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Gigatonne Carbon Dioxide Removal Can Reverse Global Heating Trend

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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Review Article

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ABSTRACT

It is a surprising realization to many that a changing temperature *tightly* correlates with the carbon dioxide (CO2) levels worldwide in a linear, lockstep manner with a reversible but very short temporal feedback loop of only a few decades. A mapping of the past 400,000 years of earth's climate history by Hansen, based on the Vostok ice core sampling, offers a glimpse into this remarkably tight relationship between CO2 and global temperature levels but also the average sea level over four ice ages that are clearly delineated in his historic depiction of all three quantities. As his Table accompanying the graph is analyzed, an equation linking the three variables has now been generated, yielding a fresh view into how past decades of hundreds of gigatons of atmospheric increase will continue to affect a worldwide temperature rise, also called "global warming." The implication that is inescapable from such an analysis is that the presently stored CO2 level, far surpassing by over 40% those present in 1950, is the real cause of the physics "heat-trapping effect" seen worldwide. (Note: US tons are 0.907 of metric tonnes and both are used in this article.) Research accomplished in this review point to the heat-trapping property of CO2 as the major contributor to increasing heat worldwide and lead to the prediction of how much higher global temperature will rise if left unchecked, with the level of CO2 over 40% higher than it has ever been in more than 400,000 years. The proposed solution offered in this review is to initiate a 40 gigatonne carbon dioxide removal (CDR) annually in order to stabilize atmospheric CO2, to be followed by an expanded CDR effort toward a goal of 100 gigatonnes/year to begin reversing and lowering global temperature.

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Keywords: Carbon dioxide; global temperature average; gigatonnes. ice core record.

1. INTRODUCTION

"The 2022 summer caused China's heat wave to shatter records, bringing hydropower electricity into question, while in the U.S., it delivered five 1,000-year rain events in five weeks to several Midwest United States" [1]. For the first time in history, global population has tripled (3 times = "3x") within less than one 70- year lifetime (mine in particular), with another 50% increase expected by 2100 up to 11 billion (see Fig. 1). Following suit, global annual carbon dioxide emissions *growth rate* has quadrupled (4x) since 1950 and global energy demand has quintupled (5x), all in the same time period. This **3-4-5 triad** has wrecked havoc on the environment, most notably in the past few decades. More importantly, the energy demand at 5x is outstripping the other two and pulling them along, figuratively speaking, to catch up to the leader: the global demand for more and more energy, seen historically in every major society that has grown and declined.

This clearly means that as the population explodes at 3x, those young people also want more than the usual share as fossil fueled generators spread around the globe and modern conveniences including added air conditioner, become more and more desirable. Furthermore, with increasing global warming, Rocky Mountain Institute has predicted that soon, *a billion* new window-mounted air conditioners, each using a kilowatt on the average, will add even more burden to the increasing energy demand by 2050.

Besides all of these inconvenient megafacts, what really matters to everyone is how it will affect us personally. All of the images in this article are taken from a *slideshow that I gave in November, 2019* at Tufts University for the **IEEE** Science and Technology Society conference **(ISTAS).** In the first figure, we see the 3-4-5 triad emphasized on the left and the source of the problem graphically illustrated on the right, which is very revealing. The important takeaway here is the difference between the World Population (say, Quantity "P") and the RATE of change of that Quantity per Time (this slope = $\Delta P/\Delta T$). What is super valuable to us concerned with climatology in this double illustration graph is that the $\Delta P/\Delta T$ rate for population has reached its peak of growth way back in 1975. However, the World Population Quantity P will not be reaching its subsequent peak until a projected date of around 2100, as the $\Delta P/\Delta T$ rate continues to visibly decline as P slowly levels out over 100 years later. If I was still teaching community college environmental science, I would tell the class at this point: "Remember this unfortunate ***one century delay*** between the PEAK of a slowly changing growth RATE and the PEAK of the actual Quantity itself, when the number in the set is very large."

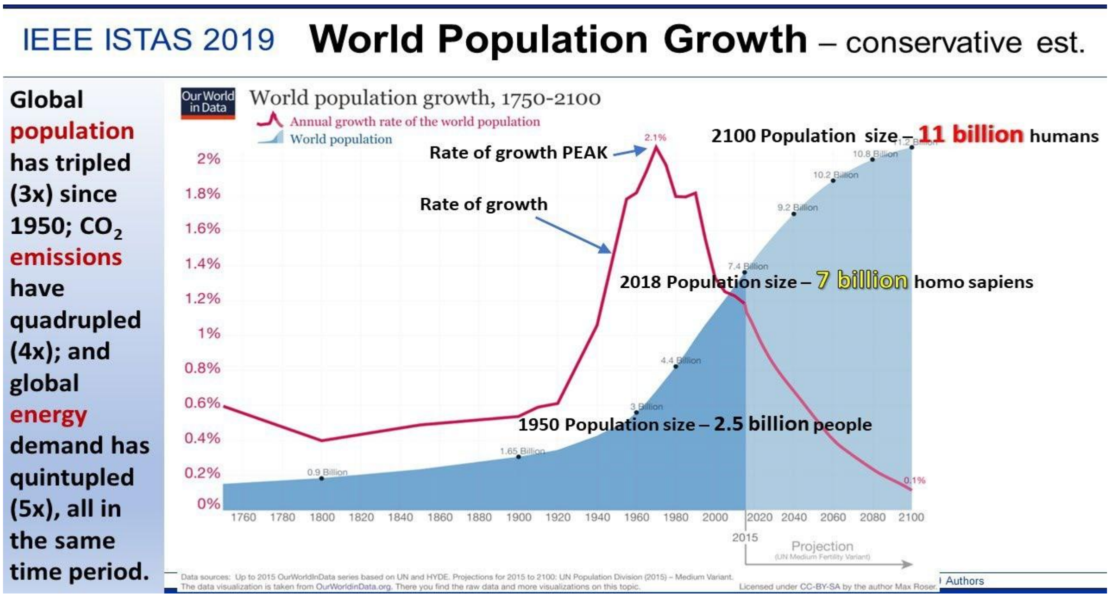


Fig. 1. World population growth [2]

It should be obvious from this image that the 4x CO2 emission rate since 1950 and the 5x energy demand since 1950 are intimately connected to the 3x global population growth. So, let's look at the consequential CO2 emission details to get a feeling for the physics which are somewhat hidden to most of the world at this time. Climatologist **Dr. James Hansen** (from NASA Goddard) predicted in 1988 the one degree Celsius increase in global temperature for 2019, which we are now realizing worldwide. Recently called the most accurate 30-year climate projection that any climatologist has achieved, James Hansen's famous paper of 1988 was *the very first* to contain predictions of a global "greenhouse effect" from a 3-D model developed at the NASA Goddard Institute for Space Studies but using the onerous phrase "climate forcing" [3]. Since such a concept was not yet accepted by the public, the paper was shunned by academic critics and Hansen was declared to be "wrong" by most of the media at the time.

For that 30-year anniversary of his 1988 article (the first of its kind, using NASA's computer climate modeling), I wrote a long 32-page article and published it in the *International Journal of Environment and Climate Change* in 2019. In it I even included a school teacher's flood lamp experiment and graph of the heating of two soda bottles half filled with water and one with an Alka Selzer tablet dissolved in it. It becomes crystal clear that a little bit of CO2 added to the air from the dissolved Alka Selzer in the soda bottle drove the final temperature to 44˚C, since CO2 is a "heat-trapping gas", while the clean air bottle settles down and levels out at 35˚C. It provides irrefutable evidence for students that only the carbon dioxide makes the difference in how much heat is retained in a closed system from incoming radiant energy, like the sun.

Now comparing the first illustration of Fig. 1 for World Population Quantity and the Rate of Global Population growth per Time to this second illustration of World CO2 Emissions Quantity and the Rate of Global CO2 Emissions growth per Time, it is disturbing to most of environmentalists to see the continually INCREASING rate on the right, which now in 2020 surpasses even the 1975 peak population growth rate of 2.1% with no sign of slowing down or reaching its own peak. From this double graphic illustration, any climatologist can speculate that such a large system will not peak for decades to come, since any change in a global phenomenon is gradual. Furthermore, the CO2 emissions QUANTITY peak is reasonably projected to be at least 100 to 150 years in the future, from the behavior of the intimately connected population graphs of Fig. 1 which actually causes the Fig. 2 data. This scientific conclusion of such a systems behavior is a difficult concept to work around or argue against. Everyone in the world is under an apparent misconception that the CO2 emissions Quantity is immediately controllable with a little more renewable energy adaptation to replace fossil fuel usage, which somehow magically will keep global warming under a tiny one degree or two of change. This brings up the purpose of this article:

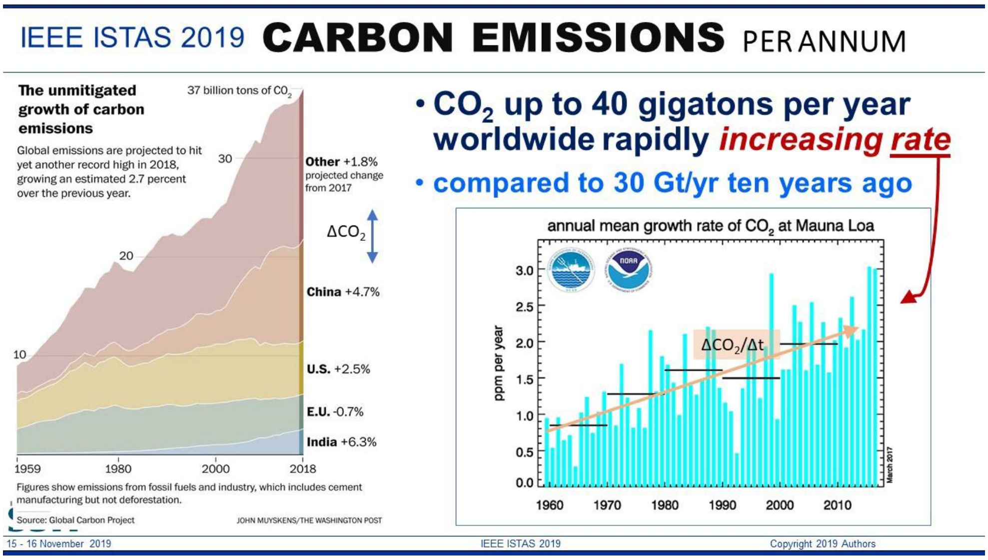


Fig. 2. Rate of change for CO2 emissions per year [4]

Explain the actual control for atmospheric CO2 levels and what can bring global temperature into a stable region of the pre-industrial age.

In that regard, it may be more understandable to the reader what Hansen also discovered in 2006 which he published in MIT's *Technology Review*. Hansen found a little-known *linear relationship* between CO2, temperature, and sea level rise in the Vostok ice core data for the past 400,000 years, which can be applied today. He made it clear that the baseline maximum CO2 concentration for almost a half million years or so was *290 ppm*, which we got used to up to the Industrial Age. However, now in 2020, we were experiencing a surprisingly increasing level of CO2 that has surpassed 410 ppm, with its rate of growth ALSO increasing.

What Dr. Hansen did for scientists like me was to tell us the details of the linear relationship between CO2, temperature, and sea level rise which also gave us quantitative, locked-in estimates of temperature and sea level rise for the coming centuries. While consequential global warming due to the projected doubling and tripling of the greenhouse gas content of the atmosphere is clearly destined, there still are minority numbers of climate deniers controlling major policies in the United States and elsewhere. Recently a 30% drop in the publication rate of the phrase "climate change" has been noted from US government publications, even in the midst of record-breaking heat, fire, and drought.

2. TEMPERATURE TRACKS CO2 LEVELS

It is a surprising realization to many that global temperature *tightly* correlates with and tracks the CO2 levels worldwide, in a "lockstep" with a very short temporal feedback loop. The most convincing for me was to see the Vostok 420,000 year record in Fig. 3 of both variables matching each other's lead on the same graph. It clearly does not matter which appears to change first (which is a really assuring relationship as we will see later in this article), since the other will invariably follow.

In Fig. 3 is "a plot of the world average temperature and CO2 data from air bubble analysis of the Vostok Station Antarctica ice core. In 1999, the Vostok ice core 420,000-year record of carbon dioxide" was published by Petit et al. [6] "*Exhibiting great stability, the CO2 levels clearly have never exceeded 290 ppm worldwide even through four ice ages.* However, in the isolated monitoring station cited above for our modern, with our wanton fossil fuel carnage, the latest global carbon dioxide levels have now exceeded 410 ppm, with apparent disregard for the consequences. Notice in Fig. 3 the important clearly tight correlation of temperature (blue graph) and carbon dioxide (red graph) for the

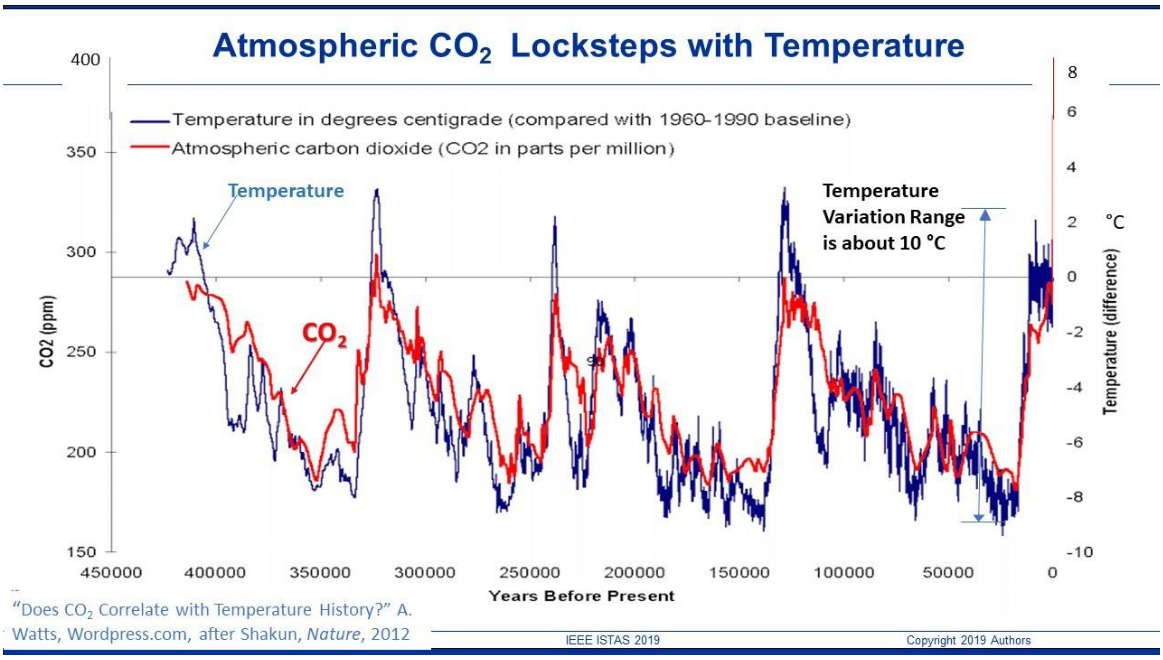


Fig. 3. Global average temperature tracks CO2 levels [5]

past 420,000 years, which leads us to the obvious problem of the red line at the end (present time)" [6]. If we are forced to admit the historic red and blue data lines don't lie, then the axis label of CO2 concentration on the left necessarily correlate to the axis label of global temperature on the right. This is, to me, the most important realization and conclusion for the reader to grasp from this article. While climatologists know this relationship exists, the United Nations Environmental Program (UNEP) and the International Panel on Climate Change (IPCC) among others are clueless or simply choose to ignore the consequences of the present CO2 excess, which now surpasses 40% of the maximum 290 ppm the earth has ever experienced in over 420,000 years. It is vital that the reader comprehends the blatant fact that we are indebted for at least 8 degrees C increase in temperature, which will manifest approximately by 2100, unless something drastic is done to reduce the amount of carbon dioxide in the atmosphere globally, as compared to simply reducing emissions which cannot have any major effect in reducing global temperature except in the long term. Before we explore these two differences, let's look at the corroborating evidence that Jim Hansen brought to the table in 2006.

While Petit et al. show us the correlation for CO2 and temperature, Hansen brings in the sea level data as well in Fig. 4. You can also see that even in 2006, the CO2 value of 377 ppm was already shooting way above the millennial maximum of 290 ppm (regarded as the baseline). I have inserted the similar graph from the National Oceanic and Atmospheric Administration (NOAA) as well to show that they are all speaking the same language. While sea level also tracks the other two variables of CO2 and temperature, it has a longer temporal feedback loop. In other words, it takes hundreds or even a thousand years for sea level to reach the correlated value that climate forcing dictates. And what is the "correlated value" for sea level that even the present 410 ppm of CO2 dictates, you might ask? I usually hesitate to even mention it during interviews or lectures. The reason is that most people, including me (for over ten years), don't believe the number. To prepare the reader for a shock, let me introduce the next figure first, to reinforce the LINEAR relationship between all three (3) variables that Dr. Hansen discovered and published in 2006.

Here in Fig. 5, all of the facts are laid bare for the reader to contemplate and absorb fully. The Table on the left is Hansen's data which comes from his Fig. 4, with the zero (0) value of sea level corresponding to the maximum 290 ppm and 15 degrees C which we experienced recently as the average global values up until around 1960.

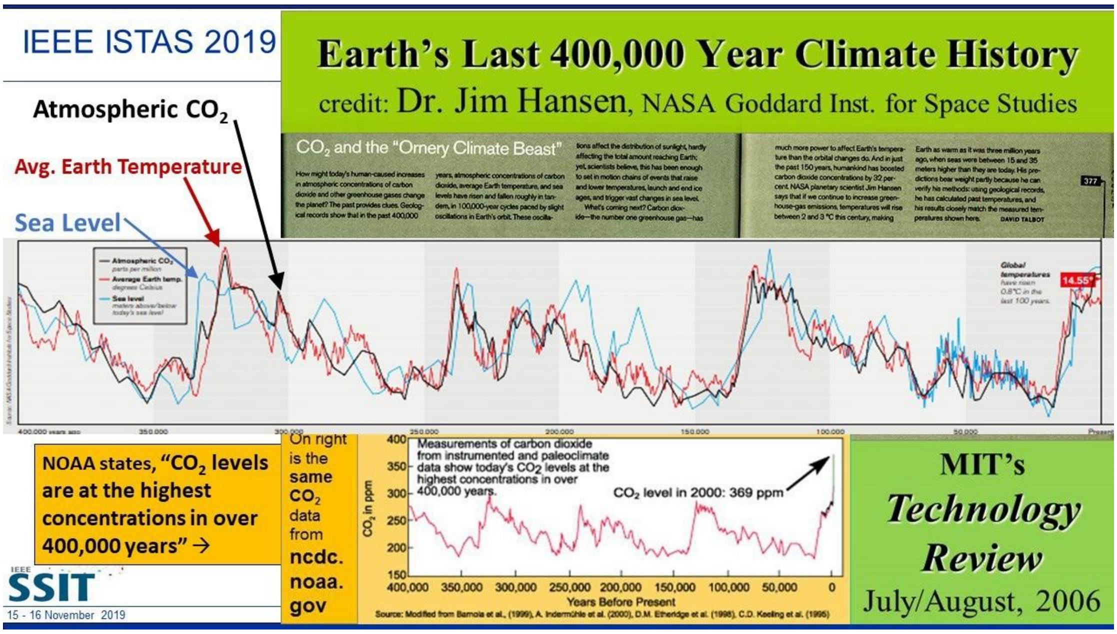


Fig. 4. Hansen graph correlating global CO2 and temperature and sea level [7]

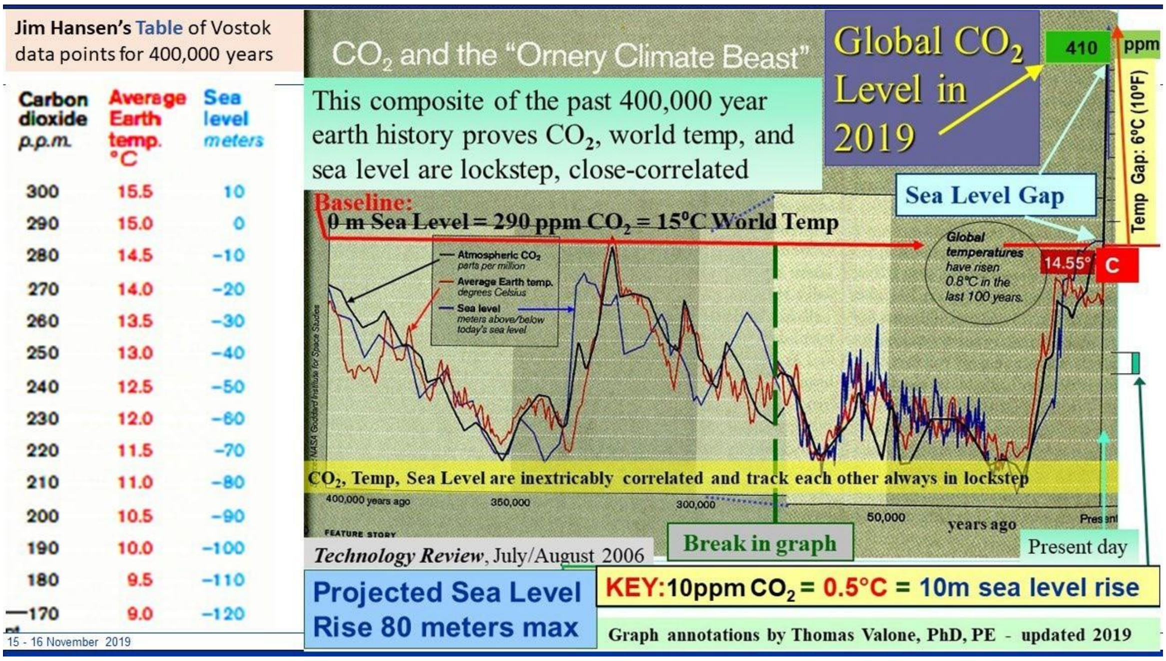


Fig. 5. Hansen's data table and interpretation of his graph by the author [8]

However, the sea level data is clearly shown in the Table which I translated into a simple equation seen in Fig. 5. The equation (double of the KEY in Fig. 5 for convenience) is designed to allow anyone to compress the Table data into a formula that is easy to memorize:

+/- 20 ppm = 1˚C = 20 meters

What may be the most reassuring part of the formula here is the +/- sign. As clearly seen in Figs. 4 and 5, the response of the earth (I like to call it "Gaia" after James Lovelock) system to any change in global CO2 levels entrains the other two to follow, with a corresponding delay. In other words, as humans wantonly pushed the CO2 level rapidly above the 290 ppm baseline only in the past few decades with very little delay in the rising temperature response to the heat-trapping gas increase, I am confident that we will learn in the very near future to bring down the global level to 290 ppm, by CCS on the gigaton (gigatonne) level, as renewable energy is gradually brought online in a slower, parallel effort by many nations globally.

3. GLACIERS ARE MELTING FAST

Now we can disclose the sea level rise that the world is indebted for, just from the 370 ppm of CO2 we saw in the air around the year 2000. We can take the rounded number 370-290 (zero value) = 80 ppm and divide by the 20 ppm from the formula into 80 ppm to get the disturbing number of 4 to multiply by 20 meters. Or we can just simply note that the numerical values of CO2 and sea level change are the same, so sea level increase destined by Gaia is 80 meters, which is probably the maximum sea level increase possible. Any CO2 value above the 30% increase from baseline, or about 370 ppm of that year, is hitting the ceiling of globally available ice since the major contributors to sea level rise, as I found out, are Antarctica and Greenland. These huge glaciated island continents are the only two main landlocked glacier ice of frozen water on earth. Antarctica will contribute about 60 meters of sea level rise and Greenland is estimated to contribute about 10 meters which equals 70 meters, so even the 80 meter result may an overestimate.

This brings us to the unavoidable conclusion which is a real shocker:

Around the turn of the millennium (year 2000) the human race as a whole threw in all of its chips of the earth's reservoir of frozen water in exchange for the freedom of emitting a few more gigatons of CO2 (as seen in previous figures). As a consequence, we quickly maxed out ALL of the earth's glacier ice, which now is equivalent to a "dead man walking." They are already gone, in the Gaia Ledger Book, and will continue to melt for the next thousand years without a letup UNLESS the amount of CO2 in the atmosphere is brought back down to equal the pre-industrial value of 290 ppm or at least to about 350 ppm. Look at Fig. 6 for visible evidence of the melting speed already happening.

Such an observation renders all other arguments moot since the only cause and driver for the sea level and the global warming of the atmosphere is the incremental amounts of CO2 above the baseline of 290 ppm. The best climate estimates of the trendlines for temperature increase is **about 1˚C every decade or so**, reaching the 6 to 8˚C increase of Fig. 3 by 2100. There are already pockets of 1.5˚C and even 2˚C average increase occurring in geographically suitable regions already. Next is an example of the speed of the warming trends that are happening and expected to happen.

Fig. 6. Extreme climatic event [9]

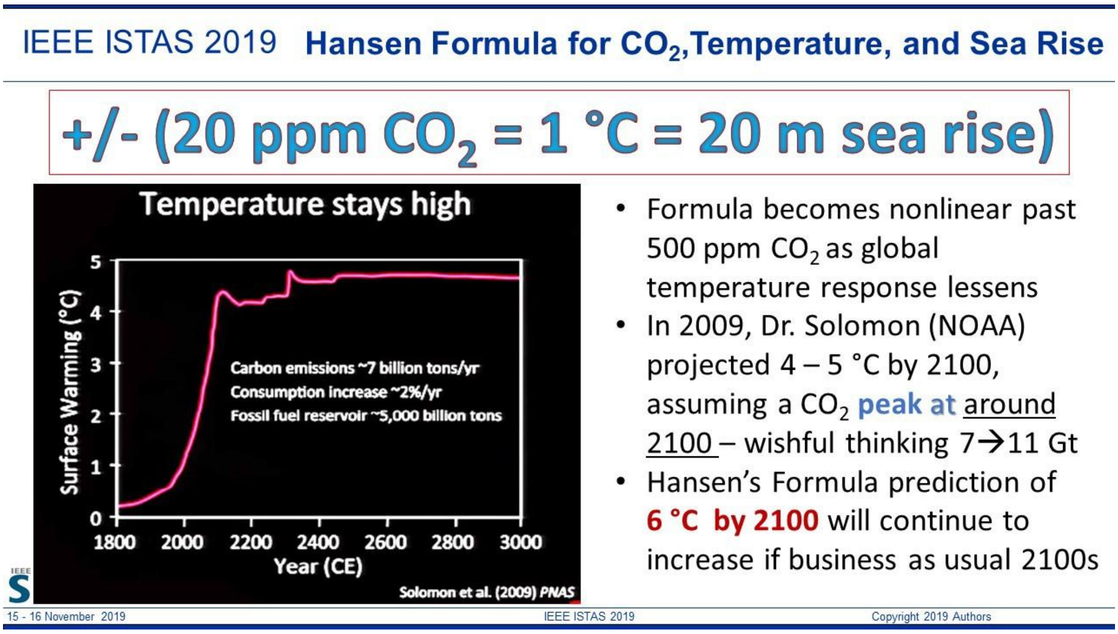


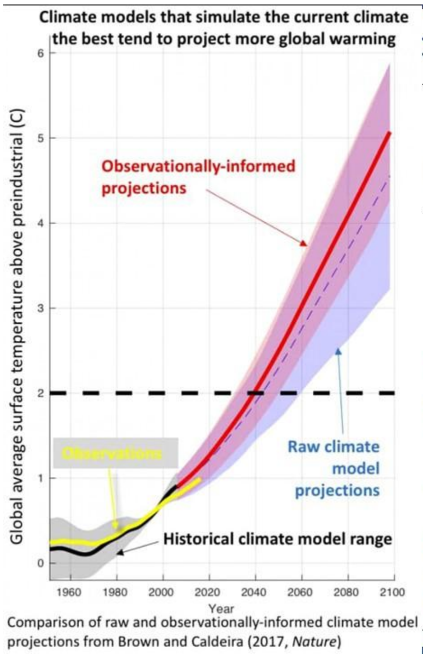
Fig. 7. Hansen formula with corroboration by Solomon et al. [11]

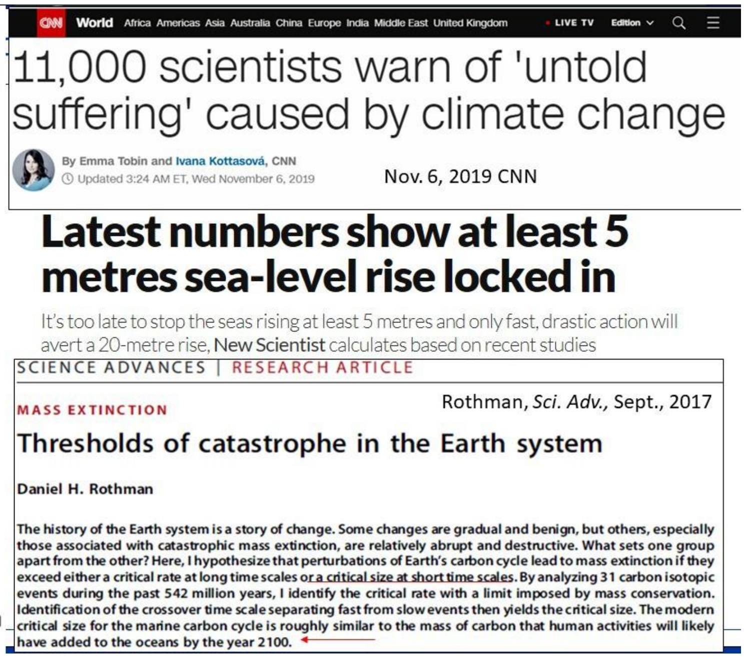
This record of a glacier melting at a record speed is surprising, since we often think these things happen very slowly. Not anymore! Below is NOAA climatologist Solomon's prediction of how long a temperature increase will last, along with the convenient form of the Hansen equation recited earlier. Note that Dr. Solomon made her estimate about ten years ago, when we were pumping only 30 gigatons of CO2 into the atmosphere annually. Now that the amount has risen to 40 gigatons annually, the peak amount of temperature increase has to be updated. Regarding Fig. 7, Solomon explains, "After emissions cease, the temperature change approaches equilibrium with respect to the slowly decreasing carbon dioxide concentrations" which she calls "irreversible climate change" [10]. This is based on a 7 billion ton carbon (25 gigatons of CO2) annual emissions in 2009 which has now increased to a 40 gigaton CO2 level annually a decade later, so the leveling off long term temperature is more realistically projected to be around 6°C, as seen elsewhere in this review, and expected to last thousands of years before decreasing to present day levels.

Probably the most provocative and disturbing for any audience is a composite temperature trend graph which "reduces uncertainty" (says *Nature* magazine's editorial introduction) in Fig. 8. "The best performing models are shown in dark red, projecting above 5°C. Climate models generally agree that greenhouse-gas emissions will continue to raise global temperatures, but the amount of warming predicted varies considerably. To narrow the field of probability, Patrick Brown and Ken Caldeira at the Carnegie Institution for Science in Stanford, California, assessed a plethora of current climate models. They found that some models more accurately simulate the amount of radiation entering and leaving the atmosphere, a flow known as Earth's energy budget, than others" [12].

"The team combined a number of models but reduced the influence of those that less realistically represent the energy budget. It predicts at least a *five degree (5°C) increase by 2100* (red line) with an uncertainty range that reaches 6°C. Much is known about the present exponential trend in temperature up to 2020 but with Brown and Caldeira's integrated approach, the climate models are merged to include "observationally- informed projections" of *global temperature to 2100*" [13].

The question is often asked by the public if CO2 is going to level out or 'peak' soon. The 9th UN Emissions Gap Report states there is "no sign of peaking" and emphatically issues a warning that carbon emissions are *actually* increasing [15]. "In Fig. 9, the A2 line for CO2 levels is "business as usual" and most likely by economists and policy makers, according to the University of




CNN World Africa Americas Asia Australia China Europe India Middle East United Kingdom LIVE TV Edition

11,000 scientists warn of 'untold suffering' caused by climate change

By Emma Tobin and Ivana Kottasová, CNN
Updated 3:24 AM ET, Wed November 6, 2019

Nov. 6, 2019 CNN

Latest numbers show at least 5 metres sea-level rise locked in

It's too late to stop the seas rising at least 5 metres and only fast, drastic action will avert a 20-metre rise, New Scientist calculates based on recent studies

SCIENCE ADVANCES | RESEARCH ARTICLE

MASS EXTINCTION

Rothman, *Sci. Adv.*, Sept., 2017

Thresholds of catastrophe in the Earth system

Daniel H. Rothman

The history of the Earth system is a story of change. Some changes are gradual and benign, but others, especially those associated with catastrophic mass extinction, are relatively abrupt and destructive. What sets one group apart from the other? Here, I hypothesize that perturbations of Earth's carbon cycle lead to mass extinction if they exceed either a critical rate at long time scales or a critical size at short time scales. By analyzing 31 carbon isotopic events during the past 542 million years, I identify the critical rate with a limit imposed by mass conservation. Identification of the crossover time scale separating fast from slow events then yields the critical size. The modern critical size for the marine carbon cycle is roughly similar to the mass of carbon that human activities will likely have added to the oceans by the year 2100.

Fig. 8. Climate model simulation [14]

Washington" [16]. "It is estimated that humans have emitted about 550 gigatonnes of carbon (multiply by 3.67 for CO2 gas amount) from 1870 – 2013" [17]. "In addition to this global atmospheric volume of human-created CO2, the world adds about 40 gigatons of CO2 emissions each year to the atmosphere, which stays there" [18]. Climate reports cited throughout this review acknowledge the Paris limits *are not happening*. No major country is willing to reverse its long- standing use of fossil fuels with a carbon tax, *even if the entire tax goes to funding more renewable energy*.

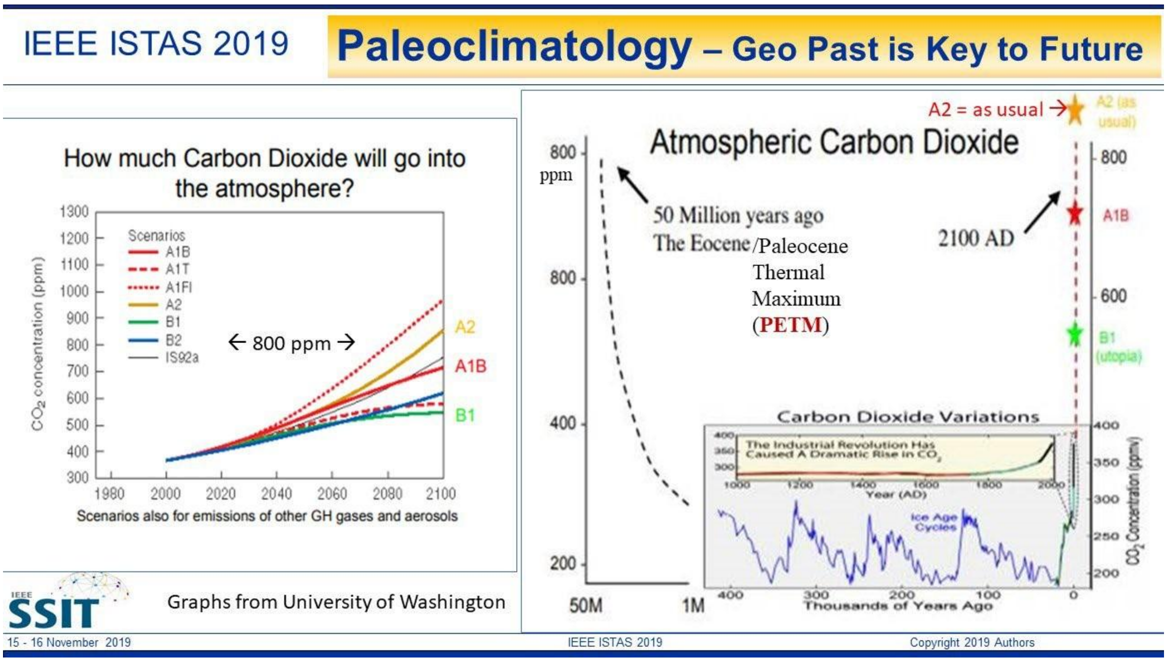


Fig. 9. Climate scenario model projections versus paleoclimatology [19]

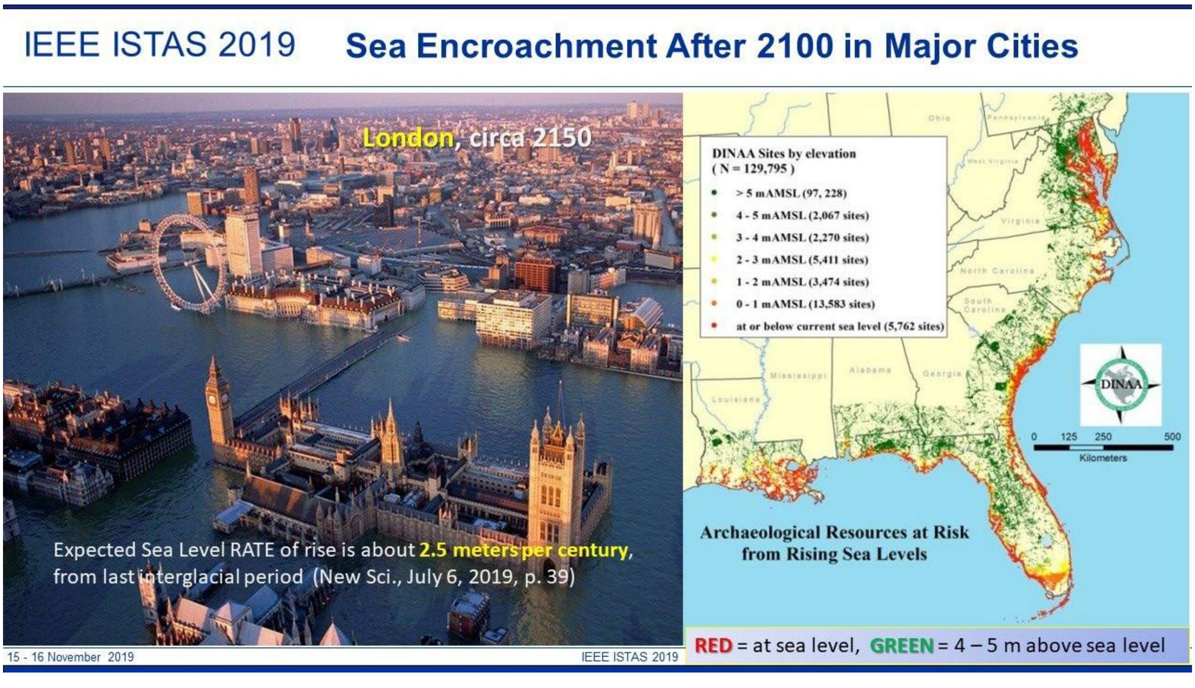


Fig. 10. Expected moderate increase in sea level from best estimates [22]

"There are numerous educational videos with detailed reviews of the PETM on YouTube, such as from BBC Radio [20] and a very popular, ten-minute PBS-TV summary (with 2.5 million views)" [21]. Referring to Fig. 9, one can see the PETM peak and to note that during the geologically short PETM period of about 200,000 years, the earth's atmosphere was gaining CO2 at a rate of about 1.7 billion tons (1.5 gigatonnes) per year by the best estimates, compared to about 40 billion tons (36 gigatonnes) worldwide per year at our present rate. The vital point though is the estimate of the CO2 concentration in the atmosphere at that time and the corresponding average temperature, which seems to parallel the University of Washington's most likely estimate of the CO2 concentration for 2100.

Of course, the projection of sea level rise, even by a few meters by 2100, is also a disturbing problem that has not been adequately addressed by any government or municipality in the world. The next Fig. 10 gives us a graphic image of the extend of this problem, to help us prepare for the inevitable encroachment of the sea as it continues to rise for the next few millennia.

What we see in Fig. 10 are the best estimates of a moderate increase in sea level of only a few meters by 2100. However, it has a major effect on coastal cities that are already at sea level to begin with. When I see high rise hotels right on the coast of many cities around the world, including Miami Florida, I think of how unsustainable that property will be in less than a century.

While the global increase in average temperature has reached 1 degree Celsius, an analysis of more than a century of National Oceanic and Atmospheric Administration temperature data across the lower 48 U.S. states and 3,107 U.S. counties has found that major areas are nearing or have already crossed 2-degree Celsius increase in average temperature, thus representing "hot spots." Today, more than 10% of Americans, or about 34 million people, are living in rapidly heating regions, including New York City and Los Angeles. Alaska is the fastest-warming state in the country, but Rhode Island is the first state in the Lower 48 whose average temperature rise eclipsed 2 degrees Celsius. Scientists do not completely understand the Northeast hot spot. But fading winters and very warm water offshore are the most likely culprits, experts say. That's because climate change is a cycle that feeds on itself. Daniel Pauly, an influential marine scientist at the University of British Columbia, says the 2-degree Celsius hot spots are early warning sirens of a climate shift. "Basically," he said, "these hot spots are chunks of the future in the present" [23].

"An ice-free Iceland is not an isolated phenomenon. Glaciers are melting all across the world, contributing enormously to rising sea levels. Himalayan glaciers help regulate the water supply of a quarter of humankind. Natural systems will be disrupted. The great thaw will also unfreeze vast areas of permafrost, releasing methane, a potent greenhouse gas. The melting of ice sheets in Greenland and Antarctica will, in the long term, result in dozens of feet of sea-level rise. Scientists cannot pinpoint at what level the melting of Greenland or the West Antarctica ice sheets becomes irreversible" [24].

"Greenland holds the second largest store of land-locked ice in the world, after Antarctica. A major reason for including Greenland's ice loss is that upon comparison to Antarctica, it becomes abundantly clear that Greenland is losing twice as much ice mass as Antarctica, *in the same time frame"* [25]. "Such a major influx of fresh water from Greenland into the Atlantic ocean, with less density than salt water, has also been connected to the decrease in flow of the North Atlantic Conveyor System (NACS) by about 20% in the past few decades. This has major implications for Scandinavia which, along with the UK, receives returning NACS warm sea water current northward from the Mediterranean. Ironically, if the NACS slows down much more, which in all probability it will with present GHG emission trends, the Scandinavian countries may experience a short term cooling trend as the rest of the world continues to rise in average temperature, since there will be a deprivation of the warm northward NACS current to Scandinavia, until global temperature rise dominates. Greenland has also made the news recently because rain-associated melting became twice as frequent in summer and three times as frequent in winter, for the past several years" [26]. "Rain now seems to account for 28 per cent of the [Greenland's] ice sheet melt." [26].

There are generally foreseen and widely accepted consequences of the extreme conditions outlined above as 4 degrees to even 10 degrees Celsius are anticipated in various areas of the globe, whether "hot spots" or "cool spots," accompanying the projected average global increase of about 6 degrees C in the next several decades [27] "These include the inundation of coastal cities; increasing risks for food production potentially leading to higher malnutrition rates; many dry regions becoming dryer and wet regions wetter; unprecedented heat waves in many regions, especially in the tropics; substantially exacerbated water scarcity in many regions; increased frequency of high-intensity tropical cyclones and hurricanes; irreversible loss of biodiversity, including coral reef systems, as carbonic acidity decreases oceanic pH. Increasing aridity and drought are likely to increase substantially in many developing country regions located in tropical and subtropical areas, as well as in the central and midwestern United States" [27]. "Although it is often difficult to make comparisons across individual assessments, there are a number of extremely severe risks for vital human support systems. Large-scale and disruptive changes in the earth system are generally not included in climate models, and rarely in impact assessments. One example of such a change would be the collapse of the West Antarctic Ice Sheet, which would lead to much larger sea level rise than projected in the present analysis for the next few decades. Extreme temperatures and new invading pests and diseases that can take over in areas where it was too cold for them to thrive in the past are to be expected, especially in the northern latitudes. Projections of damage costs for climate change impacts typically assess the costs of local damages, including infrastructure of national and regional scales" [28].

"Thus, given that uncertainties remain about the full nature and scale of impacts, there is also no certainty that adaptation even to a 4°C temperature increase is possible. A 4°C world is likely to be one in which communities, cities and countries would experience severe disruptions, damage, and dislocation, and civil unrest, with many of these risks spread unequally. It is likely that the poor will suffer the most and the global community could become more fractured with a dramatic increase in border wars and migration. The largest warming will occur over land and range from 4°C to 10°C. Increases of 6°C or more in average monthly summer temperatures would be expected in large regions of the world, including the Mediterranean, North Africa, the Middle East. Almost all summer months are likely to be warmer than the most extreme heat waves presently experienced and, for example, the warmest July in the Mediterranean region could be 9°C warmer than today's warmest July. With pressures increasing as warming progresses toward 4°C, and combining with social, economic, and population stresses, the risk of crossing critical social system thresholds will grow" [28]. " At such tipping points, the existing global governments would likely become much less effective at supporting the needed social remedies or could even collapse. Similarly, stresses on human health, such as heat waves, malnutrition, and decreasing quality of drinking water or complete loss of available water as presently persisting in over a dozen countries worldwide, have the potential to overburden health-care systems to a point where adaptation is no longer possible, and dislocation is forced" [28].

In Fig. 11 we see the extreme potential of the facts shown in graphic form in Fig. 9. The Paleocene Eocene Thermal Maximum (PETM), which reached 800 ppm at its peak with alligators in the Arctic, is exactly the level which the experts predict for present day earth by the end of this century (2100). This is because of the clear trend in the exponential growth of CO2 emissions worldwide, with no rate peak in sight, which is reflected in our Fig. 2. The world's CO2 emissions graph shows the rate of CO2 emissions increasing to about 3% in 202. Furthermore, the shocking Fig. 9 projection of 800 ppm by 2100 confirms the PETM return for us since the "business as usual" graph is the most likely scenario for planet earth. Note that the earth is presently experiencing a very short temporal feedback loop between CO2 average levels and global temperature: every report indicates hotter seasons than the previous ones as each year goes by. It can be estimated that there may be only a 20-year gap in the response curve of an increased (or decreased) global average level of CO2 and the increase (or decrease) in worldwide average temperature. This is bad news for global warming but good news for a multi-gigaton direct air carbon capture program to exhibit rapid results in an equivalent time frame.

4. CARBON DIOXIDE REMOVAL

More and more the primary recommendation of informed climatologists is that carbon capture and storage (CCS) also called "carbon sequestration" from direct air capture (DAC) is the combination that fulfills carbon dioxide removal (CDR). Informed atmospheric physicists

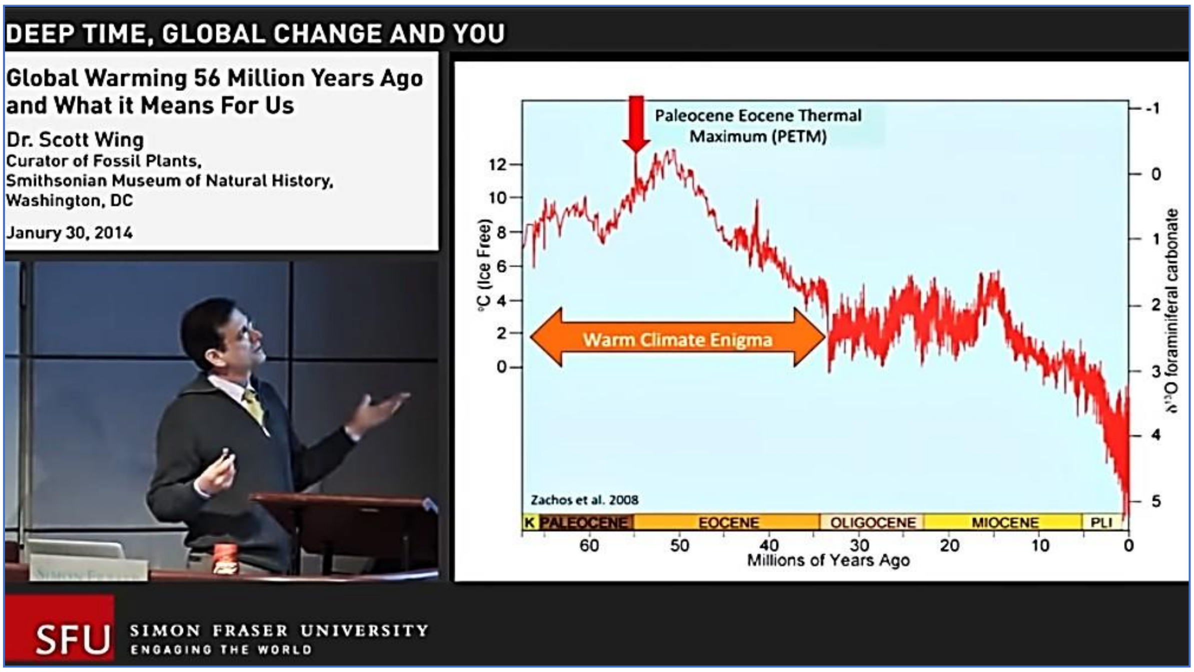


Fig. 11. Scott Wing explaining the PETM temperature maximum versus today's global warming climate [29]

find this is the only hope for controlling the world's average temperature for the immediate and long-term future. In addition, a new, powerful insight is gained from study of the Hansen graph, as well as from reviewing Fig. 2 in comparison to Fig. 1. Both indicate a destined outcome of present trends based on scientific principles, such as a rate peak must precede the quantity peak, which in such a large system as the earth-atmosphere combination, will involve a hundred or more years. Furthermore, to address even the short-term annual emission quantity, the amount of CO2 CDR or CCS needed is indeed staggering but not impossible, if a multination, international consortium is formed in the next decade, if not sooner. At the present global emissions rate, every year we wait adds another 36 gigatonnes (40 gigatons) to the total stored in our thin blue blanket above our heads.

In recent years, there has been a growing interest in carbon dioxide removal (CDR) methods that can help mitigate the impacts of climate change. There are several CDR methods, but not all are effective, affordable, or sustainable. Here are some of the best carbon dioxide removal methods from air:

1. Afforestation and reforestation: Planting trees is one of the most effective, short term ways to remove carbon dioxide from the atmosphere. Trees absorb carbon dioxide during photosynthesis and store it in their trunks, branches, and roots. Forests also provide other benefits like preventing soil erosion, regulating water cycles, and supporting biodiversity. However, after about a century, most of the trees will give the sequestered CO2 back to the environment as they die and decay, so it is mostly just a delay tactic.
2. Direct air capture (DAC): Direct air capture technology uses machines to capture carbon dioxide from the atmosphere. The captured carbon dioxide can then be stored underground or used for industrial purposes. DAC technology is still in its early stages and is expensive, but it has the potential to remove large amounts into the gigaton range of carbon dioxide from the atmosphere. Recently, Dawid Hanak at Cranfield University in the UK reports on research that has the ability to substantially reduce the cost of DAC. He refers to the new discovery by Arup SenGupta at Lehigh University in Bethlehem, Pennsylvania, and his colleagues who developed a new absorbent material – called a sorbent – capable of pulling more CO2 from the air than current materials can. They use a copper-based solution by modifying amine solvents to produce

baking soda from CO2 captured from the air and stored in the world's oceans, In addition to inexpensively capturing CO2, by storing it in the ocean, the process will also help to alkalinize the oceans which are becoming more acidic from absorbing CO2 directly [30]. The good news is that a demonstration project has already been in place for the past year in the UK, capturing over 40,000 tonnes of CO2 per year at a Tata Chemicals plant in Northwich [31].

3. Ocean fertilization: Ocean fertilization involves adding nutrients to the ocean to stimulate the growth of phytoplankton. These tiny organisms absorb carbon dioxide during photosynthesis and sink to the bottom of the ocean, where the carbon dioxide is stored. However, there are concerns about gigatonne levels of algae bloom capture of CO2 and the environmental impacts of such high levels of ocean fertilization, so it is not a widely recommended method but nicely proven in the megatonne range.
4. Soil carbon sequestration: Soil carbon sequestration involves storing carbon in the soil through agricultural practices like crop rotation, conservation tillage, and cover cropping. These practices increase the amount of organic matter in the soil, which helps store carbon. Soil carbon sequestration is a low-cost method and has other benefits like improving soil health and increasing crop yields.
5. Bioenergy with carbon capture and storage (BECCS): BECCS is a combination of bioenergy production and carbon capture and storage. Biomass is burned to generate energy, and the carbon dioxide produced is captured and stored underground. BECCS is a relatively new technology, but it has the potential to remove large amounts of carbon dioxide from the atmosphere while also producing energy.

Such carbon dioxide removal methods are important in mitigating the impacts of climate change. Afforestation and reforestation, direct air capture, ocean fertilization, soil carbon sequestration, and BECCS are some of the best methods for removing carbon dioxide from the atmosphere. Each method has its benefits and drawbacks, and the choice of method will depend on factors like cost, effectiveness, and sustainability. CarbonBrief.org also has a free report on CDR released 2023: https://www.stateofcdr.org/.

Recently another leading company has emerged for gigaton carbon capture called Project Vesta, which has as its website motto, "Harnessing the power of the oceans to remove excess CO_2 from the atmosphere." Visit https://www.vesta.earth/ for their exciting gigaton carbon capture technique under evaluation in the environment at this moment. "Carbon-removing sand made of the mineral olivine is added to the ocean. There, the sand dissolves, countering ocean acidification and permanently removing carbon dioxide from the atmosphere" [32].

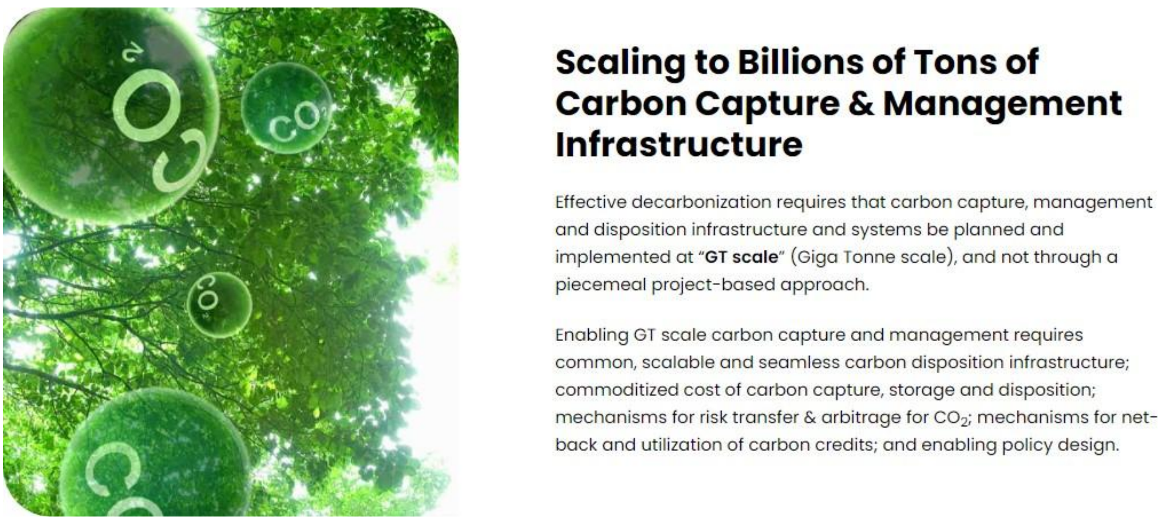


Fig. 12. Scaling to billions of tons of carbon capture [33]

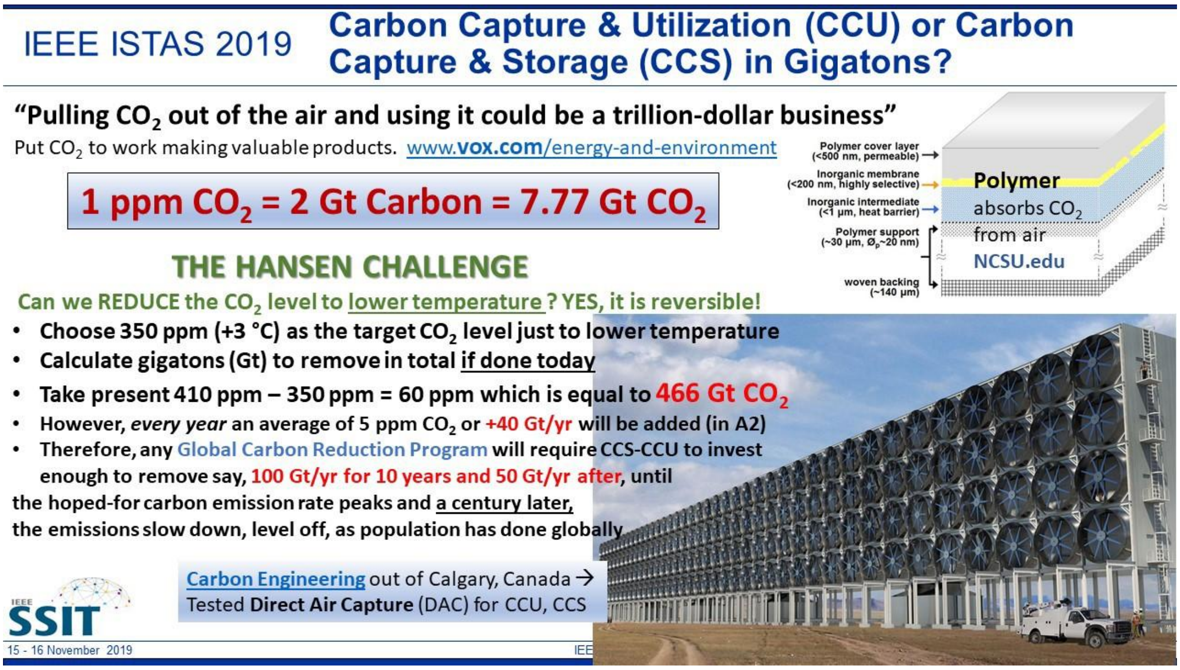


Fig. 13. Proposed CCS for excess atmospheric CO2 to restore 20th century 350 ppm levels [34]

Capturing gigatons of CO2 is a vision of the American Dastur Energy which is summarized in Fig. 12. Dastur seeks to implement large scale direct air carbon capture technologies as well as decarbonizing industrial activity as well, aiming for a net zero world.

Note the challenging calculation in Fig. 13 of the numbers resulting from an attempt to sequester 50 gigatons (45 gigatonnes) every year if the world is fortunate enough to discover a very inexpensive means to capture CO2 in that quantity reliably. A possible process for doing this is reflected in Fig. 13, though the cost estimated in the trillion-dollar range is a present barrier to its realization, so a compromise is to at least aim for the 20th century level of 350 ppm as a "middle of the road" goal, with the Carbon Engineering process that is already capturing in the megaton-scale. The equivalent formula in Fig. 13 is given for converting the parts-per-million (ppm) amount of CO2 to gigatons (Gt) of CO2 helps to determine the appropriate capture mode. (Divide gigatons by 0.907 to get gigatonnes if needed.)

In 2022, the International Energy Agency released a report entitled, "Direct Air Capture--A key technology for net zero" with a full report but also an Executive Summary available online: https://www.iea.org/reports/direct-air-capture-2022/executive-summary. Almost all of IEA's findings result in megaton (Mt CO2) removal as seen in the first paragraph from the Executive Summary below:

Direct air capture (DAC) plays an important and growing role in net zero pathways. Capturing CO2 directly from the air and permanently storing it removes the CO2 from the atmosphere, providing a way to balance emissions that are difficult to avoid, including from long-distance transport and heavy industry, as well as offering a solution for legacy emissions. In the IEA Net Zero Emissions by 2050 Scenario, DAC technologies capture more than 85 Mt of CO2 in 2030 and around 980 Mt CO2 in 2050, requiring a large and accelerated scale-up from almost 0.01 Mt CO2 today.

To its credit, the IEA report does focus on the geological CO2 storage where the chemical reaction underground forms a carbonate rock permanently and "has several advantages as a CDR approach, including a relatively small land and water footprint, and high degree of assurance in both the permanence of the storage and the quantification of CO2 removed."

Besides the basic CDR findings of the IPCC and other agencies like the IEA, more detailed research findings on CDR are presented in Figs. 14 and 15.

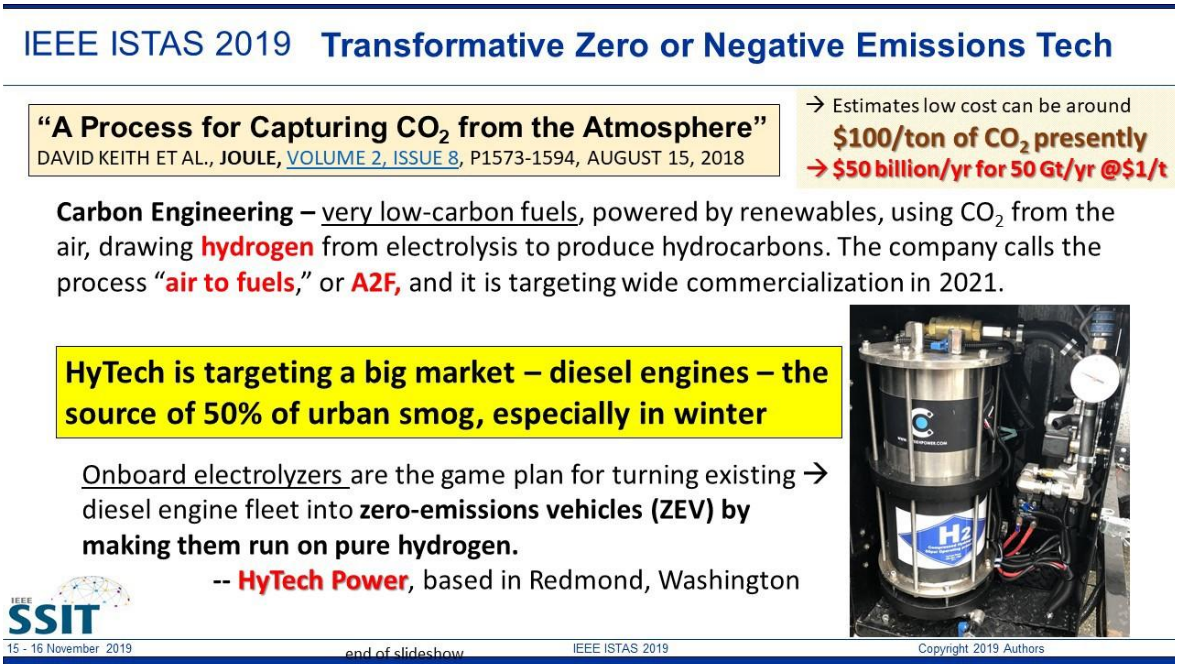


Fig. 14. Transformative zero or negative emission technology [35]

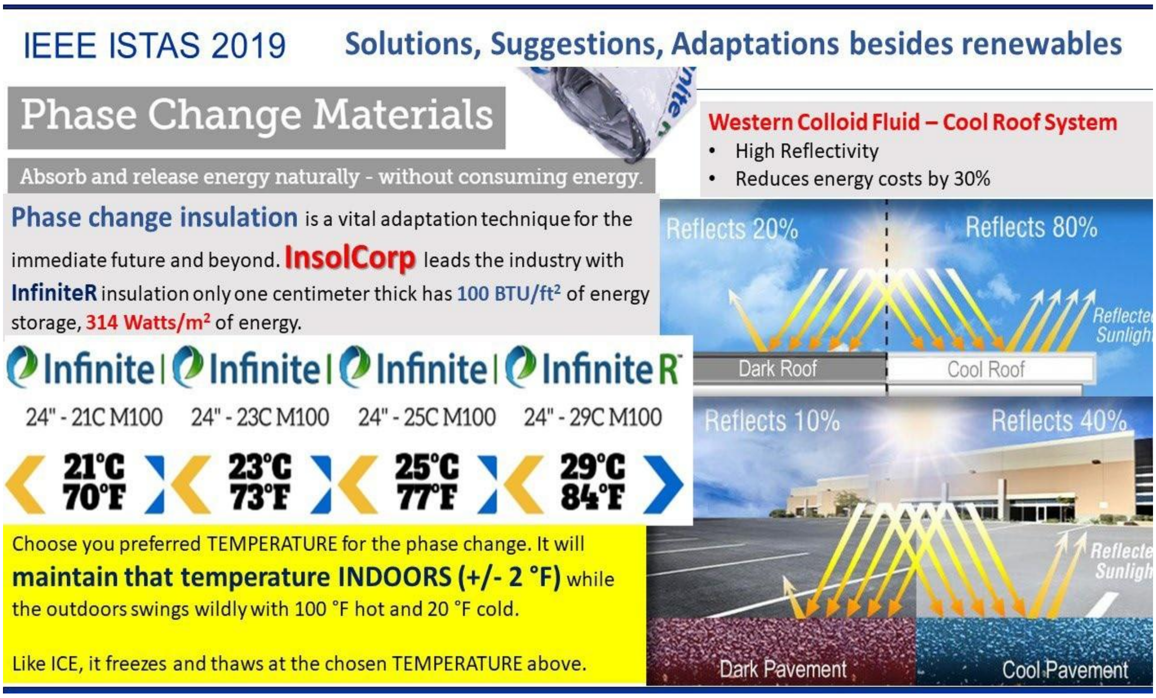


Fig. 15. Adapting to an impending hot climate with phase change insulation and white surfaces [36]

A very good guide for personal adaptation to the impending hot climate is in Fig. 15. I met the CEO of the InsolCorp at a recent World Energy Engineering Conference in Washington DC. They have proven their very thin phase change insulation *outperforms any other much thicker insulation* and in many cases, can replace the need for air conditioning. This is because the temperature variation inside any enclosure or building will be very stable with such a material absorbing and releasing heat energy next to the walls or simply under the ceiling or roof.

5. CONCLUSION

It is hoped that the simple, inextricably tight connection between global CO2 values and global temperature, delineated and publicized by James Hansen and others, will finally create an urgency in the minds and hearts of all people, so that global atmospheric carbon capture by the gigaton can begin in earnest and in parallel with carbon-free fuels, zero carbon emissions, renewable energy, and even negative carbon emissions, implemented worldwide. One ray of hope, among many suggested climate solutions, which can comprise another separate article, is the recent discovery of an alloy of gallium, indium, and tin that is liquid at room temperature and conducts electricity. By spiking the silvery mixture with a sprinkling of catalytically active cerium and placing it inside a glass tube, along with a splash of water, scientists have now proven a room temperature method to convert CO2 to carbon, instead of the usual high temperature procedure. Chemists Dorna Esrafilzadeh and Torben Daeneke at RMIT University in Melbourne, Australia, turned to a new class of catalysts made from metal alloys that are liquid at room temperature [37]. This is a process that can be scaled up and may someday offer a novel and inexpensive method for capturing billions of tons of atmospheric carbon that can immediately begin the reversal of the temperature and CO2 relationship that is so tightly correlated. In that way, more time could be allowed for the world to convert to 100% renewable energy and thus begin to drastically reduce its carbon emissions.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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