

Is the Earth Now in a Multifactorial CO₂ Tipping Point?

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Abstract

Even if none of the proposed climate change tipping points have currently been fully activated, the additive effect of many partially activated tipping points has already begun and unless significant steps are taken to control global warming, as temperatures continue to rise this multifactorial tipping point will become a significant contributor to atmospheric CO₂ levels and could lead to an irreversible positive feedback loop. It is proposed that the only way out is to globally activate multiple Negative Emission Technologies.

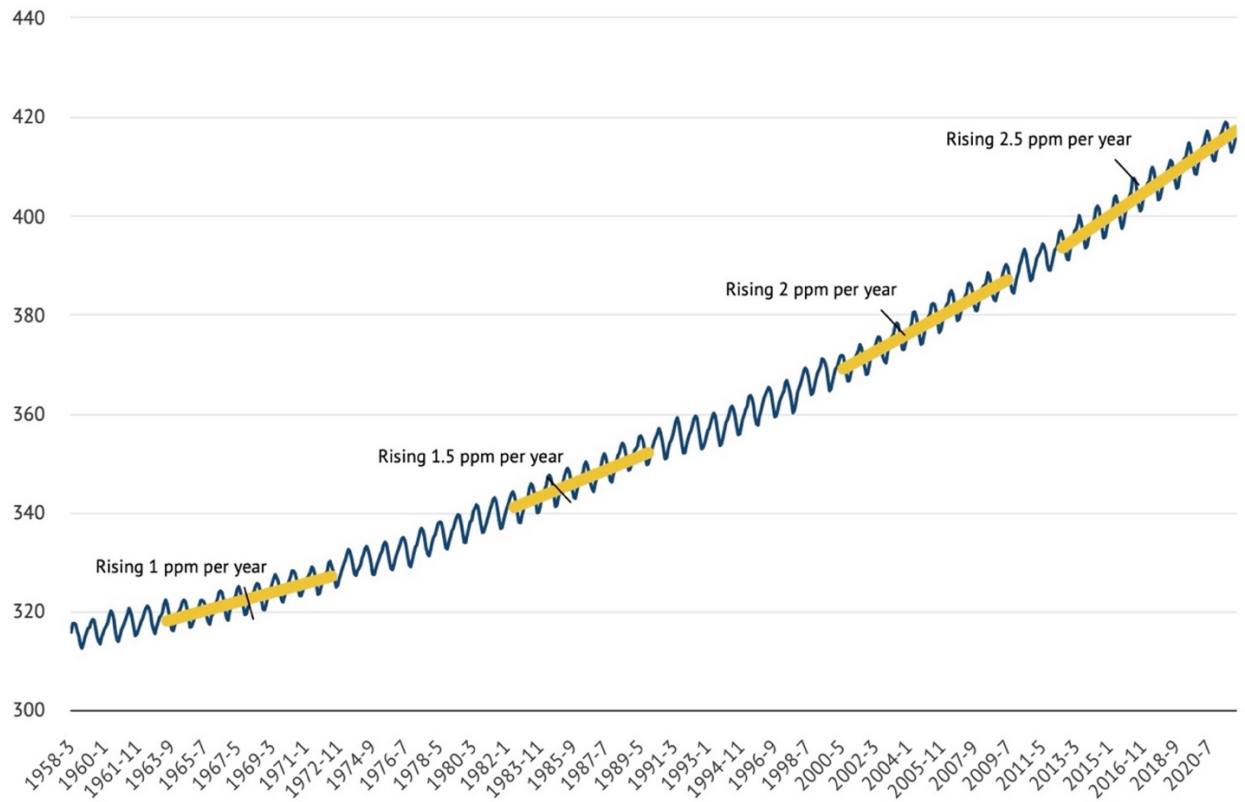
Article

Tipping points represent times when a given potential source of greenhouse gases becomes so activated it enters a positive feedback loop where the CO₂ or methane released promotes further releases. Many tipping points have been described.^{1,2} It is generally felt that none of them have yet been fully activated.

The Keeling Curve is based on atmospheric CO₂ levels sampled on Mona Loa in Hawaii^{3,4} and provides valuable information on atmospheric CO₂ levels over time. In an effort to control CO₂ emissions, since their inception in 1995, 27 COPs or Conference of the Parties have been held. At each, most of the countries of the world renew their pledges to cut down on greenhouse emissions. Hopefully, the Keeling curve would begin to level off and the rate of increase would begin to decrease. Is it? The latest results, Fig 1, indicate that in fact the rate of increase is steadily increasing.⁵

The build-up of CO₂ in the air has been accelerating

Atmospheric CO₂ concentration (parts per million, ppm)



Data from Scripps Institution of Oceanography at UC San Diego.

Chart by Joe Goodman for Carbon Brief

In 1967 the rate of increase was 1.0 ppm/year, in 1987 1.5 ppm/year, in 2007 2.0 ppm/year, in 2017 2.5 ppm/yr, and in 2023 2.8 ppm/yr. Why is this happening? The quick answer is that countries are not trying hard enough. However, the Global Carbon Project reported that despite increases in domestic economic growth 24 countries, including the U.S and China, are showing a decrease in emissions and the level global emissions is leveling off.⁶ Emissions from land use, such as deforestation, are also stable.^{6,7} Any decrease in CO₂ sinks would result in increased atmospheric CO₂. A recent Global Carbon Budget⁷ report states that climate change has already reduced the CO₂ uptake of the ocean sink by around 4% and the land sink by around 17%, compared to a theoretical world without climate change.

This article explores the possibility that even though none of the individual tipping points are fully activated, several of them are partially activated. The following are some potential partial tipping point candidates.

1. **Forest fires.** In the past few years there have been massive forest fires in the United States, Canada, Greece, Australia, and other countries. Van der Werf⁸ estimated that wildfires

have emitted about 8 gigatons of CO₂ per year for the past 20 years. The 2020 California wildfires generated more than 91 million metric tons of CO₂⁹ which was about 25% of the annual emissions from fossil fuels in that state. Also, in 2020 the bushfires in Australia, released twofold more carbon than what was usually emitted in that country by fossil fuel emissions in an entire year. The 2023 Canadian wildfires produced more CO₂ emissions than for any of the prior seasons.¹⁰ Global forest fires in 2019 and 2020, like those in Indonesia, Brazil, Central Africa, Siberia, Australia, and California, accounted for 10–15% of all global greenhouse gas emissions.¹¹

2. Additional deforestation. Forest fires cause deforestation by burning trees. Humans add additional deforestation by cutting down trees both for lumber and to clear land for agriculture. When deforestation occurs, much of the carbon stored by trees is released back into the atmosphere as carbon dioxide. In the last decade, the largest amounts of deforestation occurred across the humid tropics, mostly in Africa, followed by South America.¹² The UN Food and Agriculture Organization (FAO) estimates that 178 million hectares forest were lost between 1990 and 2020. The most important driver of deforestation is the global demand for high-value cash crops like palm oil and soya, and for cattle ranching. This deforestation contributes to 12–20% of global greenhouse gas emissions.¹³ As a result of deforestation and degradation, some tropical forests now emit more carbon than they capture, turning them from a carbon ‘sink’ into a carbon source. For example, the south-eastern part of the Amazon Rainforest is now considered a net carbon source.¹²

3. Burning peat. Current estimates suggest that the carbon stored by peatlands is at least twice as much as all other vegetation types together.^{14–17} When burned it releases large amounts of CO₂. Indonesia experienced an exceptional number of peat fires in 2015. These fires released approximately 1.1 gigatons of carbon dioxide (CO₂) into the atmosphere.¹⁶ Barber and Burgess¹⁵ concluded that protecting and restoring peatlands can reduce global greenhouse gas emissions by about 800 million metric tons per year, roughly equivalent to the country of Germany’s annual emissions.

4. Burning Boreal Forests. A boreal forest is a forest that grows in regions of the northern hemisphere with cold temperatures. They are made up mostly of cold tolerant coniferous species such as spruce and fir. In the massive Yukon Flats National Wildlife Refuge in east Alaska, boreal fires have long been allowed to burn unchecked unless they threaten human life and property.¹⁸ Due to climate change, the frequency of these fires has increased four times since 1988. These more-frequent fires can burn carbon that has accumulated over centuries.¹⁹ Canada’s boreal forest fires last year released more than three times as much carbon dioxide as the entire country emitted from burning fossil fuels. Because of this, efforts are now being made to extinguish these fires. The boreal forest in the Yukon Flats Refuge cover a uniquely vulnerable type of permafrost called Yedoma, which contains deep ice wedges that often melt after fires.

This causes the land to collapse, exposing the ancient carbon to microorganisms and releasing greenhouse gases. The target areas of the fire suppression areas contain some 1.1 gigatons of carbon, which if released would be equivalent to 7 years of emissions from U.S. coal burning.¹⁸

5. Warming ocean water. The oceans are a huge CO₂ sink. They hold 60 times more carbon than the atmosphere and absorb almost 30% of carbon dioxide emissions from human activities. The summer of 2023 saw record sea temperatures. For example, some areas of the Gulf of Mexico reached 100°F. As shown in figure 2, the amount of CO₂ the ocean can adsorb is critically dependent on temperature.

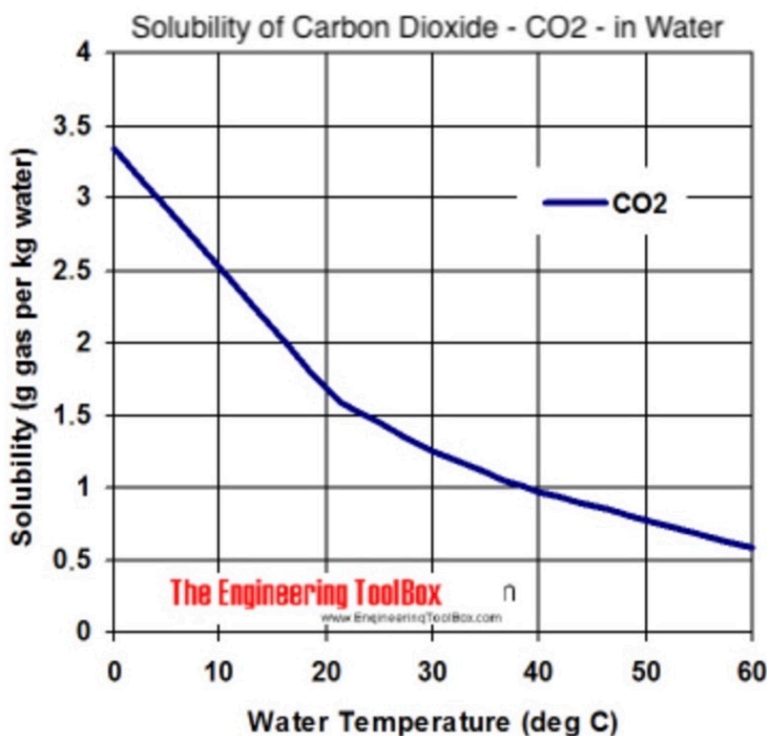


Figure 2. Solubility of CO₂ in water by temperature.

The average temperature for the sea water is 15 to 18°C. At 100°F or 38°C, the ability of the ocean to hold CO₂ would be decreased from 2 grams per kilogram of water to 1 gram, or by 50%. Figure 3 shows the increase in heat content of the ocean by year in Zetajoules.

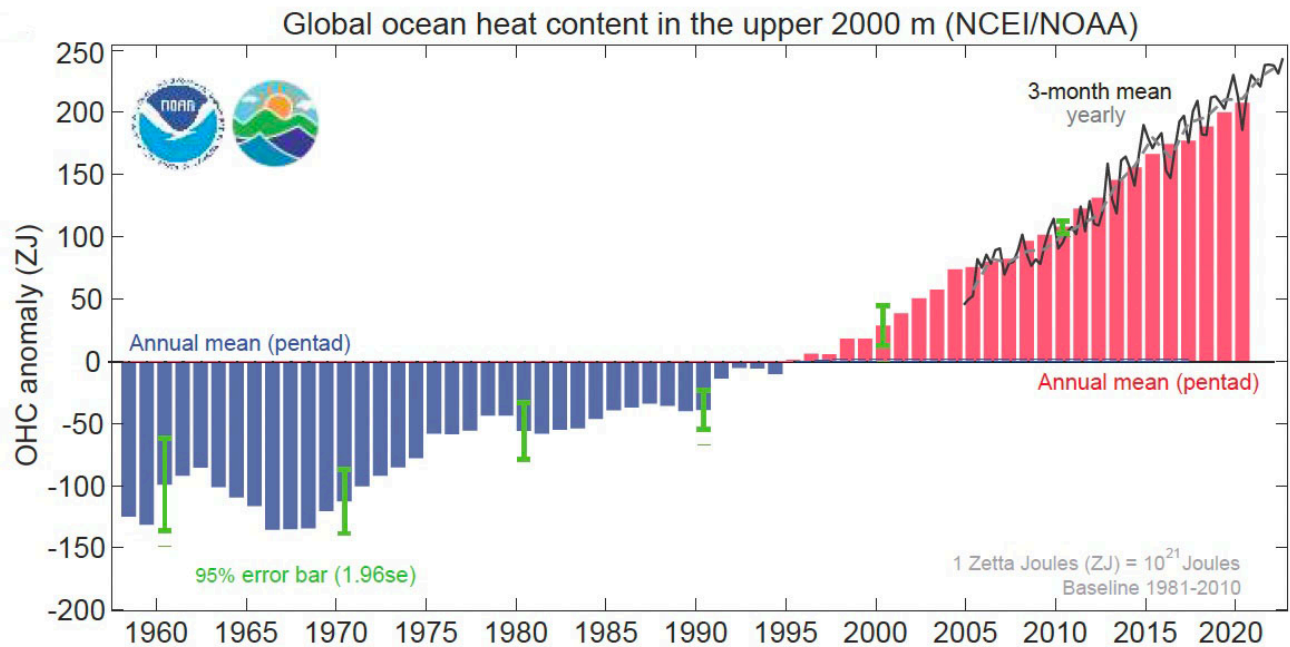


Figure 3. Ocean Heat Content by year. From NCE/NOAA.

The massive amounts of excess CO₂ in the atmosphere traps an enormous amount of energy from the sun that would otherwise have dissipated into space—about 93% of all this excess heat is absorbed into the ocean. The quantity is staggering, calculated at about 14 zettajoules of heat every year.²⁰ This is one joule with 21 zeros after it 1,000,000,000,000,000,000,000 joules. It is roughly equivalent to five Hiroshima type atomic bombs worth of heat energy going into the ocean every second. This means that, every day, 432,000 atomic bombs' worth of excess heat energy enters the ocean. Figure 3 shows the result of this heat transfer into the ocean. Rising ocean temperatures bolster the energy exchanges from ocean to atmosphere, increase the quantity of atmospheric moisture, and change the patterns of precipitation and temperature globally.²¹ Among other effects, this means more severe hurricanes.

Between 1982 and 2016, the number of days with marine heatwaves—defined as days on which the sea-surface temperature (SST) exceeds its local 99th percentile—has doubled. Warmer oceans also hold less oxygen, leading to anoxia contributing to ocean blobs. In October 2013, as described by the National Park Service, a strong and long-lasting high-pressure ridge in the Pacific Ocean created a mass of warmer-than-normal water by between 4- and 10-degrees F above average, that stretched over 1,000 miles between the North American and Asian continents and was up to 300 feet deep. It was the size of Texas and called the Blob after a science fiction movie of the same name. It later split into three distinct masses between 2013 and 2018. This produced three patches, one in the Bering Sea, one off the California/Mexico coast, and one off the coast of Canada, Washington, and Oregon. The many devastating effects of the blob included

killing phytoplankton which disrupted the entire Pacific food chain starving whales, salmon, herring, sardines, Alaskan cod, kelp, seals, and others. An elevation of nighttime temperatures even exacerbated forest fires.²²

In their article *Let Oceans Breathe*, Goodkin and Pullen²³ point out that while sea level rise and acidification have been the main focus of the effects of global warming on the oceans, deoxygenation should have equal prominence. They state that, “roughly 40 percent of the world’s people depend on the ocean for their livelihoods. If we do not save marine life from oxygen starvation, we starve ourselves.” Penn & Deutsch²⁴ report that the current rate of ocean warming could bring the greatest extinction of sea life in 250 million years.

Bolin and Eriksson²⁵ used an ocean model in which, correctly, only the surface or top two percent, mixed quickly with the atmosphere. This was a reality check which made it that much slower for the great bulk of the oceans to absorb CO₂. This indicated we could not rely on the oceans to absorb all our emissions of fossil fuels. As the ocean warms, it removes less CO₂ from the atmosphere, which leads to increased atmospheric CO₂ and increased warming.

6. Ocean Outgassing of CO₂. While the adsorption of CO₂ by the oceans is well recognized, it is much less appreciated that some areas of the ocean also release huge amounts of CO₂ back into the atmosphere. The areas of the greatest year-round out gassing are in the Equatorial Pacific west of Ecuador. Other areas such as the Arctic Ocean, the Southern Ocean around Antarctica and the Arabian Sea vary by season. In terms of gigatons of CO₂ per year the figures are 2.26 for the equatorial area, 2.6 to 7.7 for the arctic, 1.4 to 2.1 for the Southern Ocean, and 0.59 for the Arabian Sea.²⁶⁻³⁴ All together they amount to 6.85 to 12.65 gigatons of CO₂ per year. While this is an enormous amount of CO₂, it is generally considered that when balanced against the amount of CO₂ adsorbed by the ocean it is net zero. However, it is likely that as the ocean warms the balance may tip in favor of outgassing, leading to a significant bump in atmospheric CO₂

7. CO₂ Efflux from Rivers Liu et al.³⁵ reported that 112-to 209 million tons of CO₂ are taken up from the soil and then emitted into the atmosphere from streams and rivers each month worldwide, or 1.3 to 2.5 gigatons of CO₂ per year. They provided maps showing where this emission is the greatest.

8. Soil. The soil is also large reservoir of carbon and changes in the size of the soil carbon pool can significantly affect atmospheric CO₂ concentration. Warming would also increase rates of CO₂ production by soils, thereby exacerbating the CO₂ loading of the atmosphere and providing positive feedback to climate warming.³⁶ The rate of soil CO₂ emission varies for different crops and different organic fertilizers.³⁷ The higher the amount of organic fertilization

(chicken manure, dairy manure, and Milorganite) the higher the CO₂ emissions. Proper soil management can shift the balance to sequestration of CO₂.³⁸

9. Loss of albedo. The ice in the Greenland and the Antarctic reflect large amounts of solar radiation back away from the earth cooling it. The pair of GRACE satellites have shown that Greenland and Antarctic glaciers lost mass at a rate of 199 ± 32 Gt per year during a 14-yr period from 2002 to 2016.³⁹ This destroys this albedo effect⁴⁰ which means more of the sun's heat is retained in the earth. There is clear evidence that this is already having a major effect. The Arctic Region is warming up to four times faster than elsewhere.⁴¹⁻⁴³ This is called Arctic or Polar Amplification. The warming in the Arctic since the 1980s has been particularly strong, and the different datasets are in a close agreement. While several causative factors have been suggested⁴¹ the loss of sea ice with a resultant loss of albedo is the best documented cause. Figure 4 shows the effect of the loss of this albedo on Arctic warming.

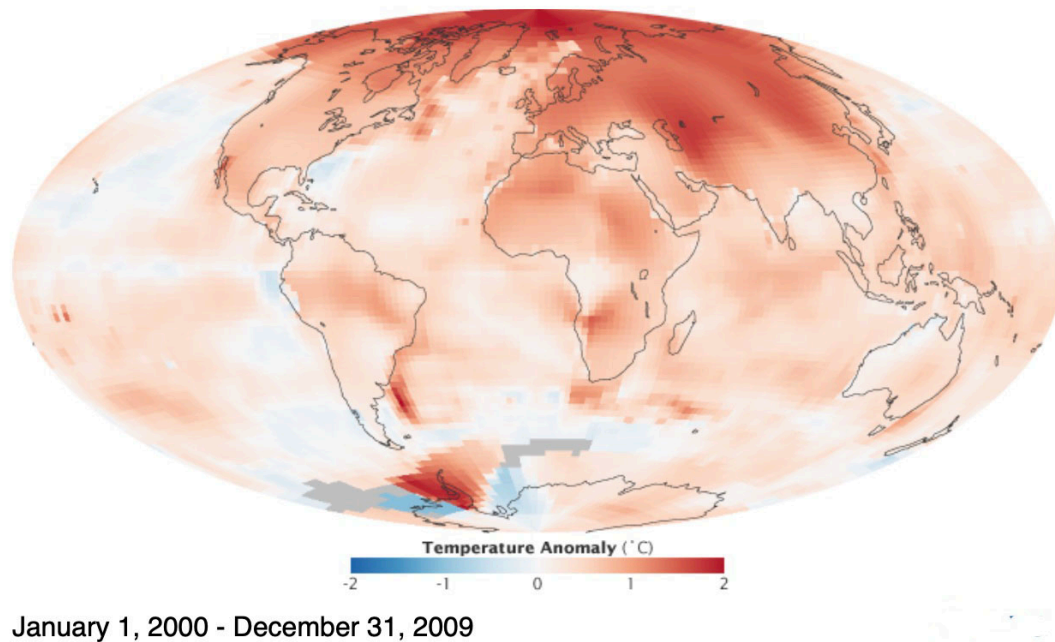


Figure 4. Warming of the Arctic. NASA image by Robert Simmon, based on data including ship and buoy data from the Hadley Centre. Caption by Adam Voiland. (NASA Earth Observatory, Arctic Amplification).

10. Melting permafrost. Beneath the Arctic's frozen surface there are huge amounts of organic carbon matter in the form of frozen soil and ancient plant matter called permafrost. It is estimated that there are 1.7 trillion tons of carbon as methane and CO₂ are stored in the arctic. This is 250 times the amount of methane currently in the atmosphere. In Alaska alone over 70

sites of leaking surface methane from melting permafrost have been found.⁴⁴ This is illustrated in Figure 5.



Figure 5. Melting permafrost in Alaska.⁵³ Photo: EnviroNews

It is estimated that even larger amounts of methane are stored deeper underground as fossil methane. This is also beginning to melt in an explosive manner, producing large sinkholes.⁴⁶ When permafrost begins to melt it releases large amounts of methane, which is 80 times more potent as a greenhouse gas than CO₂. This has already started in parts of Siberia and the Arctic.⁴⁷⁻⁴⁹ Permafrost thaw will add carbon dioxide and methane to the atmosphere at a rate on par with human emissions from India today and totaling around 150–200 Gt CO₂ by 2100.⁴⁹ The released methane is eventually oxidized to CO₂.

Several recent studies further illustrate the critical nature of the problem. A Swedish study⁵⁰ reported that between 2000 and 2020 the northern permafrost region emitted 12 Tg of CO₂-C/yr, 38 Tg of CH₃-C/yr and 0.67 Tg of N₂O-N/yr. (12 Tg of CO₂ = 12 million tons of CO₂.) When lateral fluxes were also included, the complete C and N budgets of the permafrost region result in net sources of 144 TgC/yr (including CO₂ and CH₄) and 3 Tg N yr. Lateral fluxes refer to the loss of soil carbon by leaching with water.⁵¹ Methane and nitrous oxide are far more potent greenhouse gases than CO₂. Of interest, melting of the permafrost has also played a role in arctic warming.⁵²

11. Melting of Methane Hydrates Gas hydrates are icelike structures formed when water and low molecular weight gases such as CO₂, H₂S and methane (CH₄), combine into a clathrate structure. Since methane is the primary gas involved, they are termed methane hydrates. The word clathrate is derived from the Latin *clathratus* meaning ‘with bars or latticed’. Methane

clathrates are especially common along the continental shelf where they are stable at 300 to 600 meters under the surface and at the low temperatures close to the sea floor. Worldwide it is estimated that gas hydrates contain up to 12,000 gigatons tons of carbon, more than the amount of carbon held in all fossil fuels on earth.⁵⁴ This shows why it is a tipping point. If ocean temperatures keep raising this trapped methane could be released to the atmosphere. There is evidence that this has happened before. The Paleocene-Eocene Thermal Maximum, (PETM) 55 million years ago, is believed to have been due in part to the release of many tons of methane from methane clathrates. This has been referred to as the methane burp hypothesis, or more technically as the gas hydrate dissociation hypothesis. It has been estimated that during PETM up to 1,600 gigatons of carbon were added to the atmosphere resulting in global warming of 5 to 7 °C (41 to 45 °F). Recent studies suggest that while some of the carbon was due to a methane burp, most may have come from volcanism.⁵⁵

On the bright side, there are several sinks that would mitigate the amount of methane leaked to the atmosphere if methane hydrates melted.⁵⁴ These included the anaerobic oxidation of methane by various microbes, the dissolution of methane bubbles by dissolving methane in sea water, the atmospheric oxidation of methane to CO₂ which is a less potent greenhouse gas, and others. None-the-less, the PETM, which is presumed to be due in part to gas hydrate dissociation, illustrates the potential risk despite the sinks.

12. Die off of phytoplankton. It is rarely appreciated that phytoplankton in the ocean sequesters as much CO₂ and produces as much oxygen as all the trees on land. ⁵⁶⁻⁵⁹ A major outstanding question is the sensitivity of this biomass to future ocean warming, both regionally and globally. If these die off because of increased temperature, ocean acidification, deoxygenation, or other changes in ocean chemistry, this huge reservoir of carbon dioxide will be lost. It would be the equivalent of a massive underwater forest fire.

The size of ocean biomass production is referred to as Net Primary Productivity or NPP. It is defined as gross primary productivity minus the rate of energy loss to metabolism and maintenance. It is the rate at which energy is stored as biomass by marine organisms and made available to the consumers in the ecosystem.

In the April 2023 heat wave NPP dropped by 22% in the equatorial regions of the Atlantic and Pacific, as well as the northern Atlantic.⁶⁰ All of these areas exhibited positive sea surface temperature (SST) anomalies. This decrease is not limited to a few heat waves. Based on satellite-in situ blended ocean chlorophyll records, Gregg, et al ⁶¹ reported that global ocean annual primary production has declined more than 6% since the early 1980's. The decadal decline in global ocean annual primary production corresponded with an increase in global sea surface temperature of 0.2°C ($P < 0.05$) over the same time period. Not only do phytoplankton generate half the atmosphere's oxygen they also form the base of virtually every ocean food chain, making most other ocean life possible. ⁶² A prolonged increase in ocean temperature would not only seriously compromise this important source of CO₂ fixation and O₂ production,

but also affect the food source for other marine life and billions of humans. The loss of this carbon sink would contribute to a major increase in atmospheric CO₂.

13. Plants switch from photosynthesis to respiration. As global temperatures increase a point is reached at which plants on earth begin to switch from photosynthesis (consuming CO₂ and producing oxygen), to respiration (consuming oxygen and producing CO₂). Duffy et al ⁶³ showed this by accessing measurements from the largest continuous carbon monitoring network, FLUXNET to determine the temperature dependence of global rates of photosynthesis and respiration. This was based on ~1500 site years of daily data from all major biomes and plant functional types. The photosynthetic machinery in tropical trees begins to fall at 46.7°C (117°F) (T_{crit}). Doughty et al ⁶⁴ using leaf thermocouples, pyrgeometers and remote sensing (ECOSTRESS) at multiple sites across the tropics, found mid-day peak temperatures of 34°C during dry seasons with temperature tails of over 40°C and T_{crit} temperatures 0.01% of the time. They concluded that that tropical forests can only withstand an additional temperature increase of 3.9 ± 0.5 °C before reaching a potential tipping point in metabolic function. If a significant percentage of terrestrial plants were to switch from photosynthesis to respiration the large amount of the resultant CO₂ would be catastrophic.

14. Air Conditioning This may seem like a strange candidate for a partial tipping point, but the hotter it gets the greater the need for air conditioning, and the greater the need for air conditioning to more greenhouse gases that are produced to run it, forming a positive feedback loop. Globally, 20 percent of the total electricity used in buildings goes to air conditioning. It has been estimated that by 2050 there will be 4.5 billion air condition units. Currently, this option is largely restricted to the wealthier countries forming one of the reasons climate change has a greater impact on the less wealthy countries.

More on rates Keeling's group at Scripps Institute published plots for the increase in the *rate of increase* in atmospheric CO₂ levels over time ⁶⁵ These were based on the variable Atmosphere Growth Rate (AGR) measured in gigatons carbon per year (Figure 6).

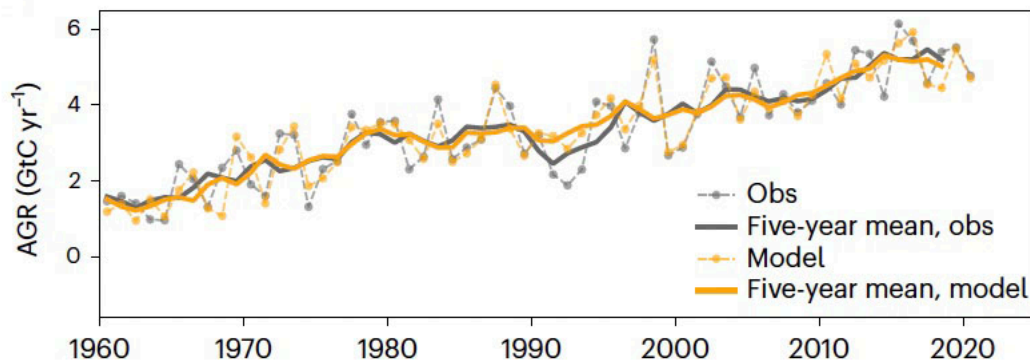


Figure 6. Comparison of the observed AGR to the growth rate. From Briner et al, 2023 ⁶⁵.

Over the time frame of 1960 to 2020, except for the time around the eruption of Mount Pinatubo in 1991 when AGR dipped, there was a steady increase from a AGR of about 1.8 gigatons carbon per year in 1960 to about 5 gigatons carbon per year in 2020. This generally agrees with Figure 1 where the rate was measured in ppm per year. Both showed a progressive increase in *rate of accumulation* over time. It is important to note that regardless of the rate or AGR, at any rate the level of CO₂ is additive and the absolute amounts in the atmosphere would continuously increase, minus that due to the slow degradation of CO₂. They also showed a progressive decrease in the ocean CO₂ sink from about 0.9 gigatons carbon per year in 1960 to about 3 gigatons per year in 2020. Their modeling, that includes AGR + land use + terrestrial carbon exchange + delta or budget imbalance + the ocean sink, accurately predicts the earth's carbon cycle to within 0.5 gigatons per year.⁶⁵ A significant contribution of multiple partial tipping points would show up in one or more of these variables, possibly in AGR or terrestrial carbon exchange.

Discussion

The best evidence that a multifactorial CO₂ tipping point is already occurring comes the fact that a number of the above candidates are clearly already happening. These are temperate area forest fires, boreal area forest fires, the burning of peat, melting of the permafrost, loss of albedo resulting in accelerated Arctic warming, a periodic die off of phytoplankton, and warming of the land and ocean. The years 2023 and 2024 have already shown the highest levels of global temperature on record ⁶⁶. This suggests that it is not necessary to wait until one or more tipping points becomes fully expressed for tipping points to make a significant contribution to atmospheric CO₂ levels. Such a multifactor tipping point would produce a positive feedback loop that could become irreversible. What are the implications of this?

Does it mean cutting down on emissions is fruitless? Of course not. It would suggest just the opposite. We must redouble our efforts world-wide to more quickly get to net zero emissions.

Does it mean massive efforts at carbon dioxide removal (CDR) are necessary? This is a definite yes! These are called Negative Emission Technologies or NETs. It has been suggested that it will be necessary to permanently remove 10 gigatons of CO₂ from the atmosphere each year until 2050 and then 20 gigaton of CO₂ to the end of the century.⁶⁷ This may be too conservative. Currently the emphasis is on direct air capture and sequestration of CO₂ (DACS) with the sequestration being done by burying the CO₂ underground. While this can easily remove thousands and even millions of tons of CO₂ there are problems and some skepticism both about its safety and if it can reach multiple gigatons levels.⁶⁸

It is clear that additional NETs must quickly be added to the list. Enhanced Weathering uses crushed ultramafic rocks such as magnesium silicates (olivine) and mafic rocks such as basalt.⁶⁸⁻⁷⁴ that capture CO₂ and convert it to a permanent mineralized form. There are significant deposits of ultramafic rocks in the U.S. and world-wide but currently very little of these ‘climate rocks’ are being mined for this purpose. It has been suggested that enhanced weathering could be scaled up to capture 2–4 gigatons of CO₂ per year by 2050, with rates of more than 20 gigatons per year theoretically possible by 2100.⁷⁵ Cost estimates vary widely, from less than \$50 per ton of CO₂ sequestered to more than \$200 per ton.

In addition to spreading finely ground ultramafic rocks on land, they can also be placed in the ocean. This is called OAE or Ocean Alkalinization Enhancement.^{68,76,77} Like Enhanced Weathering this also requires large amounts of ground ultramafic rocks.⁷⁸

There are many minor NETs that should also be utilized. Together they could contribute multiple gigatons per year of sequestered CO₂.⁷⁹ In its 2023 Sixth Assessment Report, the Intergovernmental Panel on Climate Change⁸⁰ pointed out that the many other NETs such as “biological CDR methods like reforestation, improved forest management, soil carbon sequestration, peatland restoration and coastal blue carbon management can be utilized.”

Just as a combination of multiple partial tipping points may have brought us to the current situation, multiple NETs will be necessary to solve the problem. I have suggested that enhanced weathering and OAE needs to be added to the mix.⁶⁸ They have the advantage that the CO₂ is safely sequestered above ground or in the ocean, and there is far more room above ground and in the ocean than underground. There are many other advantages.⁶⁸

If the earth enters a multifactorial tipping point forming a positive feed-back loop, as proposed here, it does not bode well for easy answers to global warming. It is analogous to a swimmer caught in a whirl pool – very difficult to swim out of. Cutting emissions to zero will be necessary but that will not be enough because many of the multiple partial tripping points, such as forest fires, melting permafrost, melting sea ice with a decrease in albedo, die off of phytoplankton, and others, will continue to grow. A herculean, Manhattan/Apollo type project,

activating many different NETs will be required. And the last thing needed is political interference by climate change deniers. That would be disastrous.

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