DOI: https://doi.org/10.36094/sc.v86.2020.Climate_Change.Adve.04

ARTICLE

THE SCIENCE OF CLIMATE CHANGE

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This essay presents the basic science of global warming. At its base is human interference with the carbon cycle. Major current impacts, worldwide and in India, are discussed. We also present the latest science pertaining to the attribution of extreme events in India. Key to understanding climatic impacts in India is the excessive warming of the Indian Ocean. Planetary feedbacks and tipping points that are being crossed suggest that the urgency to intervene has never been greater.

Introduction

Carbon dioxide is essential to life on Earth. Its presence in the atmosphere, along with other greenhouse gases, is what has enabled the Earth to maintain temperatures that have allowed for the development of agriculture and the growth of human civilizations. In their absence, the Earth would have an average temperature of about minus 16 degrees Celsius (ºC).[1]

Human Interference in the Carbon Cycle

Carbon dioxide (CO_2) moves between different parts of the Earth's system in a slow cycle, but one that operates at multiple time frames. On a timescale of a million years or longer, carbon dioxide gets added to the atmosphere via degassing from volcanoes and deep-sea vents. This CO_2 is drawn down from the atmosphere through weathering, the erosion and dissolution of rocks into water. Through these two processes, CO_2 concentrations in the atmosphere and hence the Earth's climate have been regulated over very long periods of time.

In shorter, glacial periods of a 100,000 years or so, as the planet emerged from an Ice Age triggered by a change in sunlight received due to small changes in the Earth's orbit, the carbon dioxide released from the subsequently warmer oceans and soils (along with reduced albedo (the proportion of incident light reflected back into the atmosphere) due to less ice, significantly amplifies the warming.

At the base of global warming is human interference with the carbon cycle through the combustion of coal, oil, and gas. However, in contrast to what happened in the Ice Age amplifications, the carbon cycle is currently helping us by the oceans and land ecosystems absorbing over half the excess CO_2 humans are pumping into the atmosphere.[2]

At its political base, though elaboration is outside the scope of this essay, are the growing inequalities of incomes and wealth worldwide, and an economic system whose inherent drivers are incessant expansion, profit-maximization, and an obsession with economic growth. These have been amply discussed elsewhere.[3] Human activity, in general for centuries but in particular for the last 250 years with the establishment and spread of industrial capitalism, has tapped into fossilized carbon as primary energy sources. The burning of coal of varying qualities for long, and later, oil and gas from the 19th century onwards, accelerated parts of the carbon cycle. Carbon dioxide is now being added to the atmosphere at hundreds of times the long-term natural rate. Many ask whether climate change has not happened naturally in the Earth's history, and if so, what is so special about the current changes? The fact is, the current rate of carbon dioxide additions to the atmosphere, and the warming that ensues, is happening at a rate far faster than ecosystems and most species are accustomed to.

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Before we proceed, I might add that I have – for simplicity and want of space – largely focused on carbon dioxide in this essay, and refrained from discussing methane (CH_4), nitrous oxide (N_2O), and other anthropogenic greenhouse gases. CO_2 is the most significant greenhouse gas anyway. It is the most widely emitted from various economic activities worldwide. It has caused the most warming since the Industrial Revolution. CO_2 also has an extraordinarily long lifespan – a portion of it stays in the atmosphere for 100,000 years. While being more powerful warming agents, methane has a lifespan in the atmosphere of 12 years, and nitrous oxide roughly 120 years. The contribution of these other greenhouse gases is calculated as an equivalent of carbon dioxide (CO_2eq) in their capacity to cause warming.

Emissions, Heat Energy, and Where They Go

In 2017, the latest year for which reliable worldwide data is available, human societies emitted approximately 37 billion tons of carbon dioxide (Gt CO_2) from fossil fuel burning, cement production, international aviation, and international shipping.[4] A few years earlier, methane's share was 9 billion tons of CO_2eq, and nitrous oxide and other greenhouse gases, four billion tons of CO_2eq. In 2017, the emissions of greenhouse gases worldwide totalled 53 billion tons of CO_2eq.

Between 1750 and 2011, carbon dioxide emissions from all these sources totalled 1,375 Gt-CO_2. Another 660 Gt-CO_2 were released by deforestation and other land use changes, resulting in total anthropogenic emissions of approximately 2,035 Gt-CO_2 since the start of the industrial era.[5]

Of this, nearly 29% has been absorbed by forests, grasslands, and other land-based ecosystems. Another 28% has been taken up by the oceans, making the oceans more acidic. Ocean waters today are 26% less alkaline than they were around 1750. These 'carbon sinks' are vital. Their absorption rates over the past few decades reveal that the Earth's systems are taking up more CO_2 even as we keep increasing our emissions. However, it would be foolhardy to assume that these ecosystems will play that role endlessly, or to the same extent. Any anthropogenic damage to, or change in them, such as deforestation in the Amazon, or warmer soils emitting CO_2 instead of absorbing it or the southern oceans absorbing less carbon dioxide, currently being studied – would result in these ecosystems taking up less CO_2, thus leaving more of it in the atmosphere and hence adding to global warming.

To return to the numbers, about 880 billion tonnes, or roughly 43% of anthropogenic CO_2 emitted since 1750 has remained in the atmosphere.[6] This 'excess' CO_2, along with methane, nitrous oxide, and other trace greenhouse gases in the atmosphere, partially absorb some of the Earth's infrared radiation and radiate it back towards the Earth's surface. This results in an imbalance in the Earth's energy budget, with more energy coming in from the Sun than leaving the Earth. The Earth will seek to balance its energy budget by warming to the point at which its energy loss to space equals the energy it gets from the Sun.[7]

Atmospheric carbon dioxide levels, which used to be 315 parts per million (ppm) when daily measurements began to be taken in the observatory at Mauna Loa, Hawaii, in March 1958, are in 2019 at an annual average of 410 ppm. What is more, whereas CO_2 levels used to rise at barely 0.5 ppm, going up to 1 ppm annually in the 1960s, they are currently galloping at over 2 ppm/year.[8]

The heat energy these anthropogenic greenhouse gases trap is staggering. "The Earth," says the IPCC, "has gained substantial energy from 1971–2010. The estimated increase in energy inventory between 1971 and 2010 is 274×10^{21} J [joules]." Put more colourfully, as some scientists have, that is the energy equal to four Hiroshima-size bombs every second for the past 50 years. And because a significant portion of the planet is ocean, and primarily because water has a high heat absorption capacity, a very large proportion of that excess heat gets trapped by the oceans, as much as 93%, with the upper oceans alone taking up about two-thirds of this excess heat energy. What is left melts the cryosphere (3%), and warms the Earth's landmass (3%) and the atmosphere (1%).[9]

A Warming Planet and Some Key Impacts

There has been a reasonable coverage of instrumental temperature recordings in many parts of the world since 1880. The temperature on land is measured, in the shade and just above the surface, at tens of thousands of places all over the globe. Floating instruments earlier dragged by ships, and by more comprehensive Argo floats since 2004, at and below the ocean surface, measure temperatures at sea.

Data from NASA's Goddard Institute for Space Studies (GISTEMP) – which is part of IPCC's datasets and is considered the most comprehensive worldwide as it also covers temperatures in the Arctic – shows that the planet was, after accounting for natural fluctuations and as a linear trend, 1.1ºC warmer in 2018 than the 1880–1920 average.[10] A recent report by the WMO, IPCC, and other institutions also puts the rise at “1.1ºC above pre-industrial times”.[11] This rise in the Earth’s near-surface temperature has not occurred in a smooth upward line, it tends to jump in fits and starts, with periods of a lull followed by sudden sharp spikes.

There is more warming in the pipeline. Since much of the heat trapped by greenhouse gases goes into the oceans and gets transported via convection and ocean currents, some of it is yet to surface. Because of this thermal inertia of the oceans, an additional warming of 0.6 ºC, over and above the 1.1ºC already mentioned, is effectively unavoidable. It may well be even higher.[12]

The massive excess energy being absorbed, manifesting as a rise in temperatures, has also had a number of other climatic impacts worldwide. Here, I touch upon just three. Intense, extreme heat, which used to cover barely 0.1–0.2% of the Earth’s landmass in the 1950s, has now spread to 10% of the Earth’s landmass.[13] Two, meta-surveys of hundreds of peer-reviewed studies covering thousands of flora and fauna species found that they are being forced to change their normal habitat range, and also undergo phenological changes, the annual timing of lifecycle events, which is causing havoc to their interdependence. Extinction of a many species due to climate change has also been reported. “Around 1 million species face extinction, many within decades,” a landmark report recently warned us, “unless action is taken to reduce the intensity of drivers of biodiversity loss.”[14] Intensified global warming will increasingly contribute to that mayhem.

Three, the Earth is not just warming, it is also melting. A recent paper in *Nature* revealed that the Earth’s glaciers have lost 9,625 billion tonnes of ice from 1961 to 2016. Most of today’s glacier volume, it states, would “vanish in the Caucasus, Central Europe, the Low Latitudes, Western Canada, the USA, and New Zealand in the second half of this century”.[15] Closer home, the 2019 landmark study by ICIMOD of the Hindu Kush Himalayan ecosystem said that Himalayan glaciers have been receding since the 1950s, particularly in the eastern Himalaya and have faced significant loss of mass since “at least the 1970s”.[16] Arctic ice is melting at rates far faster, and earlier, than climate models had predicted.

Climate Change Impacts in India

Surface temperature in India has risen, on average, by about 0.8 ºC since 1901, based on long-term records and current warming trends. The warming trend in annual mean temperatures has been much sharper since the 1980s, and is currently rising by 0.18 ºC per decade. The rise in both maximum and minimum temperatures has accelerated in India since 1981. Warming is not just limited to India’s surface, but “also extends up to 3 km in the troposphere”.[17] Temperatures rise in different seasons and rates with varying effects. For instance, rise in winter temperatures and summer temperatures have differential impacts on kharif and rabi crops. A rise in minimum temperatures in summer may imply that the urban poor may get little relief even at night during severely hot spells.

Other anthropogenic factors, such as urbanization or increased atmospheric pollutants, also have a role to play in accentuating or dampening warming and, in particular, affecting rainfall in India in various ways. Anthropogenic warming is the only causal factor behind such changes. However anthropogenic warming is going to intensify, whereas urban heating, may be abated by far-thinking environmental policy, as has happened in other countries.

Peer-reviewed studies reveal a range of other climate change impacts in India. Here, we touch upon a few key ones. Their effects on society and some communities in India have recently been discussed elsewhere.[18]

There has been a “statistically significant increase in the frequency, duration, and maximum length of duration of heat waves over India” in the 50-year period between 1961 and 2013, caused, among other factors, by increased sea surface temperatures and depleted soil moisture.[19] Sea level rise (SLR), occurring all over the world, is also happening along many parts of India’s 7,000 kilometre coastline. It is particularly severe for multiple reasons in the Sunderbans in West Bengal.[20] Data from the Sagar Island observatory there suggests that SLR was 3.14 mm/year between 1985–1998, but the relative SLR over the past 25 years has been much higher.[21]

With rainfall, certain changing patterns have begun to reveal themselves. The most crucial, and perhaps worrying, change has been that, over 1901–2012, the southwest or summer monsoon, during which India gets 75% of its total annual rainfall, has reduced in northern, central, eastern, and northeast India, and the southern Western Ghats. In central east India, the reduction is as much as 10–20%. A key factor is a significant rise in sea surface temperature (SST) in the western Indian Ocean, relative to that of India’s landmass.[22] This is reducing the temperature differential that drives the Indian summer monsoon: the South Asian subcontinent used to be 1.2 ºC warmer than the western Indian Ocean in the 1950s, but the temperature difference has been declining since then, and for the last 25 years, the difference has been just 0.8 ºC.

There has been a tripling of geographically widespread extreme rainfall events during 1950–2012.[23] There has also been a significant increase in the intensity and area of monsoon droughts since the mid-1950s.[24] Monsoon variability has also increased over the last few decades. In many places, the timing of rains has become very unpredictable : it rains when it should not, and does not rain when it is needed. In changing rainfall patterns in India, anthropogenic factors other than global warming, such as increased atmospheric pollutants, urbanization, or land use changes, may also have a role to play.

Finally, in keeping with patterns elsewhere in the world, innumerable species in India are having to shift their habitat. Studies by the Central Marine Fisheries Research Institute in Kochi have shown that key fish species such as mackerel and sardines have extended their species range northwards by several hundred kilometres along both coasts as the ocean waters have got warmer. As the Himalayas have warmed significantly above India's average, the ranges of dozens of species, including apples, birds, reptiles, butterflies, and other trees have all shifted higher, moving to altitudes with temperatures to which they are accustomed.[25] Warming of both the land surface and the oceans has also significantly altered phenological patterns in a number of species in India, including spawning in some marine species.

The Recent Science of Attribution

As can be seen from the previous two sections, climate change is demonstrated by trends over time, not single events. However, as extreme events occur more frequently across the globe, there is an important, growing body of work on the science of attribution, which seeks to examine whether the occurrence of a specific extreme event—such as extreme rainfall, drought, or acute heat stress—was made more probable due to anthropogenic climate change. Some of this scientific literature is collected each year in a special issue of the Bulletin of the American Meteorological Society (BAMS). Three studies in that journal that have specific relevance for India are mentioned here.

In the first such attribution study of its kind for India, Deepti Singh et al analysed the intense precipitation that had devastated Kedarnath in Uttarakhand and surrounding states in general in June 2013. It concluded that "the observed and simulated June precipitation provide evidence that anthropogenic forcing of the climate system has increased the likelihood of such an event".[26] In contrast, an attributional analysis of the intense Chennai rains of December 2015 showed no trends in extreme one-day precipitation events due to "a lack of increase in SST [sea surface temperature] in the western Bay of Bengal over the past 40 years", in turn due to the opposing effects of greenhouse gases (causing warming) and aerosols (dampening it). It "precludes an attribution of the floods to anthropogenic factors".[27]

In the same issue of that journal, M. Wehner et al analysed the 2015 heat wave in India and Pakistan, which had caused 2,500 excess deaths in India and at least 700 deaths in Karachi. During a heat wave, the human body may be stressed not just by high temperatures but also by excess humidity : a measure called the 'heat index' captures the effects of both heat and relative humidity on the human body. This study analysed the heat indices for both locations to conclude that they both undeniably had the fingerprint of anthropogenic global warming. "We find," the study concluded, "a substantial human-induced increase (roughly 800%–100,000%) in the likelihood of the observed heat indices… This anthropogenic influence is found to be higher for pentadal [5-day] than daily measures of heat wave severity, with potential implications for human health and mortality".[28]

Centrality of Indian Ocean Warming

A number of studies on the changing climate in India taken together show, that a warmer Indian Ocean is a common factor in phenomena as varied as reduced rainfall in several regions, wider spread of droughts, increased extreme rainfall, longer heat waves, and an increase in the frequency and duration of rainstorms, among others. Some of these have been discussed above.[29] These are undoubtedly complex phenomena, with multiple factors at play. But the centrality of Indian ocean warming to climate change in India, rarely discussed in the non-specialized literature or appreciated by the wider public, needs to be underlined.

The Indian Ocean, like all the world's oceans, is warming primarily because, as mentioned earlier, over 90% of the excess heat trapped by greenhouse gases is taken up by the oceans. A recent paper underlines that Indian Ocean warming has been "particularly pronounced" during 1950–2015, with "anthropogenic causes … contributing over 95% to the trend since the 1950s".[30]

The Indian Ocean is warming more than other equatorial oceans. The western Indian Ocean region, in particular, has warmed by 1.2 ^{o}C over 1901–2012.[31] As Raghu Murtugudde, Professor of Atmospheric and Oceanic

Science and Earth System Science, University of Maryland, and co-author of two of the papers cited above explained, the Indian Ocean also receives heat from other oceans. "If the Southern Ocean warms, then it brings more heat and if the Pacific warms, the Indonesian throughflow brings more heat."[32] As the Indian Ocean takes up more and more heat trapped by greenhouse gases, both by itself and from other oceans, each passing year, one can only infer that its largely deleterious effects, on India's climate will continue to intensify.

Complexity and Urgency

No narrative of the science of climate change would be complete without a discussion of the urgency of the problem.

Central to understanding the urgency of tackling global warming is that the Earth system is complex. The crux of any complex system is that its elements are interconnected, and that the whole is greater than the sum of its parts. The effects of changes in one element of the system could be amplified on others through feedback loops, sometimes in unexpected, non-linear ways.

The most widely discussed feedback in the context of climate change is one that could be triggered by the melting of Arctic summer sea ice. Less ice, whether in the Arctic or elsewhere, implies a reduced reflectivity, leading to greater regional or planetary warming. This might contribute to, say, greater forest dieback which causes more carbon to be emitted, or the release of more methane from the permafrost that extends over a quarter of the landmass in the northern hemisphere. The greater warming in turn could result in more water vapour, a naturally formed greenhouse gas in the atmosphere, or a weakening of the land and ocean sinks discussed above. This means even more warming over time, a further melting of Arctic ice, and so on. After a point, climate change becomes increasingly difficult to control as these feedbacks begin to feed on each other, one amplifying the other, and the two together worsening a third.

A 2018 paper by some of the world's leading Earth system scientists attempted to identify the threshold at which things may get out of our control. They analysed a series of tipping points and planetary feedbacks to suggest that "a potential planetary threshold [that locks the Earth system into a hothouse Earth pathway] could occur at a temperature rise as low as roughly 2 ºC above pre-industrial" levels. Non-linear feedbacks, they argue, would nudge significant ecosystems and the planet itself into states beyond our control.[33] In a recent landmark report, the IPCC has stated that global net anthropogenic carbon dioxide levels would need to fall by 45% (from 2010 levels) by 2030, and reach net zero emissions by 2050, for "no or limited overshoot of 1.5 ºC". They would need to reduce by 20% by 2030 and "reach net zero around 2075", and non-CO_2 emissions would need to "show deep reductions" to limit warming below 2 ºC.[34]

Such sharp reductions are extremely unlikely, but in my view, the scientific community has more than done its bit, by providing robust, detailed science for decades. It is now up to political and economic elites, policy makers and other organizations and voices in civil society, and the climate justice movement in general, to ensure that we rapidly change the transport, electricity, industrial, agricultural, and other systems in equitable ways, and the development trajectory in general, to ensure that we prevent extremely dangerous levels of warming or the planet tipping into states beyond our control. The urgency has never been greater.

Acknowledgements

My thanks to Dr. Chirag Dhara for valuable feedback on this essay, and to Prof. Vandana Singh for clarifying the significance of complex systems in global warming.❐

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