The Physics and Politics of Climate Change

By Alphonsus J. Fagan

Abstract: This essay summarizes the physics of climate change and provides commentary around some of the political challenges faced in mobilizing the actions needed to address it.

Not counting water-vapor the Earth's atmosphere contains 78% nitrogen, 21% oxygen, .93% argon, .04% carbon dioxide, and trace amounts of other gases (as measured by volume). Although the relative concentration of carbon dioxide (CO_2) is small, compared that of nitrogen and oxygen, it plays a disproportionately important role in regulating the Earth's climate. This is because carbon dioxide, along with water-vapor, methane, nitrous oxide, chlorofluorocarbons, and ozone, constitute the atmospheric *greenhouse gases*: so-called because they heat the planet by inhibiting the outflow of infrared (IR) photons from Earth to outer space.

How important are they? They are essential to our survival. For, as the nitrogen and oxygen that make up about 98% of the atmospheric gases only absorb (and reflect) incoming radiation at very short wavelengths (mostly in the upper atmosphere) then, without the greenhouse gases to absorb infrared radiation, the extreme temperatures on Earth would not be much different than what we see on the Moon: about -153^{0}C in the shade and 107^{0}C in sunlight. However, given that (unlike the moon) we have an atmosphere and ocean that can store and move heat around, without our greenhouse gases the average temperature of the Earth (at sea level) would be about -18^0 C[1]: meaning that all the oceans would be permanently frozen to a significant depth, with far less opportunity for the evolution of complex life. Therefore, we can be thankful for having just the right percentage and mixture of greenhouse gasses to keep our beautiful Earth at the relatively comfortable average sea-level temperature of 16^{0}C. By contrast, our sister planet Venus (with its a thick atmosphere of 96.5% CO_2) has a constant surface temperature of about 462^{0}C. And if you think that this hellish climate is entirely explained by Venus being closer to the Sun than Earth, think again; as Venus is 35^0 hotter than the sunny side of Mercury, at about twice its distance from our life-giving star. So yes, the greenhouse effect is quite powerful; and critical to sustaining our ecosystem.

How does it work? In the familiar glass and plastic-covered greenhouses that populate our backyards, the warming occurs because the air trapped inside these structures is not free to mix with the outside air and dissipate heat by convection[2]. Instead, the inside of a greenhouse will continue to heat up until

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[1] NASA's Cosmos. (May 7, 2015). Heating by the Greenhouse Effect. https://ase.tufts.edu/cosmos/view_chapter.asp?id=21&page=1

[2] Convection refers to heat transfer by the flow of material, as when warm air flows from the tropics to higher latitudes. Conduction means heat transfer entirely by the vibration of particles, as when you put a blowtorch on a steel rod and heat slowly spreads to the other end. For example, in a tea-kettle heat flows into the water by conduction, and spreads through the water mostly by convection (hence all the bubbling). Without convection, it would take hours to "boil the kettle" by conduction alone.

the energy outflow by radiation and conduction reaches equilibrium with the energy inflow by solar radiation. It is for this same reason that the inside of your car gets hot in the summertime: and, indeed, this is not a bad model for what's going on at a much larger scale in the atmosphere. The energy arriving from the Sun that reaches the Earth's surface is mostly in the form of visible light (along with a significant amount of infrared, with most of the incoming ultraviolet and higher energy radiation being absorbed in the upper atmosphere). As for what is radiated back out into space from the Earth's surface, this is most at infrared frequencies. And, given that the heat transfer to space by convection[3] and conduction is minuscule, it is only the outflow by radiation (and how it is affected by changes in atmospheric greenhouse gas concentrations) that we need to consider in regard to how the average temperature of the *troposphere* (discussed below under "Atmospheric Layers") - and ultimately the large-scale climate of the planet - will be affected.

As to why certain gas molecules can absorb photons while others do not, it comes down to their shape. If a molecule is asymmetric because it is composed of different kinds of atoms (as is the case for CO_2), the distribution of electrons can also be asymmetric. Such asymmetry in charge distribution means that the atoms will be subject to different forces in different positions within the molecule: which means that, if disturbed, they can *spring back* and vibrate like balls on springs. And, like all objects that can vibrate, these molecules also have certain naturally resonant vibrational modes. Therefore, when a photon with a frequency that matches the difference between two resonant modes comes along, the molecule can absorb it and be kicked into the higher frequency oscillation. And, when the particles are vibrating and jiggling at higher frequencies, this equates to a higher temperature. A familiar example of this type of heating occurs inside microwave ovens. But, in that case, it is mostly the water molecules within the food (and, to a lessor degree, fat and sugar molecules) that play the equivalent role of atmospheric greenhouse gases: such that as these molecules are excited to jiggle and rotate faster, by the absorption of microwaves, the food heats up. And if we increase the amount of water in the food (the equivalent of adding more greenhouse gases to the atmosphere) we see that the food absorbs more microwave energy and gets hotter. The reader may demonstrate this effect by heating a wet and dry cracker in a microwave oven for about 30 seconds and then (carefully) touching them to compare the resultant temperatures.

Another important factor in atmospheric greenhouse warming is that, after a photon is absorbed by a jiggling molecule, it will be re-emitted in a random direction: which means that photons that were originally heading back into space are just as likely to be re-directed downward. And, the net effect is to store more heat in the atmosphere, ground, and ocean.

[3] Although the helium released from party balloons will eventually leak off into space, we are very fortunate that the heavier gases that makeup the atmosphere do not.

Atmospheric Layers

It is also important to understand that greenhouse warming does not occur equally throughout the entire atmosphere, but is instead concentrated in its lowest layer: known as the "troposphere" (from the Greek *tropos* for turning or change). A little background will be useful here. The atmosphere is about 480 km thick and contains five recognized layers, including the troposphere, stratosphere, mesosphere, thermosphere, and exosphere. Although the troposphere has an average thickness of only about 20 kilometers, it is by far the densest layer, containing 75% of the total atmospheric mass.

This segregation of the atmosphere into defined layers is based largely on density variations with altitude, combined with the dynamics of heat-flow. For example, the troposphere is mostly heated from below, which explains why it gets colder as we climb a mountain. However, as we rise into the stratosphere, we find that the temperature stabilizes for a while and then increases with altitude. This reversal occurs because the stratosphere contains a molecule called ozone, which absorbs ultraviolet radiation coming from the Sun, and is thus being heated from above. I will not go more deeply into the physics of the atmospheric layering, as my intent on this point is merely to provide a sense as to why the greenhouse warming is concentrated in the troposphere. The point being that, when we speak of the atmospheric greenhouse effect, we are primarily talking about what's happening within the troposphere (which also happens to be where almost all of Earth's weather takes place). A common analogy for how greenhouse gases of the troposphere slow the release of heat from the Earth is that of a blanket, which keeps you cozy by slowing the release of heat from your body.

The Kitchen Sink

A more elaborate analogy, that is also commonly used to illustrate how the atmospheric greenhouse effect can change, is that of water pouring into a sink with an open drain. If the rate of inflow exactly matches the rate of outflow, it will settle into a state of equilibrium where the water level stays the same. However, if the rate of outflow drops below the inflow, because some obstacle gets stuck in the drain, then the water level will rise until the increased pressure causes the two flow-rates to match. And there it will remain, in a new equilibrium, until something changes. In this example, the inflowing water represents the energy from the Sun, the sink represents the atmosphere, the obstacle in the drain represents greenhouse gases, and the water-level represents the amount of heat in the atmosphere.

I once had it pointed out to me that an increased level of CO_2 in the atmosphere is not a bad thing, as CO_2 is crucial to supporting plant-growth. As well-meaning as this person appeared to be, it took some effort on my behalf to make it clear that I was in no way claiming that greenhouse gases are bad, any more than oxygen or water are bad. But we well know that too much oxygen can poison you and too much water can drown you. And, a plant is unlikely to benefit from a higher CO_2 concentration if the local conditions become too hot or dry to meet its other needs. Measurements show that we have already increased CO_2 concentrations by about 43% over the pre-industrial level, and the buildup will continue until we find ways to stop it. Once again, it is not a question of whether any of the atmospheric gases are good or bad, but how their changing concentration will disrupt the ecosystem – and ultimately human civilization. Or to be blunt: we'd be screwed without the greenhouse gases we have, but by significantly changing their concentrations we will drastically upset the equilibrium that supports our current ecosystem. And, this is likely to have very nasty consequences: many of which we are unlikely to have yet foreseen.

Tipping Points

Although the simplest version of the sink analogy illustrates the central aspects of the greenhouse effect, it fails to capture an important additional element: *tipping points*. For if the system drifts too far from the current equilibrium, it may cross a tipping point where the rising temperature triggers a rapid release of greenhouse gases from the soil and ocean, resulting in an accelerated and more acute climate swing. In other words, it is as if the blockage in the sink was to increase in size if the sink filled with water beyond a certain point.

Have extreme changes occurred in the past? Yes, there is ample evidence in the geologic record of dramatic swings in climate: ranging from the so-called *snowball Earth* of 650 million years ago (when glaciers covered most of the planet), to the *hot-house Earth* of 56 million years ago (when the north and south poles reached subtropical conditions). In the latter case, it was not the "day at the beach" one might imagine: as the associated droughts, floods, and insect plagues changed the course of evolution. Although it is clear that events like asteroid impacts and the eruption of super-volcanoes, which launch huge amounts of dust into the atmosphere, can have a sudden and major effect on Earth's climate; as the dust settles, it is the concentration of atmospheric greenhouse gases that is the more long-term determinant.

Water-Vapor

Notwithstanding the high public profile of CO_2, it is water-vapor that accounts for the greatest proportion of the greenhouse effect (about 60%), because of its much higher concentrations compared to the other greenhouse gases. So why don't we talk more about water-vapor pollution? In a nutshell, it's because water is condensable into its liquid form at typical atmospheric temperatures and pressures, while the other greenhouse gases (like CO_2) are not. What this means is that, with a small drop in temperature, water-vapor condenses and falls as rain. But for CO_2 to condense into dry ice[4], the temperature would have to drop to -78^{0}C. In effect, the amount of water-vapor in the air is highly dependent on temperature—and ranges from about .01% to 5%, averaging about 1% at sea level.

[4] Carbon dioxide cannot condense to a liquid form unless cooled at a pressure of about five atmospheres. In that case, it condenses at -57^{0}C.

What this amounts to, is that the atmospheric concentration of water-vapor does not so much drive the greenhouse effect as it is driven by it. Considering its condensability, a water molecule has an average atmospheric residence-time of just a few days: which is crucial to maintaining fresh water supplies and supporting plant growth. But of equal importance, is that rapid recycling prevents a continuous buildup of water-vapor and the runaway greenhouse effect it would bring. Conversely, it is the very slow re-cycling of non-condensable greenhouse gases like carbon dioxide (with an average turn-over rate per molecule in the hundreds of years) that allows them to build up in the atmosphere and punch far above their weight. We may also consider the empirical fact that: in order to have had a "snowball Earth" phase in the past, with essentially the same amount of water that we have today, then some other process must have been the driver of climate change. Current theories credit our escape from snowball Earth primarily to the release of CO_2 from volcanoes, with more coming from the ocean as the ice retreated; and, the process was likely augmented by the release of methane that had been trapped under the ice and in the soil.

The Short-Term Carbon Cycle

The main mechanisms of short-term removal of CO_2 from the atmosphere are by photosynthesis (carbon dioxide + water + sunlight → carbohydrate + oxygen) and by direct absorption at the air/ocean interface. Carbon dioxide is readily dissolved in water, which has led to most of the Earth's free carbon (i.e., which is not bound up in rocks), being stored in the ocean. Cold water is better at storing CO_2 than warm water: hence, the atmospheric CO_2 tends to be absorbed into the ocean near the poles and released near the equator. In addition to what's going on at the ground and ocean interfaces, carbon dioxide is also removed from higher in the troposphere by combining with water droplets to form carbonic acid (H_2CO_3), which falls as acidic rain. The net result of all these interactions is an ongoing *carbon cycle* that can maintain a relatively stable concentration of atmospheric CO_2, unless some significant new factor is introduced to the push system out of equilibrium.

Ocean Acidification

Some of the carbon that is directly absorbed into the ocean from the atmosphere also reacts to form carbonic acid, which combines with acidic rain to create a more acidic ocean: which has major consequences for marine life. For example, a more acidic ocean can directly kill or dissolve the shells of certain species of phytoplankton—which (very significantly) lie at the base of the marine food chain. And, given that phytoplankton are also responsible for re-charging about half the oxygen in the atmosphere, a more acidic ocean presents a long-term threat to our oxygen supply. It's estimated that the average acidity of the ocean has increased by thirty percent [5]since the beginning of the industrial age, and we're on track to more than double it by 2100.

The effect of changing the temperature and chemistry of the ocean is already being observed, on a large scale, for coral reefs. Corals get about 95% of their food via a symbiotic relationship with marine algae that live within them and convert sunlight into nutrients; while the algae are provided shelter and food (in the form of biological waste) by the corals. However, a changing ocean temperature and acidity causes the algae to release toxins, which then trigger the corals to eject them in a process called *coral bleaching*: which breaks the symbiotic relationship and starves the corals. The effect of coral bleaching is illustrated in Figure 1, where the healthy reef resembles a colorful oasis of biodiversity – whereas the bleached reef might well be described as an ocean desert.

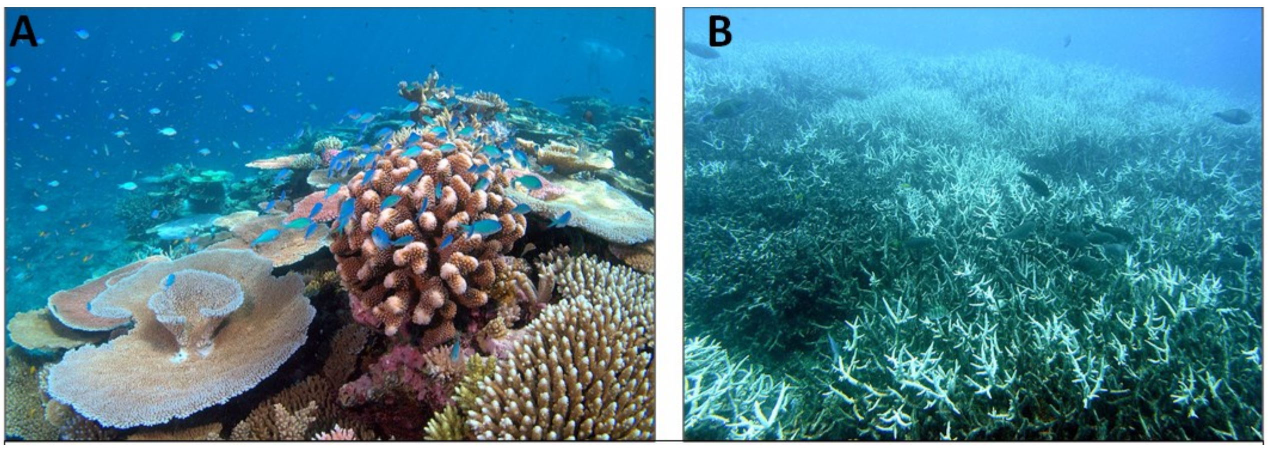

Figure 1: (A) Photograph of healthy coral and **(B)** bleached coral. Coral bleaching is driven by changes in the temperature and acidity of the water in which the coral and their symbiotic algae evolved. *Image sources, Wikipedia Commons. A: User Holobionics. B: User Acropora*

The reef may recover if normal conditions return within a year or two. But if not, it will be gradually disintegrated by waves and currents, as the rate of coral erosion exceeds the rate of re-growth. Although we tend to focus on the more direct discomforts to ourselves that will come with global warming, the widespread destruction of coral reefs, which serve as nurseries to about one-quarter of all marine species, may prove be the *canary in the coal mine* for more dangerous consequences. In April 2017, scientists at Australia's James Cook University reported that after experiencing the two hottest summers on record, about two thirds (1500km) of the Great Barrier Reef had undergone coral bleaching for two

[5] CO2 and Ocean Acidification: Causes, Impacts, Solutions; Union of Concerned Scientists, https://www.ucsusa.org/global-warming/global-warming-impacts/co2-ocean-acidification

consecutive years[6]. And, a 2019 article in Nature[7] reported that the coral larvae population of the reef was down by 89% compared to historic levels: clearly an ominous signal.

The Long-Term Carbon Cycle

In the longer-term carbon cycle, which typically plays out over millions of years, carbon is removed from the ecosystem by both chemical and organic processes. Where carbonic acid falls on land, it weathers silicate rocks and thereby bonds carbon from the atmosphere with clay minerals that are eventually deposited on the seabed. In seawater, carbon can directly bond with minerals, such as calcium and magnesium, and precipitate into solid grains that fall to the seabed like snow and gradually coalesce into layers of carbonate rock. Carbon is also used to build the bodies of a great variety of organisms, including shellfish: the hard parts of which accumulate on the seabed, and also form a significant component in carbonate rocks. Although the carbon contained in the soft tissue and excrement of most marine organisms is recycled (when eaten by predators and bacteria), significant amounts of organic material can be sequestered when seasonal blooms of marine algae and plankton die, sink, and settle into the mud. When such organic-rich mud is located in stagnant anoxic conditions, it can be buried by further sedimentation, and (over millions of years) become the source-rock for oil and gas deposits. Plant material captured in anoxic swamps on land, and buried in the same way, is transformed into coal and methane.

Such bonded and buried carbon can eventually be re-introduced into the atmosphere tens or hundreds of millions of years later by: the weathering of carbonate rocks, volcanic eruptions, or the natural burning of coal seams and evaporation of oil and gas deposits that have been exposed by tectonic uplift and erosion. It is this too-and-fro between periods of carbon burial and release, at varying locations and times that backstops the long-term carbon dioxide levels in the atmosphere and sustains major climate trends.

The Carbon Economy

The big carbon-related challenge we face today is that, for the past couple of hundred years, we've been pushing the ecosystem out of equilibrium at an unprecedented rate by removing carbon from the subsurface in the form of coal and petroleum, and releasing it (along with some other pollutants) as CO_2 exhaust from our automobiles, planes, ships, and power plants. To provide a sense of scale, the typical

[6] James Cook University website: https://www.jcu.edu.au/news/releases/2017/april/two-thirds-of-great-barrier-reef-hit-by-back-to-back-mass-coral-bleaching

[7] Hughes, Kerry, Baird et. al.: April 3, 2019: Global Warming Impairs Stock Recruitment Dynamics of Corals: https://www.nature.com/articles/s41586-019-1081-y

car emits about 5200 kg of CO_2 per year along with about 300 kg of other pollutants[8]. Now, consider that there are currently about 1.5 billion automobiles in operation around the world, with projections to double over the next twenty years, and you get a sense that something significant and unprecedented is in play. Besides the exhaust from transportation, manufacturing, power production and certain types of farming, we are also faced with the compounding effect of increased deforestation: which not only reduces the ability of the ecosystem to remove carbon from the atmosphere, but can also put additional carbon into the atmosphere (if the burn and decay rates of trees and plants outpace their rate of re-growth). Of the 36 billion tons of human-sourced CO_2 emitted in 2015, 41% came from the burning of coal, 53% from the burning of oil and natural gas, and 6% from the grinding and heating of carbonate rocks to make cement[9].

According to physicist James Hansen (of Colombia University), we are currently infusing CO_2 into the air at a far greater rate than natural processes have done in tens of millions of years. Even volcanic eruptions, which are one of Nature's more effective means of returning carbon to the atmosphere, are dwarfed by our output: equating to less than one percent of human emissions[10]. Current estimates are that we are releasing about 37 billion tonnes[11] per year of CO_2 into the atmosphere: a mass of carbon (i.e., not including the mass contribution of oxygen) that is equivalent to a cube of coal 2.25 kilometers on each side. As to the fate of all this newly released carbon, it is clearly not escaping into space. And, to those who claim that this is all part of some cycle, I am compelled to ask: When do we enter the down-phase, where our cars and smokestacks start breathing in CO_2 instead of spewing it out?

Scientists can reconstruct the Earth's climate history by a variety of means. And the record does indicate significant longer-term and shorter-term climate cycles driven by increased volcanic activity, wobbles in the Earth's rotation axis, changes in solar output, and changes in ocean circulation. On this, we can point to the Medieval Warm Period (between about 950 and 1250) and the Little Ice Age (between about 1300 and 1850) as examples of significant shorter-term climatic variations. But even these widely-cited examples were not global events, but restricted to the North Atlantic Ocean and surrounding lands in north-west Europe, Greenland, Iceland, and eastern North America. Considering longer-term global trends, over thousands of years, it's even possible that the increased CO_2 emissions that began in the 1800s might have prevented an oncoming ice age, which we may count as a benefit. If this is the case then it’s well and good. But, like wine and ice-cream, too much of good thing can also be a bad thing.

[8] US Environmental Protection Agency, 2000. To get an estimate of how much CO_2 your car emits consider that each tank of gasoline contains 45 to 60 liters (12 to 16 gallons) depending on the size of the car. This amounts to about 35 to 46 kg (77 to 101 lbs), which is predominantly carbon by mass. As each carbon atom (atomic weight 12) combines with two oxygen atoms (atomic weight 16) from the atmosphere, the mass of CO_2 (molecular weight of 44) produced is 3.66 times the weight of carbon burned. Thus, a typical tank of gas puts about 125 kg (275 lbs) of CO_2 into the atmosphere. The hydrogen that was originally bonded to the carbon is also bonded to oxygen after burning to form H_2O.

[9] Carbon Dioxide Information Analysis Center: https://cdiac.ess-dive.lbl.gov/

[10] US Geological Survey: http://volcanoes.usgs.gov/vhp/gas_climate.html

[11] Global Carbon Project: https://www.globalcarbonproject.org/

As to the fate of this additional carbon: according to NASA, about half of what we currently release gets absorbed into oceans, forests, and grasslands (which represents a significant mitigation to atmospheric effects). But it remains unclear as to when these carbon sinks will reach a point of saturation.

Our best models indicate that we need to turn things around very soon, or we may reach a tipping point, where increased temperatures result in the catastrophic release of huge reservoirs of methane (CH_4), currently frozen as methane-hydrate just below the surface in the Arctic tundra[12] and also within seabed sediments. In this, it is clear that a temperature increase, which may have been initiated by any cause (such as increased solar output), may subsequently be carried to an extreme because of the extra carbon it causes to be released from the soil and oceans. Indeed, the data indicate several past hot-cycles where the temperature-increase at first led the increase in CO_2 concentration and subsequently followed it.

How dangerous is the methane-hydrate tipping point? **Very dangerous!** As the amount of carbon involved rivals and may surpass the carbon stores of all the world's conventional oil, gas, and coal reserves. Recent reports of methane bubbling out of Siberian lakes "like Jacuzzis", and large gas bubbles exploding out of the tundra, indicate that significant Arctic methane release has already begun. Although methane only stays in the atmosphere for a decade or two (before breaking down into CO_2 and H_2O), while present it is 20 times[13] as effective per molecule at trapping heat as carbon dioxide. Compounding these effects, as the temperature of the atmosphere increases so does its capacity to hold water-vapor (equating to an additional seven percent for each increase of one degree Celsius): which then absorbs even more heat than the carbon dioxide and methane that are driving the system out of equilibrium.

According to NASA's Goddard Institute for Space Studies, the average global temperature increased by 0.8^0C (1.4^0F) between 1900 and 2014, with two-thirds of the increase occurring since 1975. Although this may sound like a small number, a change of just a couple of degrees in the average temperature of the entire Earth can have major consequences. And since the ocean warms more slowly than the continents, we will see much larger increases in temperature on land then the global average. NASA also informs us that the Earth's average temperature has increased between **4 and 7 degrees Celsius**[14] since the last ice age: a change that took **7000 years**. By comparison, current models indicate that the Earth will warm between **2 and 6 degrees Celsius** over the next **one hundred years,** if we are not successful in curbing carbon emissions. Yes, things could change drastically and very fast!

Rising Seas

The interaction between a hotter atmosphere and the ocean represents a powerful feedback loop that makes our challenge all the greater. It is because water has a much greater heat capacity than air (i.e.,

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[12]Source: IMPACTS: On the Threshold of Abrupt Climate Changes, Paul Preuss, Berkley Lab: https://newscenter.lbl.gov/2008/09/17/impacts-on-the-threshold-of-abrupt-climate-changes/

[13] Source: IMPACTS: On the Threshold of Abrupt Climate Changes, Paul Preuss, Berkley Lab: https://newscenter.lbl.gov/2008/09/17/impacts-on-the-threshold-of-abrupt-climate-changes/

[14] How is Today's Warming Different from the Past? https://earthobservatory.nasa.gov/Features/GlobalWarming/page3.php

ability to absorb and store heat), that the oceans play such an important role in regulating the Earth's temperature[15]. About 93% of the additional heat from increased greenhouse gases in the atmosphere gets stored in the oceans, with melting ice absorbing 3%, and 4% going into the continents and atmosphere[16]. To put it into perspective, a 2020 report[17] from the Chinese Academy of Sciences indicates that the ocean has absorbed the energy equivalent of 3.6 billion Hiroshima-type bombs in surplus heat over the past 25 years, because of global warming: which averages to 4.5 such "atomic" bombs per second.

Although the oceans ability to absorb such vast amounts of heat has a moderating effect for us land animals, it also causes the ocean to expand—which combines with melting icecaps to raise sea-level, flood coastal regions, and pollute aquifers and low-lying freshwater lakes. The moderating effect of the ocean on atmospheric temperature also has the potential to lull us into complacency: but the effects will accelerate, as the seas become hotter and the atmosphere becomes more humid. And, along with the effect of increased humidity in increasing the heat capacity of the atmosphere, we have an additional feedback mechanism in that as the icecaps shrink, the photons they would have reflected back into space get absorbed by newly exposed ocean and land. These effects will multiply as we go further down this road; and there appears to be little, beyond our actions as individuals and as a species, that can slow the change to our ecosystem and eventually reverse it.

What Are We to Do?

The hope is that we can stop the rise in temperature before any major feedback process kicks in, and takes the whole thing out of our hands. Finding a way to stabilize the climate (and address the associated acidification of the oceans) is the great environmental challenge of our age, and will likely be the case for several generations. Delaying action will make things more difficult in our own time—and potentially devastating for those who come after us. Notwithstanding the extinction of other species, a major change in climate is likely to make parts of the planet, in which billions of people have settled, effectively uninhabitable: because of a rising sea-level, heat, drought, pests, and the drying up of glacier and snow-fed rivers.

Desperate people will take desperate measures, greatly increasing the risk of war over necessities like drinking-water – and also resulting in an unprecedented and overwhelming refugee crisis. It would seem that since we understand the basic physics of the situation, it would make more sense that we look for ways to prevent a climate swing than to be the agents of its acceleration.

[15] Without greenhouse gases the oceans would eventually freeze and reflect energy back into space rather than store it.
[16] National Geographic, "The Climate Issue", November 2015
[17] Institute of Atmospheric Physics, Chinese Academy of Sciences: http://english.iap.cas.cn/RE/202001/t20200114_229373.html

Denial?

To those who honestly believe the entire climate change and ocean acidification issue is a "hoax", I suggest that you seriously consider this question: What evidence would be sufficient to convince you of its reality? If the answer is something like: a sudden one-meter rise in sea level; a massive die-off of species; or an additional one-degree increase in worldwide temperatures—then it will already be too late for your opinion to matter in helping to address the issue. And yes, your opinion and your voice most certainly do matter in influencing what you and your neighbors do, and what our various levels of government are empowered to do.

And yet you remain skeptical? Fine. Maintaining a healthy degree of skepticism is a useful practice. But on critically important questions, where you absolutely must get it right, it also demands some very careful work. For, if you genuinely want to make an informed judgment, the first thing to do is seek out credible[18] sources of information with a strong track record of integrity and a minimal conflict of interest. In other words, don't go to the tobacco industry for information on the health risks of cigarettes and don't go to the coal industry for information on the relationship between fossil fuel use and climate change. And *never* accept a position on an issue simply because it is the position of a favored political party or politician. For, to do so is to forfeit your freedom and **responsibility** to reason for yourself: which are essential ingredients in the maintenance of a free and successful society. As it goes, there is a strong tendency for a certain type of person who seeks political power—at any cost—to oversimplify issues and to conflate ideas that have nothing to do with one another. And, it is only our ability to call them on their BS that prevents us from being led down a rat-hole.

For example: Why should your position on climate change be in any way linked to your position on who is allowed to own a machine gun? These are markedly unrelated issues that require independent analysis by experts in very different fields of knowledge. Without such independent analysis, good ideas can be stymied by their political baggage, while bad ideas can be advanced because of unexamined populist appeal. Whether this tendency (of certain politicians) is rooted in ignorance or unmitigated power-lust, the result is often the same. The water gets muddied, the facts drowned in facile rhetoric, and the population is significantly the worse for it.

Having worked my entire career in the petroleum industry, I was originally quite skeptical of the significance of human-induced climate change. But, having done considerable reading on the physics behind it and the evidence for it, I could not help but change my mind. The greenhouse effect is real and easily demonstrated in the laboratory by measuring how different mixes of gases exposed to sunlight absorb and store heat. Carbon dioxide is a greenhouse gas that is blown out of our exhaust pipes and

[18] Two of the most respected scientific agencies in the world, the Royal Society and the US Academy of Sciences joined forces to produce this clear and concise report on the issue of climate change: https://royalsociety.org/-/media/Royal_Society_Content/policy/projects/climate-evidence-causes/climate-change-evidence-causes.pdf. Also, the US National Oceanographic and Atmospheric Administration is home to many top experts on climate and weather: https://www.noaa.gov/resource-collections/climate-education-resources

smokestacks by the billions of tons per year, and is accumulating in the atmosphere at a measurable rate. We have already reached a CO_2 concentration beyond anything that has existed in millions of years. So, just considering these basic facts, it would be rather surprizing if the atmosphere and oceans were not getting hotter. And really, what else does one need to know?

Unfortunately, we are now seeing direct evidence writ large in melting icecaps, more frequent occurrences of intense weather and wild-fires, large-scale coral bleaching, hotter atmospheric and ocean temperatures, pole-ward migration of tropical species, and so on. It is clear that we need to act decisively at both an individual and societal level to wind down the use of fossil fuels, mitigate the changes that are unavoidable and, in time, remove a good deal of the surplus greenhouse gases from the atmosphere.

Perhaps it was inevitable when we emerged as the planet's *thinking species*, that it would eventually fall to us to become the custodians of its ecosystem; which we now know can be catastrophically disrupted by both terrestrial and extraterrestrial processes. Let's hope we can become wise custodians, as the alternative is not something I want to contemplate for humanity and many of our co-traveler-species on “the good Earth”. As for those who assert that there is simply no evidence that will ever convince you of the challenge we face: you have, by definition, closed your mind. And, given that we live in an ever-changing world, that demands constant learning and adaptation, this is most definitely not a good thing for you, your family, or your community.

Reason vs. Emotion

In my efforts herein to present evidence and appeal to reason, I am fully aware that there are many who instinctively reject anything that challenges their worldview. After all, changing our minds can be emotionally difficult and may even put us at odds with friends and colleagues who may see us as "defecting to the other side". But it bears repeating that Nature rolls with the laws of physics, and does not bow to our politics, religion, ideologies, or feelings. And if our beliefs and actions are out of sync with reality, then reality can bite back hard.

The advantages of preserving the worldwide ecosystem, upon which we all depend, should not be a hard-sell. For, along with the avoidance of pain, there's the bonus of new business opportunities that arise with the development of new technologies. After all, it is not about "getting off energy" as some dissemblers like to characterize it, but of finding new ways to produce energy that do not "mess our nest". Given the facts, there really should be no reason that bona fide conservatives and liberals cannot agree on the nature of the problem, and focus the debate to where it needs to be: on finding the best solutions. Of course, there is—as always— the tribal aspect of politics to contend with: so deeply rooted in our more-base instincts and so avidly exploited by demagogues seeking power for power’s sake. But frankly, if you as a competent and responsible individual are going to go tribal on an issue, or cast doubt for purely emotional reasons: **This is not the issue!**

Whatever your politics, it will be useful to consider two scenarios: (1) The climate scientists turn out to have been right, but we did nothing? Or (2) The climate scientists turn out to have been wrong, but we accelerated development of non-polluting energy sources? On balance of risk vs. reward, the choice should be obvious: especially when we get only one chance to get it right. Afterall, the downside of curtailing our fossil fuel use is a possible (but not guaranteed) reduction in economic activity for a period of time: while the downside of inaction against climate disruption is an imminent and accelerating threat to the very ecosystem that sustains us.

In addressing economic risk, we may also consider the following question: Is it likely that the wide-ranging respect for the "rule-of-law" that underpins what we call "civilization" will endure as billions of people all over the planet face drought, intolerable heat, pests, wildfires, and famine? In a word, no. The more likely outcome will be mass civil unrest, war, and a refugee crisis of horrendous scale. And, facing such conditions, the worldwide economy will not only contract but will (more likely) suffer complete devastation: clearly, not the legacy we want to bequeath to our children and grandchildren.

All told, the rational choice on such an existential question should be clear. And, as for those who think that their riches will shelter them from whatever horrors may come, they'd do well to heed the lesson of Poe's "The Masque of the Red Death": where in the end "darkness and decay and the red death held illimitable dominion over all".

Alphonsus Fagan is a retired geophysicist, Fellow Geoscientists Canada, and author of "Mind Openers 1.0: A Conceptual Review of Modern Physics" and "Mind Openers 2.0: A Conceptual Reinterpretation of Modern Physics"