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Article

The reality and cause of global warming and what can be done about it

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Abstract: The observed mean global surface temperature has increased 1.2 °C above pre-industrial values along with an increase of atmospheric carbon dioxide (CO_2) above 400 ppm last seen millions of years ago when sea-levels were 20 meters higher. A causal link between the rising global temperatures with accumulating atmospheric greenhouse gases is established using a simple no-feedback radiative model and shows changing CO_2 concentration is the dominant driver. Extrapolating fits to temperatures and CO_2 observations on a "business-as-usual" basis yields an additional 0.32 °C temperature rise in 20 years with CO_2 doubling to 556 ppm in 31 years and suggests an equilibrium climate sensitivity of 3.4 °C. An aggressive pursuit of carbon replacement and sequestration strategies is recommended, employing limited solar geoengineering in the polar regions if necessary to limit further erosion of ice-shelves. Policies should be rendered, not only to achieve net-zero goals, but to reduce CO_2 levels below 400 ppm to avoid risking an otherwise inevitable and dramatic sea-level rise.

Keywords: climate change, greenhouse gases, atmospheric CO_2, sea-level rise, advanced nuclear, regenerative agriculture, solar geoengineering

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1. Introduction

1.1. Warming oceans, surface temperatures rising with atmospheric greenhouse gas concentrations

Recent extreme weather events have shocked the meteorological and climate research communities. Intense rainfalls have hit Libya, Greece and California resulting in historic flooding and loss of life and are widely attributed to extreme ocean warming [1] (see Figure 1). The Artic has warmed four times faster than the rest of Earth's surface over the

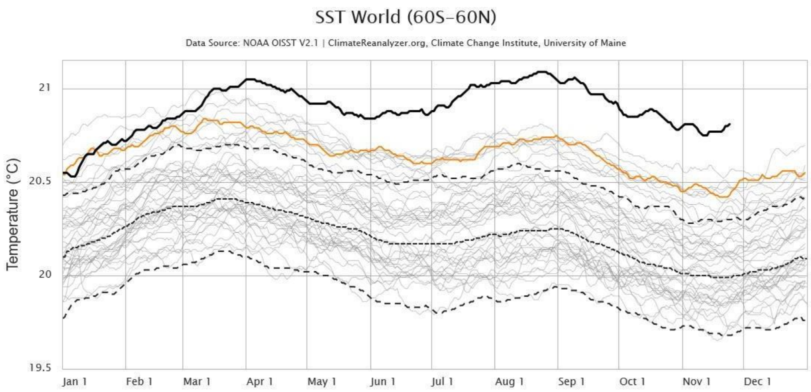

Figure 1. University of Maine's Climate Re-analyzer [2] shows an ocean surface warming event 4σ away from the 1979-2022 dotted-line median as of November 2023. It is due to an El-Nino on top of a mean surface climate warming trend located near the orange curve.

past four decades [3] causing significant sea-ice loss and a reduction of the meridonial thermal gradient. The result is blocking weather patterns [4] that prolong heat-domes [5] and together with a warmer wetter atmosphere drives brush growth through heavy rains followed by droguths in many semi-arid areas, and has led to terrible conflagrations in Maui and Canada (cf. Figure 2). While part of this year's ocean warming can be attributed to

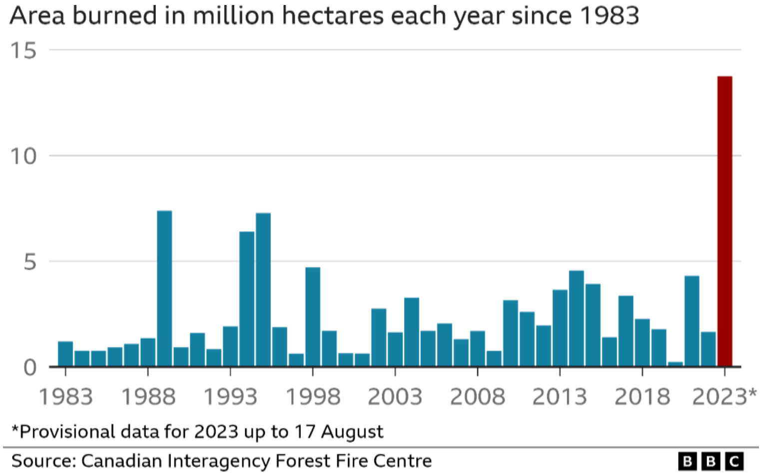

Figure 2. Canadian wildfires have burned an astronomical amount of land this year with over 1000 fires active mid-August, two-thirds of which remained out of control [6] at that time.

the El-Nino phase of the Southern Oscillation, the latter comes on top of the much larger warming trend (see Figure 3). Global mean surface temperatures have risen 1.2 °C since 1750, three-quarters of it in just the last 50 years.

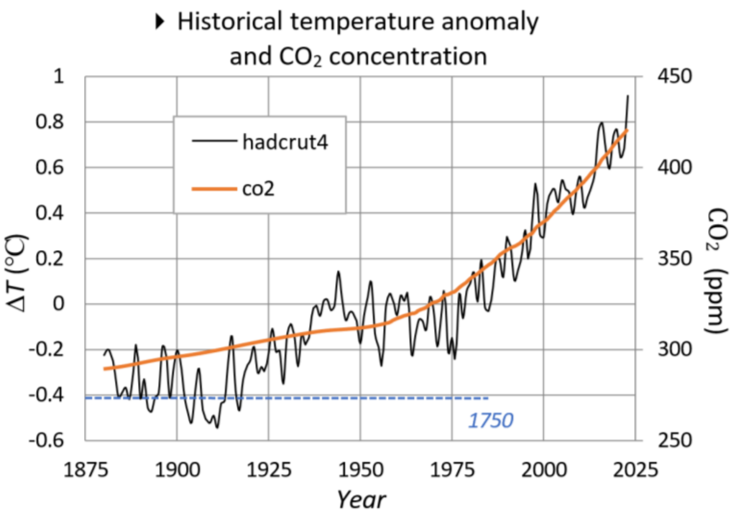

Figure 3. The global temperature anomaly Δ*T* (left-scale) [7] and CO2c (right-scale) [8] are compared. The value -0.41°C is the estimated offset to pre-industrial temperatures (1750-1800 using HadCet in [7]) when CO2c was 278 ppm.

Remarkably, what looks like a temperature "trendline" in Figure 3 is actually the CO_2 concentration (CO2c) plotted on a well-chosen scale. The correlation is self-evident, where the rates of change in temperature and CO2c in the 48 years since 1975 are, respectively, 12× and 8× those in the 200 years prior.

1.2. Natural vs Man-made greenhouse warming and climate sensitivity

A study of paleoclimate yields deep insight into the cause-and-effect relationship of CO2c and temperature change. During the ice-ages of the last half-million years temperature, CO2c and sea-levels have moved together in cycles [9] (see Figure 4). Note the temperature rise of Figure 3 only appears as a blip in Figure 4 due to differences in plot resolution and scale. A significant milestone the understanding of ice-ages was achieved when Hansen, et al. [10] reproduced the ice-age temperature time-series. during the ice-ages over the last 800-Kyr. Their calculation was based upon albedo and changing greenhouse gas (GG) concentrations. These drive surface temperature change and, in turn, altered ice-sheet area (as inferred from sea-level change) causing positive albedo feedback.

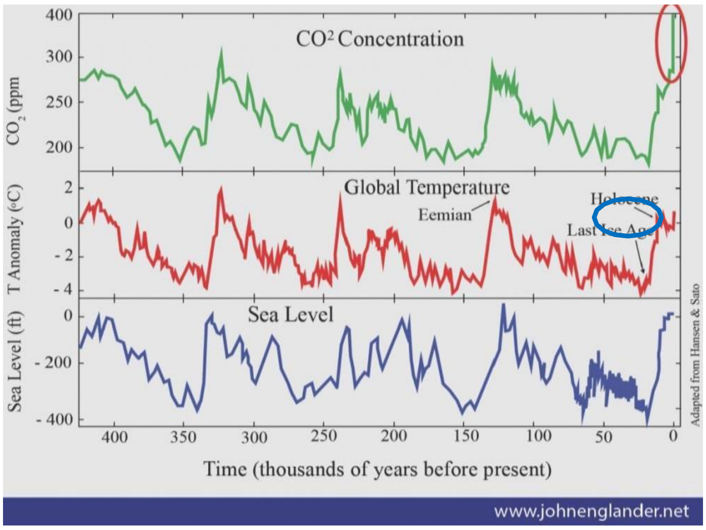

Figure 4. 100-Kyr cycles of temperatures, sea level and CO2c dance in phase. Circles denote recent temperatures of the Holocene which currently lags behind the upward explosion of CO2c to 420 ppm - well above prior interglacial highs near 300 ppm.

This process continues until reversed at turning points in Milankovitch axial tilt and orbital eccentricity cycles where the latter slowly modify the absorbed solar flux due to changing solar incidence angle on Earth's north-south land mass asymmetry.

However, fundamental changes to the global climate system have arisen since the beginning of fossil fuel powered industrialization. Despite negligible surface albedo change from polar ice reduction and too short a time scale for orbital cycles to come into play, CO2c has shot up to 420 ppm. The last time it was this high was five million years ago during the Pliocene when Greenland was devoid of ice and beech trees grew along Antarctic coasts (cf. Fig. 8 in [11]). Abrupt changes have also appeared in rates of change of temperature and CO2c: it took only 120 y for the CO2c to rise 120 ppm in the industrial era (Figure 3) while it took 9,000 y to rise 100 ppm from the last glacial maximum (Figure 4), a ratio of over 100 to 1; similarly, rates of temperature change exhibit a ratio of 30 to 1 during their respective periods. Natural climate drivers are insufficient to account for these differences – only man's activity can account for them (at greater than 95% likelihood [12]) – especially in the burning of fossil fuels.

The notion that fossil fuel burning might itself cause GG warming was first proposed in 1896 by Swedish Nobel chemist Svante Arrhenius. In trying to explain ice-age cycles, he concluded Earth's atmosphere would warm roughly 5 °C for every doubling of CO2c [13]. Now understood to be an asymptotic temperature shift resulting from a doubling of CO2c, it is called the "equilibrium sensitivity", "doubling sensitivity", "climate sensitivity", or simply "sensitivity". Modern values determined from global circulation simulations are closer to 3.0 °C (cf. [10, 14]) to 3.5 °C [15] which agree independently with values determined from recent observations of clouds and their inferred feedbacks [16, 17].

In section 3 the causal link between rising CO2c and global temperatures is solidified with a "toy" climate model that shows the time-series of modern warming is driven almost exclusively by the accumulation of atmospheric GGs, CO2 being the primary agent. Extrapolations of temperature and CO2c data show there is little time before levels of CO2c (e.g., doubling) and global surface temperatures (e.g., the value of 1.5°C generally deemed a critical value [18]) are breached. Therefore, recommendations are made in section 4 for policies that limit and reverse damage done by CO2c increase.

2. Methods and Materials

The thermometric data from the Hadley Climate Research Unit (HadCRU) version 4 (hadcrut4) is augmented by the 2021-2023 years of version 5 data so the 2021 version 5 value is coincident with the 2021 version 4 [7], retaining differences after that. This yields better agreement with the satellite data of the last 20 years than version 5 alone. Satellite data from the University of Alabama at Huntsville (UAH) is found on Roy Spencer's website [19]. The GG concentration data is obtained from Scripps [8] and Meinhausen, et al. [20] to apply in model calculations, while forcing time-series are obtained from the Prather, et al. [21] and calculated using Etminan, et al. [22]. Data is loaded into Excel spreadsheets for the calculation of model results and the rendering of Figures 3, 5 and 6.

3. Results

3.1. A simple radiative forcing model of greenhouse gas driven global warming

The Central to understanding sensitivity is the concept of "radiative forcing" (RF). RF is a perturbation in the Earth's surface-tropospheric energy budget that drives (or "forces") the global mean surface temperature away from an initial equilibrium temperature T by an amount

$$\Delta T = \lambda \Delta F \tag{1}$$

where λ is the "sensitivity parameter" and ΔF is the net RF (1 unit of forcing is 1 W/m^2). The latter can be decomposed into a sum over individual forcings from such sources as land-use, solar intensity, CO2c, other GGs or aerosols. A radiative energy budget, where feedbacks and thermal inertia of oceans are ignored, yields [23, 24]

$$\Delta T = T\,\Delta F/[S(1 - \alpha)] \tag{2}$$

where $S = 1367 \pm 7$ W/m^2 is the solar constant [25] and $\alpha = 0.306$ is Earth's albedo [26]. Using $T = 288K$ in 1750

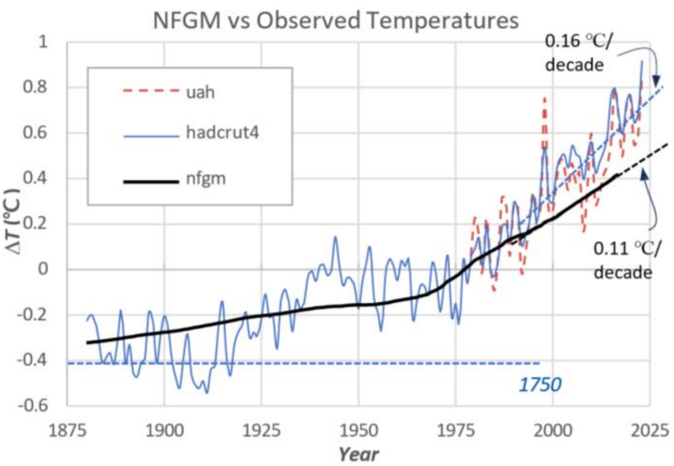

Figure 5. Global temperatures from hadcrut4 and UAH through 2023 are plotted along with the NFGM from 1880 to 2018. Dashed lines with slopes are linear fits for years after 1990.

and the RF time series [21, 22], eq (2) yields the curve in Figure 5. Results are obtained just using Excel, i.e., without resorting to super-computers and months of computation. To keep the curve simple and smooth small contributions of the 11-year sunspot cycle and volcanic forcings are excluded. Since GG forcings dominate it is called the no-feedback greenhouse model (NFGM). Interestingly, agreement with the observed trend up to about 1990 shows that thermal inertia lag of the oceans apparently negate amplifying feedbacks. After 1990, however, the observed and NFGM diverge with linear regression slopes of 0.16 vs 0.11 °C/decade, respectively. The discrepancy is likely due to those same feedbacks and thermal inertia ignored in the model. A full linear response theory (cf. [27]) that includes those effects should be explored to confirm that hypothesis.

3.2. Future projections of CO2c and implications for temperature and sensitivity

We can extrapolate both the temperature and CO2c time series into the future and obtain the doubling sensitivity. Plotted in Figure 6 are both the observed CO2c [8] and an exponential fit. The extension into the future time is

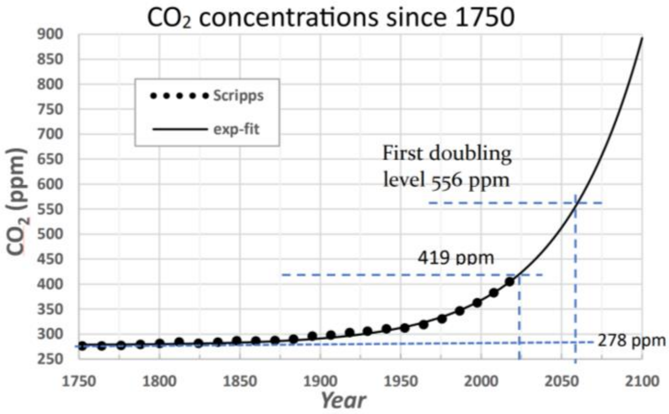

Figure 6. An exponential fit to the Scripps CO2c data as it rises above its 278 ppm asymptote. Extrapolating out in time leads the first "business-as-usual" doubling of CO2c in about 30 y while the next doubling takes an additional 50 y or so. Compare the latter to the time from 1750 to first doubling of about 300 y.

thus made on a "business-as-usual" basis. The first doubling to 556 ppm is reached in 2055 or so. A linear extrapolation of temperature beyond the 1.2℃ already seen since 1750 by using 0.16 ℃/decade from Figure 5 yields an additional 0.32 ℃ above to 1.5 ℃ in 20 years, and 1.7 ℃ at doubling in 32 years.

Continuing further, the 2.0 ℃ level will be breached by the early 2070's, although the exponential nature of the CO2c curve suggests that accelerating temperatures would reach that mark some years earlier. Of course, these are rough estimates as RF from aerosols or land-use can also undergo significant change.

Interestingly, global ocean-atmosphere coupled circulation simulations reveal that half the equilibrium sensitivity is achieved in just a few simulated decades from fast feedbacks (that include cloud modeling implicitly) and ocean mixing in upper layers, the rest taking much longer (~ millennia) due to deeper down- mixing [27]. This suggests that a rule of "roughly half-now, half-later" pertains, especially for the rapid rise of CO2c since 1970 or so. Following that line of reasoning the equilibrium sensitivity becomes 3.4 ℃, i.e., roughly twice the "transient" temperature at doubling, and within the range of values noted in section 1.2.

4. Discussion

The effect of climate change so far has been a kind of "slow cook" with subtle changes happening over a lifetime, and those mostly at the poles. This, along with shortsighted financial considerations of industry, the complexities of the climate system, and alarmist claims that didn't pan out, has led many to dismiss or minimize the urgency of global warming, its human origins, and potential consequences. It was only the NFGM that convinced this author of the underlying validity of anthropomorphic GG driven climate change.

But times are changing. Without addressing man-made increases in atmospheric GG concentrations, we can expect more serious versions of events experienced this summer, with temperatures to reach 1.5 ℃ in 20 years, with occasional El-Ninos adding another 0.2-0.3 ℃. The negative phase of the Atlantic Multi-decadal Oscillation might mitigate that over the next decade or two, but what of 20 years past that? A more serious risk is an Eemian-like future when sea-levels were 5 m higher (cf. [28]), and to think that sea- levels were 20 m higher in the Pliocene when the CO2c was at similar levels as today [29] is even more troubling. We are not nomads; coastal city skyscrapers cannot be relocated.

The conclusion is simple: we must return to CO2c levels below (probably well below) 400 ppm to be nearer to the historical warm cycle norms of human experience. As long as ice-shelf loss is reversible the author sees no cause for alarm – yet; however, there is a need for urgency, especially seeing much of the populace remains in denial. Regardless, the trend of GG accumulation in the atmosphere must not just be stopped, it must be reversed. Recommendations for action are found in the following.

Land-use is one of the basic forcing mechanisms that also contributes to the carbon-cycle. The Rodale Institute makes the remarkable claim that over 100% of CO_2 current emissions can be sequestered using organic agriculture as the soil binds CO_2 out of the air and limits loss once there [30]. If this is widely confirmed, it would be like a saving miracle. Deforestation has been a drag on carbon uptake, but reforestation can reverse that. One company (Flash Forest) already utilizes drones to reseed burned out timberlands. Heat-island effects in cities and suburban surroundings can be mitigated by planting trees and vegetation along streets, in parking lots and on building rooftops, cooling the surface environment, and making the environment healthier, more comfortable and more beautiful.

However, as promising as organic farming might be, widespread adoption takes time. It only seems prudent to gradually reduce reliance on fossil fuels to at least "net zero" conditions and replace with alternatives. Solar and wind are being successfully employed but they have limited availability (e.g., night vs day, windy vis quiescent) and other downsides (e.g., wind's destruction of avian life, visual and noise pollution). Nuclear power is the obvious high availability option, but older fission reactor designs will not go forward given the disasters at Fukushima, Chernobyl and Three-Mile Island. Nuclear fusion may be the ultimate hope, but neither tokomak nor laser ignition implementations have achieved breakeven.

Nevertheless, there are promising new "advanced nuclear reactor" designs, fission reactors which are smaller, cheaper, and safer that avoid inherent instabilities in older designs. Advanced designs include small modular reactors (SMR) from NuScale (that received U. S. regulatory certification early this year [31]), Bill Gates' TerraPower (Natrium), the Dow X-energy joint SMR project (using X-energy's novel TRISO- X fuel), Holtec International, Westinghouse's eVinci and BWXT Technologies micro reactors, and SMRs that employ molten-salt heat-exchange like Moltex Energy and Kairos Power [32, 33]. Adoption can be a hurdle due to cost (cf. [33]), fuel storage and recycling are headaches; however, society will have to weigh the benefits of a such highly reliable and available energy sources against 1) its costs and risks, 2) the increasingly clear costs and risks of sticking with fossil fuel, and 3) the costs and benefits of other renewables like hydro, geothermal, ocean tidal, bioenergy, and wind which all have their own limitations (e.g., availability in time and or region).

Powering transportation is another key issue. There is really no carbon-free replacement yet for diesel or gasoline powered cars or trucks. Electric vehicles (EV) are only clean if they work off non-fossil fuel infrastructures which are not so common today. And without fast charge-up times (on the order of that of gas or diesel refill) long-distance commercial EV transport will remain impractical and EV car travel will remain problematic on long road-trips. Hydrogen based solutions like fuel cells may be a pathway forward, but current volumetric inefficiencies make storage, delivery and use unattractive. Therefore, research into practical carbon-free transport technologies will be an important component of any net-zero strategy.

There is hope that mankind can quickly change course by combining education and regulatory encouragement of net-zero policies. However, if we continue to "drag our feet" on organic farming or power generation transformation, we will have to consider buying time through a limited application of solar geoengineering, say, by inserting an albedo enhancing aerosol like SO_2 into the stratosphere at the poles, and without prohibitive cost [34, 35]. In this way agricultural output in the mid-latitudes could be maintained while at the same time limiting or reversing ice-shelf damage. Furthermore, the short-lived nature of such an aerosol, that naturally occurs due to volcanism anyway, would limit unforeseen negative effects in case of miscalculation. Unfortunately, even this stop-gap approach has the potential of "moral hazard" that could undermine discipline in curtailing GG emissions.

It should be emphasized that the success of any carbon-reduction policy needs the participation of the entire international community, especially the key industrial nations; without it any strategy will be crippled. And whatever path is decided, action must be taken soon.

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