



What Causes Increasing Greenhouse Gases?

Summary of a Trilogy

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The Intergovernmental Panel on Climate Change (IPCC) classifies the human influence on our climate as extremely likely to be the main reason of global warming over the last decades. Particularly anthropogenic emissions of carbon compounds, with carbon dioxide (CO₂) as the main culprit and methane (CH₄) as a distant second, are made responsible for the observed temperature changes, while any natural forcings are almost completely excluded.

This post summarizes the results of three studies [1-3] addressing the question, how much human or native emissions can be made responsible for the observed increase of Greenhouse Gases (GHG), in particular the rising mixing ratio of CO₂ in the atmosphere.

I. Control of Atmospheric CO₂: Relation of Carbon 14 to the Removal of CO₂

In a first study we perform an in-depth analysis on the record of atmospheric ¹⁴CO₂, an isotopic tracer of CO₂, to better understand how CO₂ is removed from the atmosphere [1].

The observed CO₂ evolution, inclusive of its annual cycle, has recently been reproduced in numerical simulations [4-7]. They show, how the abundance of CO₂ in the atmosphere is controlled by a competition between two opposing influences, the feed of CO₂ through emission, and its removal through absorption, both at the Earth's surface. This competition governs time-mean CO₂, where absorption figures centrally. It determines if and how fast CO₂ grows, as well as the magnitude of its perturbation, e.g., by anthropogenic emission. Yet, actual observations of CO₂ absorption are scarce. However, the impact of global absorption on atmospheric CO₂ is represented in carbon 14, an isotope of atmospheric carbon that has been observed in the troposphere since the 1950s [8].

Carbon 14 has a radioactive decay time of 8267 years (e-folding time). On time scales of relevance, the operation of ¹⁴CO₂ is virtually identical to that of the preponderance of carbon dioxide molecules, ¹²CO₂, comprised chiefly of the stable isotope carbon 12. Dynamical, chemical, and thermodynamic processes acting on those two isotopes of CO₂ (including those in the biosphere) are, for practical considerations, indistinguishable.

This feature makes carbon 14 a unique tracer of atmospheric CO₂ and provides an unrivalled means, through which to understand key mechanisms controlling the evolution of atmospheric CO₂. Once CO₂ is introduced into the atmosphere, whatever influence is experienced by one isotope is experienced by the other. Owing to this property and its artificial enrichment by nuclear testing, ¹⁴C is central to estimates of CO₂ absorption, which vary widely. Absorption, in turn, is essential to understanding changes of atmospheric CO₂.

During the 1950s and early 1960s, atmospheric testing of nuclear devices sharply enriched ¹⁴C in the stratosphere. Through the atmospheric circulation, ¹⁴C-enriched air in the stratosphere was subsequently transferred into the troposphere. By 1963, when the Nuclear Test Ban Treaty

(NTBT) was implemented, tropospheric ^{14}C had increased by nearly 100%. The NTBT virtually eliminated the anomalous nuclear source of ^{14}C , leaving its perturbation of ^{14}C to decline through absorption and overall ^{14}C to return to its unperturbed equilibrium abundance. Represented in the decline of ^{14}C is the removal of all CO_2 , through its absorption at the Earth's surface.

Our analysis of the ^{14}C record reveals that in addition to long-term behavior it is also important to consider short-term changes that have been largely ignored. Those changes exhibit the underlying mechanisms responsible for the observed decline of atmospheric $^{14}\text{CO}_2$ and, thereby, for removal of overall CO_2 . They represent effective absorption that is considerably faster than appears in the average decline of $^{14}\text{CO}_2$, initially and also later in its long-term decline.

This means we have to distinguish between direct absorption with an absorption time of only about 1 yr, and an effective absorption with an absorption time τ_{eff} up to 10 yrs, the latter depending on the degree of re-emission of previously absorbed CO_2 back from the Earth's surface to the atmosphere [6].

Fluctuations of emission operating on time scales of only a couple of years introduce anomalous CO_2 that falls within the short-time regime, i.e., before re-emission can intensify and offset direct absorption. Such perturbations will therefore experience effective absorption that is fast, comparable to direct absorption. On the other hand, emission that varies slowly or is invariant will introduce anomalous CO_2 that falls within the long-time regime, when re-emission has intensified and offsets direct absorption. Such perturbations will therefore experience effective absorption that is slow, operating at only a fraction of the pace of direct absorption.

The average decline of $^{14}\text{CO}_2$ is slowed initially by periodic re-enrichment from the stratosphere, which offsets direct absorption at the surface. Finally, however, its decline is slowed by re-emission of absorbed $^{14}\text{CO}_2$ from the surface, which likewise offsets direct absorption. Based on these fundamental principles and solving the coupled balance equations for the stratosphere, the troposphere and Earth's surface this reproduces the observed evolution of $^{14}\text{CO}_2$, on long as well as short time scales.

Applying the same considerations to anthropogenic emission of CO_2 recovers effective absorption that is an order of magnitude faster than the mean decline of $^{14}\text{CO}_2$. The difference follows from magnified disequilibrium between the atmosphere and the Earth's surface. While $^{14}\text{CO}_2$ was perturbed impulsively by nuclear testing, the absorption of anthropogenic CO_2 is perturbed continuously by fossil fuel emission. This continuous anthropogenic emission maintains a disequilibrium between the atmosphere and the surface. Thereby, it inhibits a larger offset of direct absorption by re-emission and thus, results in faster effective absorption of anthropogenic CO_2 .

Altogether, the observed behavior of $^{14}\text{CO}_2$ provides an upper bound on the anthropogenic perturbation of atmospheric CO_2 , which can only contribute a few percent of the observed increase.

From the IPCC's own estimates of extraneous carbon reservoirs, the anthropogenic contribution to increased CO_2 has been shown to be no more than 15% - 35% [4 - 7]. The present analysis does not rely upon such estimates and shows that the anthropogenic perturbation must even be smaller.

II. Control of Atmospheric CO_2 : Influence of Tropical Warming

In the second part of this three-pronged study we explore an important natural influence that likewise figures in the control of atmospheric CO_2 [2]. Surface processes which regulate emission and absorption of CO_2 depend intrinsically upon temperature. Many, like soil respiration, even increase exponentially with temperature, typical of Arrhenius temperature dependence that operates in chemical reactions underpinning surface processes.

Global temperature today is ~ 0.7 K warmer than it was half a century earlier. The most reliable record of global temperature is the satellite record from the Microwave Sounding Unit (MSU) suite of instruments [9], which retrieves temperature with homogeneous and near-global sampling

of the Earth. It indicates that over much of the Earth, surface temperature underwent no systematic (e.g., ubiquitous) heating during the last four decades, over which it was observed by MSU. Perceptible heating was only introduced by just two brief intervals, both not more than about two years long: one preceding the El Niño 1997, the other the El Niño 2016. Such heating in 20 years separated steps would be virtually impossible by continuously emitted anthropogenic GHG, which are mainly released in the northern midlatitudes.

Exceptional, however, is surface temperature in the tropics, where temperature systematically increased during the four decades observed by MSU. The sustained increase is also mirrored in the independent record of anomalous sea surface temperature from the Hadley Centre [10].

Owing to the dependence on temperature of physical and chemical processes that regulate CO₂ emission, CO₂ must have experienced a parallel influence. This can directly be scrutinized by investigating the interdependence of the observed temperature records and the *net* CO₂ emission, the component of emission that actually changes CO₂ and is derived from the measured concentration in the atmosphere as the instantaneous rate of change of CO₂.

As widely accepted reference we rely on the measurements of CO₂ at Mauna Loa, Hawaii [8], which are largely free of local distortions, at least till November 2022. They approximate the global abundance of CO₂, which, on time scales longer than a month, is well mixed over the free atmosphere.

Thermally-induced emission, especially from tropical land surface is found to represent much of the observed evolution of net CO₂ emission. It accounts for sporadic intensifications of net emission that operate on interannual time scales, notably, during the episodes of El Niños, and equally well for the long-term intensification during the last half century. Jointly, these unsteady components of net emission determine the thermally-induced component of anomalous CO₂ and closely track the observed evolution of CO₂ (see also Part III, Figure 1).

The veracity with which the thermally-induced component reproduces the observed evolution of CO₂ has two important implications: (i) Tropical land temperature should be a robust predictor of atmospheric CO₂. By contrast, other contributions to net emission which operate incoherently with the temperature afford virtually no predictive skill. Such is the case for anthropogenic emission, upon which climate projections of the IPCC rest. (ii) The anthropogenic perturbation of CO₂ must be so small to lie almost within the noise of calculation. It can represent but a few percent of increased CO₂. That, in turn, requires a removal time, which must be of order only a year. Anthropogenic CO₂ is then removed from the atmosphere almost as fast as it is introduced, sharply limiting its accumulation in the atmosphere (see Part I).

In relation to CO₂, what is responsible for that warming is immaterial. Its influence on CO₂ should not be confused through circular reasoning. The observed warming, which forces increased CO₂ through intensified net emission, cannot itself be the result of increased CO₂. Otherwise, anomalous CO₂ and net emission that forces it would have increased twice as much as was observed: (i) the increase required to produce the observed warming plus (ii) the thermally-induced response to that warming, which, irrespective of what caused the warming, induces an intensification of net emission that is nearly identical to what is observed.

The direction of causation is also clear from the interdependence of net emission and temperature - for interannual fluctuations as well as for the long-term increase. In addition to having strong coherence with temperature, the two unsteady components of net emission have the same phase relationship to temperature, both varying *in phase* with temperature. The strong coherence and in-phase relationship to temperature reveal that, irrespective of time scale, changes of tropical temperature induce simultaneous changes of CO₂ net emission.

Under the opposite direction of causation, were the observed changes of tropical temperature induced by changes of CO₂, they would result in a fundamentally-different phase relationship. The time scale of thermal damping, which drives temperature towards thermal equilibrium, is only a couple of weeks. It is much shorter than both unsteady time scales. Through anomalous radiative

forcing, the comparatively gradual changes of CO₂ would therefore induce simultaneous changes of temperature, in phase with CO₂. However, net emission, which changes CO₂, must lead CO₂ by a quarter cycle. Net emission would thus also lead temperature by a quarter cycle - behavior contradicted by their observed in-phase relationship. Net emission of CO₂, which determines anomalous CO₂, is forced by changes of tropical temperature - not vice versa.

III. Theory of Increasing Greenhouse Gases

In the third and culminating part of this trilogy we investigate the physical mechanisms, through which observed warming can produce the observed evolution of CO₂ [3].

Our preceding studies on nuclear-perturbed carbon 14 [1] and on thermally-induced emission, notably in the tropics [2], were inspired by numerical simulations which, on the basis of observed temperature, were able to reproduce the observed evolution of atmospheric CO₂, including its annual variation and stepwise increase [4 - 6]. In this contribution we integrate these findings and explore the underlying physical mechanisms in an in-depth analysis by calculating the net emission of tropical oceans and land as response to temperature variations.

The conservation law governing atmospheric CO₂, supported by the *observed* temperature dependence of surface fluxes and *observed* temperature in the tropics, is then used, first to calculate the time-varying response of CO₂ net emission and as integral the atmospheric concentration or mixing ratio r_A , which can directly be compared with measurements at Mauna Loa [7].

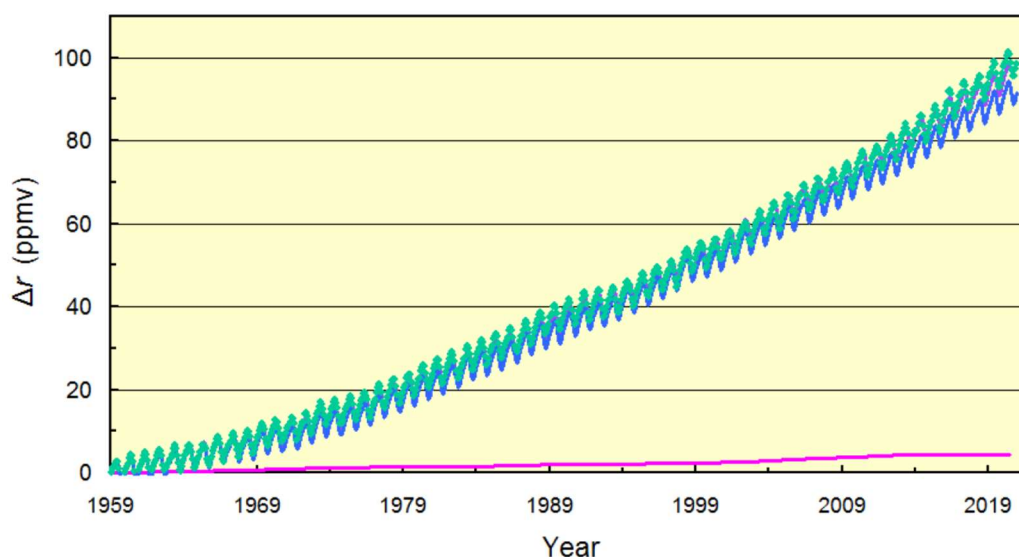


Figure 1: Observed increase of CO₂ (Green), compared against the calculated increase (Purple) that lies mostly beneath observed CO₂, but emerges near the end of the record. Plotted separately is the contribution from thermally-induced emission (Blue) and from anthropogenic emission (Magenta).

In Figure 1 is displayed the observed increase of r_A (Green). Superimposed is the calculated anomalous CO₂ that is forced by the total emission (Purple - almost completely covered by the Green Graph). It closely tracks the observed evolution of anomalous CO₂. Almost as closely tracks the calculated component of thermally-induced CO₂ (Blue).

Also superimposed in Fig. 1 is the anthropogenic component of anomalous CO₂ (Magenta). Comparatively small, it tracks the instantaneous equilibrium level of anthropogenic CO₂. With an effective absorption time of about 1 yr, as this results from an independent analysis of the induced anthropogenic CO₂ changes, relative to mean net emission during the Mauna Loa era, the anthropogenic component represents not more than 4% (see also Part I).

Like carbon dioxide emission, also CH₄ emission increases with temperature. It too is emitted by

biomass, chiefly through anaerobic processes that operate in well-irrigated regions like wetlands, and those influences magnify CH₄ emission particularly from tropical land, where biomass and precipitation are abundant.

The simultaneous intensification of CO₂ and CH₄ emission is precisely what is expected from observed warming in the tropics. Therefore, this single physical mechanism provides a unified understanding of the joint increase of these greenhouse gases, one that follows naturally from thermally-induced emission.

Altogether we find a strong correspondence to observed net emission that follows theoretically from behavior in the tropics - not in the extratropics, where anthropogenic emission is concentrated. Independently, the same correspondence to observed net emission follows empirically from anomalous temperature in the tropics (see Part II), as well as from a time-lag analysis of anomalous CO₂ [11].

In both theoretical and empirical evaluations, thermally-induced emission of CO₂ represents interannual intensifications of net emission, notably during episodes of El Niño. Represented equally well is the long-term intensification of net emission during the last half century. The strong correspondence to observed changes indicates that, although operating on disparate time scales, both unsteady components of CO₂ net emission share the same physical mechanism.

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