' into the future and how the climate system will behave depending on the emission reduction strategies we choose to pursue. From these climate projections we have learned that the ocean, with its huge thermal capacity, is fundamental to how climate change will manifest itself in the coming decades, both regionally and globally; we have learned that the response of the terrestrial biosphere to warming and to changes in rainfall patterns will likely amplify the greenhouse effect from human carbon emissions by being less efficient sinks of carbon; we have learned that, through simple physics that tells us that warmer air holds more water, climate change will lead to more extreme rainfall and flooding events; and so much more. It is also sobering to realise that, with all these scientific advances, we have found virtually nothing in the climate system that seems likely to damp the effects of our greenhouse gas emissions; instead, the more we know, the more we are faced with the uncomfortable reality that this could be even more challenging than we previously thought.

Although we often talk about uncertainty in future climate projections there are some things we can be certain about. We know that Earth will continue to warm; we know that the adverse impacts of climate change are disproportionately larger as we go to higher temperatures and that the risk of irreversible and disastrous changes increases; we know that sea levels will continue to rise long after we have stabilized the Earth's surface temperature and that melting of ice caps and glaciers will continue.

We also know that there will definitely be some level of climate change, whatever happens with future carbon emissions, because of the existing accumulation of carbon within the atmosphere. This means that some level of adaptation will be necessary whatever we do. The scale of the potential investments, the risks associated with failure, and the long lifetimes and lead-times of the infrastructure together mean that future investments are likely to be highly sensitive to how climate change evolves over the next two to three decades. We need to plan now for how we can climate-proof our lives, towns and cities and help to protect the natural environment.

So, what might the future look like? Let's imagine our climate in 2050 if we fail to curb emissions. 2050 is not that far away in terms of climate timescales, and with the existing commitment to climate change we can paint a picture of what the world's future climate might be like with some degree of certainty.

It's 2050. The Earth's surface temperature has passed 2^0C for the first time and global sea level has risen by another 30cm. The Arctic is now ice-free in summer, and there have been substantial increases in its ocean temperatures. In the Arctic, marine mammal, fish and bird populations are changing and the indigenous population is increasingly compromised by lack of food security; loss of coastal sea ice, sea level rise, and increased weather intensity are forcing relocation of some communities. The opening up of the Arctic has made it a major shipping route for international trade, and exploitation of the Arctic's natural resources is growing rapidly. New invasive species, brought in by increased human activity, are changing the natural ecosystems.

In India, pre-monsoon heat is now crippling for much of the population, especially across the northern plains, and flooding during the monsoon season is increasingly serious as daily rainfall intensities rise. Those living in low-lying coastal areas are experiencing more and more frequent incursions of seawater during storm surges as sea level rises. Fresh water supplies are contaminated, agricultural land is damaged and water-borne diseases are increasingly common. Forced migration is increasingly an issue. On the positive side though, air quality has improved substantially and fewer people are affected by respiratory ailments.

Across the Tropics, construction and maintenance of infrastructure in major towns and cities has become more difficult as daytime temperatures frequently exceed thresholds where it is safe to work outside. Electricity demand for air conditioning is putting greater and greater pressure on supplies.

Several Small Island States, such as Kiribati, are no longer habitable because of sea level rise, with the population now stateless and with an uncertain future; in others, coral bleaching has led to the loss of sustainable fisheries on which the population depend for their food security. Tourism, which was a major part of their economies, has fallen away.

Southern Australia and the Mediterranean, including the Middle East, are now in the grip of prolonged droughts and periods of extreme summer heat. Wildfires are becoming increasingly dangerous, threatening homes and urban environments, and damaging natural ecosystems. Water security is becoming more and more of an issue as aquifers are depleted.

In the UK and northern Europe, the weather is increasingly volatile with more extremes of temperature and rainfall. We have invested more and more on flood defences and learned how to manage our local environment to mitigate some of the adverse effects of climate change. Summer heatwaves are becoming more prevalent and the winter ski season is increasingly unreliable as rising temperatures lead to loss of snow cover. But longer growing seasons and warmer temperatures are providing opportunities for diversification in food production and tourism.

This small glimpse into what the climate of 2050 might be like is a stark reminder of why climate change will be such a determinant of our social and economic future, and of our role as custodians of the rich diversity of Earth's natural ecosystems. In all of this it is likely that water will become the most precious commodity on the planet. Understanding how regional rainfall patterns will change, the impacts of those on water availability and water quality, and the legal arguments of who owns water when rivers and aquifers cross national boundaries, will be defining issues in the coming decades.

So far, debates on climate change have been dominated largely by uncertainty in the projections and the economic implications of dealing with the problem. But increasingly, climate change will become a moral issue. We know that the worst impacts will be felt by the world's poorest, who are already under enormous stress and have very few resources to hand to help them survive, and that climate change has the potential to derail their socio-economic development. As the UN Deputy High Commissioner for Human Rights notes, '*Climate change affects many human rights, undercutting the rights to health, to food, to water, and for some small island nations, it may even affect the right to self-determination*'. Looking forward, the protection of basic human rights and the role of the developed world in supporting the developing world, are likely to alter fundamentally the debate on how we deal with climate change.

Despite all the debates about uncertainties in climate models and in the projections of climate change, arguably one of the most important figures from the IPCC 5th Assessment Report was the very simple and fundamental result that if we continue to accumulate carbon in the atmosphere then the planet will continue to warm, just as Arrhenius hypothesized in 1896. In fact, the relationship is almost linear, and makes clear what the choices we make around reducing emissions will mean for global warming.

In many respects 2015 was a landmark year: not only did the world endorse the Paris Agreement, but it also signed up to the Sendai Framework to work together for the substantial reduction of disaster risk and losses in lives, livelihoods and health, and it agreed on the Sustainable Development Goals to end poverty and hunger, improve health and education, make cities more sustainable, and protect oceans and forests. In all of these, combatting climate change will be fundamental to achieving these aims.

But in 2015, the Earth's surface temperature also passed the 1^0C threshold – halfway to the 2^0C limit set in Paris. Yet we have already used two-thirds of the allowable budget of carbon that we can emit if we want to stay within 2^0C. Since then new scientific evidence has indicated that this could be an optimistic budget; the effects of melting permafrost and limitations in the ability of the biosphere to take up some of our carbon emissions suggest that we have even less room to manoeuvre than we thought. So, if we want to gamble with the future of the planet we would be wise to take a cautious approach because the odds are very stacked in favour of at least uncomfortable, and at worst dangerous climate change. Lack of certainty should not be used as an excuse for inaction.

We cannot deal with global warming without accepting that the way we live has to change. We will need to transform the way we generate, store and use energy, and we will have to learn to manage more extremes of weather and climate. One of the keys to this will be preparedness; continuing improvements in weather and climate forecasting will help us to be more resilient – forewarned is forearmed. Increasingly our actions and responses to the natural environment themselves influence the environment and the impacts we feel from weather and climate hazards. For this reason, we need to make significant advances in the end-to end evaluation of environmental risk. This will require the integration of the physical simulation of weather and climate with areas such as advanced modelling of the built environment, quantification of the value of natural capital and ecosystem services, understanding of human dynamics, modelling of ecological systems, and new approaches to modelling financial and socio-economic impact.

While the focus on climate change mitigation has largely been on reducing emissions of carbon dioxide, there are other atmospheric pollutants, such as black carbon and sulphate aerosols, where reducing their emissions will have significant benefits through improving air quality and hence human, plant and animal health. China, where dealing with poor air quality is now a major driver in moving to a low-carbon economy, is a good example. But there are also risks that cleaning up those atmospheric pollutants that currently act to cool the planet might lead to acceleration in near-term warming in some parts of the world in the short term and interact adversely with regional climate variability. So, finding the best emission pathways to mitigate climate change is complex and will require an integrated approach, from the latest Earth system science to socio-economic assessments.

Another factor in the debate on mitigation is the potential role of geoengineering. This involves the deliberate large-scale intervention in the Earth's natural systems to counteract climate change, either through solar radiation management or the direct removal of carbon dioxide from the atmosphere. It is increasingly clear that to achieve the temperature goals set by the Paris Agreement may require the wholesale removal of carbon from the atmosphere through, for example, the use of bioenergy with carbon capture and storage (BECCS). These techniques would have to be implemented on a global scale to have a significant impact on carbon dioxide levels in the atmosphere.

For solar radiation management, which considers for example, the use of cloud modification or the injection of aerosols into the stratosphere to reflect more solar radiation back to space, we will need to properly understand the potential impacts. This must look beyond the effects on global surface temperature to the implications for the regional climate and hence, for example, to water and food security. These are not well understood and will require the same level of scientific diligence as has been devoted to understanding the regional consequences of greenhouse gas emissions. These techniques are particularly concerning because of social, legal and political issues; they could be implemented unilaterally by nations without due consideration for their global impacts, and mechanisms for international governance still need to be put in place.

In the end, whichever way we go, it will be up to engineers and technologists to come up with innovative solutions for solving the problems of clean energy generation, storage and distribution within a few decades and with as little disruption to the global economy as possible. At the same time, as individuals, we will need to find ways to protect the natural environment and ensure that we fulfill our responsibilities as custodians of life on Earth for future generations. That means that all of us will need to make choices about how we live and where we live.

So, to some final thoughts. I hope I have convinced you that climate change will be one of the defining challenges of the twenty-first century; how we respond will determine our future prosperity, health and well-being and the sustainability of Earth's natural environment. In 2015 over 190 nations agreed to act to limit the increase in the Earth's surface temperature to less than 2ºC, and preferably to 1.5ºC if at all possible. Future generations may well look back on 2015 as the turning point in the struggle to align policy with science. But how should we make sense of all this and the daunting prospect of what our response to the challenge of climate change might mean?

There is no doubt that climate change will affect us all profoundly in the future, but it's worth remembering that we do not go forward blindly without any sense of what we may be facing. The construction of computer models that simulate the Earth's climate and enable us to predict, from fundamental physical principles, how the weather and climate will evolve, is one of the great scientific achievements of the last 50 years. In few other areas of science are we able to look to the future with the level of confidence that we now have in our climate predictions.

It is worth reflecting on the words of Vice-Admiral Robert Fitzroy, the Captain of the Beagle who took Charles Darwin on his momentous voyages, but who was also the founder of the UK Met Office and who issued the first public weather forecasts. After the loss of the 'Royal Charter' in a terrible storm in 1859 he wrote to the 'The Times': "*Man cannot still the raging of the wind, but he can predict it. He cannot appease the storm, but he can escape its violence, and if all the appliances available for the salvation of life [from shipwreck] were but properly employed the effects of these awful visitations might be wonderfully mitigated.*"

Over 150 years ago, Fitzroy embarked on the long journey of making predictions as a means of reducing and managing the impacts of severe weather and these now apply also to how we will manage climate change. From the global to the local and from hours to decades, our understanding of weather and climate and the predictions we make, enable us to plan for the future and serve to keep us safe.

Let's leave the final word, though, to the British-born astronaut and climate scientist, Piers Sellers, who died of pancreatic cancer in December 2016. On receiving his diagnosis a year earlier, he wrote a moving piece in the New York Times on his perspectives on climate change:

'New technologies have a way of bettering our lives in ways we cannot anticipate. There is no convincing demonstrated reason to believe that our evolving future will be worse than our present, assuming careful management of the challenges and risks. History is replete with examples of us humans getting out of tight spots. The winners tended to be realistic, pragmatic and flexible; the losers were often in denial of the threat…….

As an astronaut, I spacewalked 220 miles above the Earth. Floating alongside the International Space Station, I watched hurricanes cartwheel across oceans, the Amazon snake its way to the sea through a brilliant green carpet of forest, and gigantic nighttime thunderstorms flash and flare for hundreds of miles along the Equator. From this God's-eye-view, I saw how fragile and infinitely precious the Earth is. I'm hopeful for its future.'

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