

# Near miss: the importance of the natural atmospheric CO<sub>2</sub> concentration to human historical evolution

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**Abstract** When fossil fuel energy was discovered, the timing and intensity of the resulting climate impacts depended on what the natural CO<sub>2</sub> concentration in the atmosphere was at that time. The natural CO<sub>2</sub> concentration is thought to be controlled by complex, slow-acting natural feedback mechanisms, and could easily have been different than it turned out to be. If the natural concentration had been a factor of two or more lower, the climate impacts of fossil fuel CO<sub>2</sub> release would have occurred about 50 or more years sooner, making it much more challenging for the developing human society to scientifically understand the phenomenon of anthropogenic climate change in time to prevent it.

## 1 Background

### 1.1 What sets the natural atmospheric CO<sub>2</sub> concentration?

In the year 1750, according to measurements made on bubbles trapped in ice retrieved in cores from the Antarctic ice sheet, the atmospheric CO<sub>2</sub> concentration was about 278 ppm (molecules per million molecules of dry air) (Barnola et al. 1987). The concentration drifted through a range down to about 260 through our interglacial Holocene period. Previously to that, the concentration dropped as low as 180 ppm as it fluctuated in synchrony with changes in global ice volume through the glacial / interglacial cycles. The reasons for the CO<sub>2</sub> changes are not well understood but generally assumed to arise from chemical or circulation changes in the ocean (Anderson et al. 2009).

Deeper in the geologic past, atmospheric CO<sub>2</sub> rose and fell in response to slow changes in the continental configuration of the Earth's crust. On time scales of a million years and longer, the CO<sub>2</sub> concentration in the atmosphere is thought to be set by a “thermostat” mechanism involving the dissolution of igneous rocks on land, a process known as chemical weathering (Walker et al. 1981; Berner and Lasaga 1989). When some of the CaO (calcium oxide)

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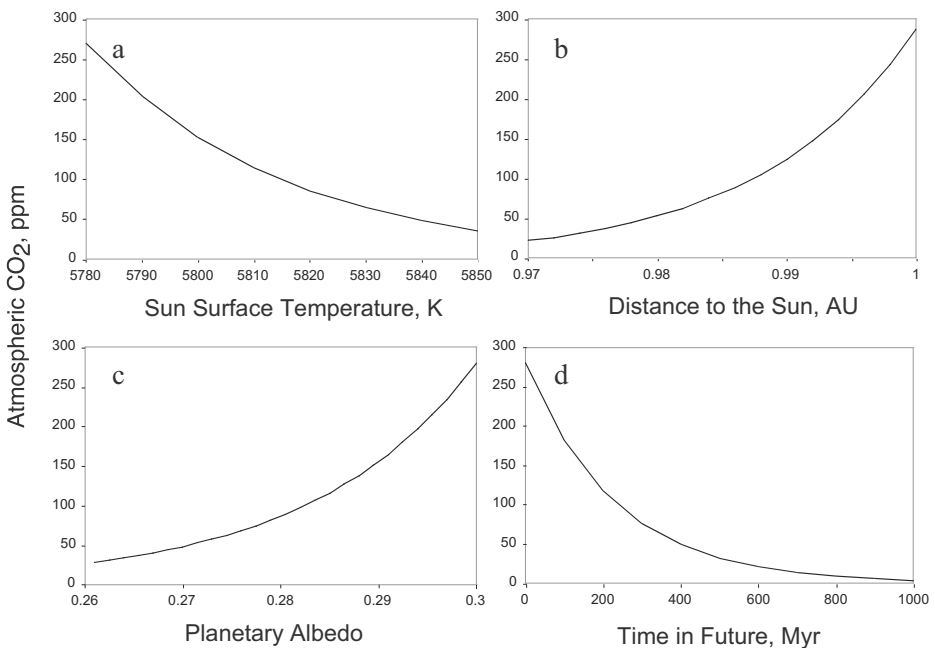
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component of an igneous rock dissolves, it eventually ends up as  $\text{CaCO}_3$  (calcium carbonate) in ocean sediments, dragging a carbon atom from the atmosphere / ocean down into the solid Earth. This downward carbon flow is counter-balanced by  $\text{CO}_2$  coming out of the solid Earth in volcanic gases and deep-sea hydrothermal vent fluids.

The thermostat-generating feedback arises from the sensitivity of the chemical weathering reaction to Earth's climate, particularly the rate of precipitation and runoff from the continents. If the rate of chemical weathering removes  $\text{CO}_2$  from the atmosphere faster than the volcanic degassing rate, the  $\text{CO}_2$  concentration will fall, climate will cool, and the hydrological cycle will slow, until balance is reached at a theoretically stable equilibrium. By changing the susceptibility of the Earth to weathering, continental drift and mountain building drive slow changes from hot-house to glacial climate epochs. On shorter time scales,  $\text{CO}_2$  can transiently fluctuate, temporarily deviating from steady state, as it did through the glacial/interglacial cycles of the last two million years.

The set point of the  $\text{CO}_2$  thermostat depends on the intensity of sunlight received at the Earth's surface, among many other things (Berner and Lasaga 1989; Berner 1997). According to the Berner formulation, if the temperature at the surface of the sun were just 1 % hotter, or if Earth were just a few percent closer to the sun, a significantly lower atmospheric  $\text{CO}_2$  concentration would have been needed, for weathering to balance the same rate of  $\text{CO}_2$  degassing (Fig 1a and b). A 10 % change in the albedo of the Earth, or in the age of the Earth (putting us later on the timeline of a warming sun), would also have had a significant impact on the steady state atmospheric  $\text{CO}_2$  concentration. The  $\text{CO}_2$  degassing rate could be a bit lower than it is. If any of these factors had been different at the time in Earth history when



**Fig. 1** Factors that would have altered the steady-state pre-anthropogenic  $\text{CO}_2$  concentration in the atmosphere, according to the GEOCARB model (Berner and Kothavala 2001). **a** Temperature of the sun, **b** Distance to the sun, **c** planetary albedo, and **d** Time in future, increasing the temperature of the sun

industrial society arose, the CO<sub>2</sub> concentration in the atmosphere could have been much different than it turned out to be, either higher or lower.

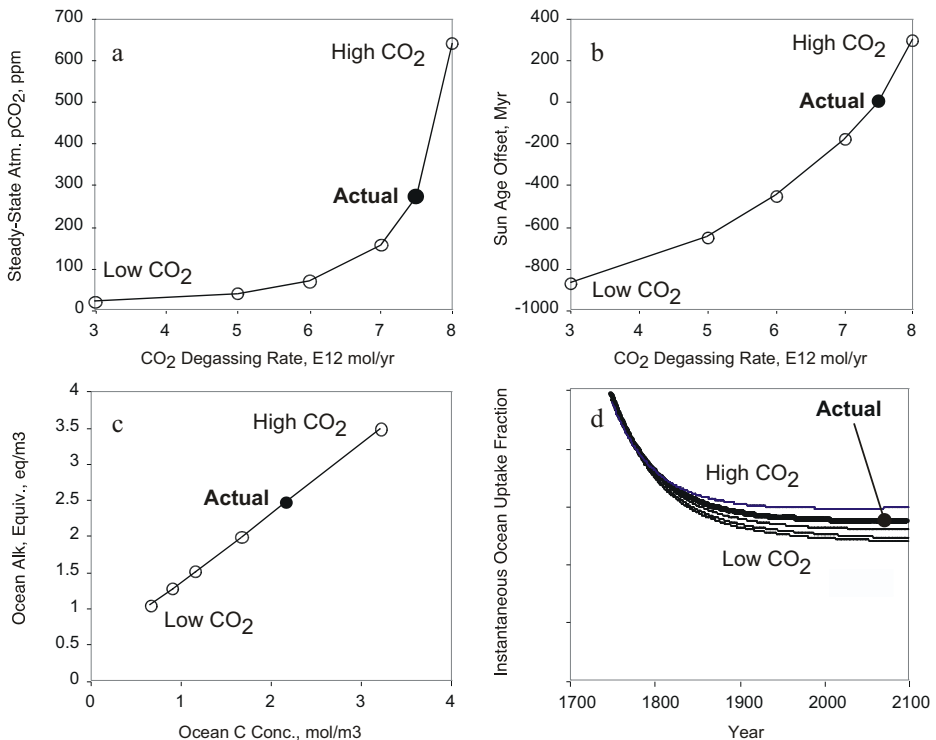
Is there a lower limit to the atmospheric CO<sub>2</sub> concentration in our biosphere? At some point in the warming future of the sun, atmospheric CO<sub>2</sub> might drop low enough to inhibit photosynthesis. The more primitive C-3 carbon uptake pathway becomes carbon-limited at about 150 ppm, which should arise in about 100 Myr (Lovelock and Whitfield 1982), but the more efficient C-4 pathway can operate down to 10 ppm, extending the lifespan of the biosphere by order 1 billion years (Caldeira and Kasting 1992). Life has proven to be quite adaptable to conditions of scarcity, however, such as the ability of plants to scavenge iron from great scarcity in oxic soils (Hell and Stephan 2003) or seawater (Sunda and Huntsman 1995), so perhaps photosynthetic pathways could evolve to survive at even lower atmospheric CO<sub>2</sub> concentrations. Ultimately, however, if atmospheric CO<sub>2</sub> dropped below, say, 10 ppm, seasonal carbon uptake and release from the land biosphere would lead to wild climate changes, setting a practical lower limit for a biosphere similar to ours.

## 1.2 Nonlinear impact of atmospheric CO<sub>2</sub> on climate

The natural atmospheric CO<sub>2</sub> concentration determines the climate response to industrialization, because it temporarily masks the climate impact of adding more CO<sub>2</sub>. The carbon dioxide molecule has a complex absorption spectrum in the infrared, with absorption coefficients that vary throughout many orders of magnitude at different frequencies, or “bands” (Pierrehumbert 2010). In high-absorbance bands the intense infrared upwelling from the warm ground is entirely absorbed and replaced by less intense emission from the colder upper atmosphere. Once these bands are “saturated” in this way, less strongly absorbing bands play a stronger role in altering the energy balance if the concentration rises further. The result is that the attenuation of the outgoing infrared energy flux by CO<sub>2</sub> (the radiative forcing) scales with the log of the CO<sub>2</sub> concentration, rather than scaling linearly. For this reason, the climate impacts from discovering fossil carbon energy would be much more severe (or, more precisely, as it will turn out, begin sooner) in an initially lower-CO<sub>2</sub> world.

## 1.3 Alternate atmospheric CO<sub>2</sub> trajectories

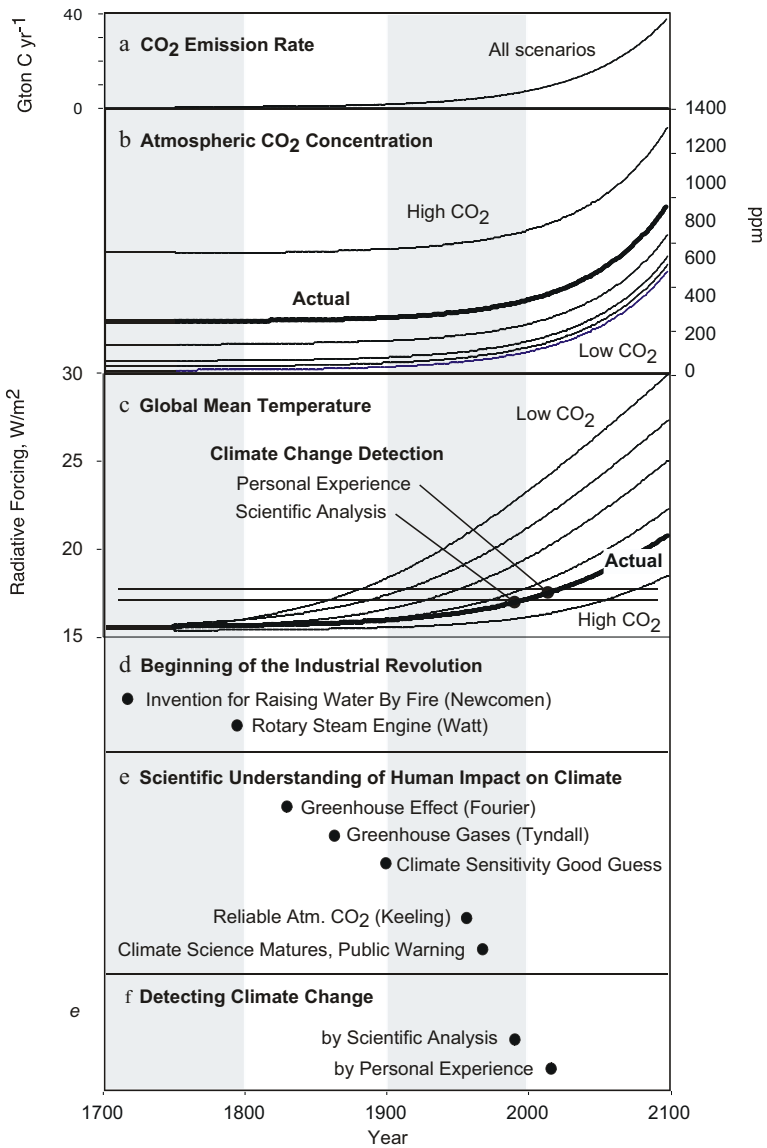
In a lower-CO<sub>2</sub> world, how would the evolution of atmospheric CO<sub>2</sub> and climate be different? People two hundred years ago did not know the atmospheric CO<sub>2</sub> concentration or the solar constant very well, but they knew how warm it was, and how big the trees are (the size of the terrestrial carbon pool). The span of their ignorance (atmospheric CO<sub>2</sub> and the solar constant could have been different, with everything else nearly the same) is represented by scenarios imposed on the Geocyc model (Archer et al. 2009), a time-stepping globally integrated weathering carbon cycle model from Berner (Berner and Kothavala 2001) with added treatment of the kinetics of CO<sub>2</sub> invasion into and CaCO<sub>3</sub> burial from its homogeneous ocean. The atmospheric CO<sub>2</sub> concentration in the model is varied by using different values of the rate of CO<sub>2</sub> degassing from the solid Earth (Fig. 2a). When the degassing rate is high, a higher igneous rock weathering flux is required to balance the degassing, and CO<sub>2</sub> rises. The value of the solar constant is adjusted in each scenario to maintain about the same mean initial temperature for all scenarios (Fig. 2b). On time scales of hundreds of thousands of years, the igneous rock



**Fig. 2** Results from Geocyc model (Archer et al. 2009). **a** Alternate pre-anthropogenic atmospheric CO<sub>2</sub> scenarios were generated by varying the rate of CO<sub>2</sub> degassing from the solid Earth, labeled “Low CO<sub>2</sub>” to “High CO<sub>2</sub>” and with scenario “Actual” corresponding to reality. Unlabeled lines follow the sequence of the unlabeled points in Fig. 1. **b** Global temperature was maintained near 15 °C in all scenarios by adjusting the age (brightness) of the sun. **c** The silicate weathering CO<sub>2</sub> thermostat as described by (Bernier and Kothavala 2001) alters the chemistry of the atmosphere and the ocean. **d** The instantaneous ocean uptake fractions through time showing near-constancy among the scenarios. Dark line indicates the Actual scenario

weathering CO<sub>2</sub> thermostat (Walker et al. 1981), coupled with the CaCO<sub>3</sub> saturation condition (Broecker and Takahashi 1978), alter the alkalinity and total CO<sub>2</sub> concentrations of the ocean as shown in Fig. 2c.

An exponentially growing CO<sub>2</sub> emission flux is imposed onto the initial steady-state conditions of these scenarios, based on historical emissions (Fig. 3a). The land biosphere, in the net, released CO<sub>2</sub> in early industrial time (the “pioneer effect”) and is absorbing it now, but integrating over time, the uptake and release fluxes approximately balance, leaving the ocean as the main fossil carbon sink (Tans 2009). For this reason terrestrial carbon fluxes are neglected in the model. To a first approximation, the CO<sub>2</sub> buffering ability of a parcel of seawater depends on the concentration of carbonate ion (CO<sub>3</sub><sup>2-</sup>), by the reaction CO<sub>2</sub> + CO<sub>3</sub><sup>2-</sup> + H<sub>2</sub>O -> 2 HCO<sub>3</sub><sup>-</sup>. The concentration of carbonate ion is controlled by the precipitation and dissolution of CaCO<sub>3</sub>, and is roughly the same between the scenarios. Because the ocean CO<sub>3</sub><sup>2-</sup> contents are similar across the scenarios, ocean uptake and hence the airborne fractions of the fossil fuel CO<sub>2</sub> are also similar across the scenarios (Fig. 2d), resulting in the parallel atmospheric CO<sub>2</sub> trajectories in Fig. 3b. The buffer capacity of the ocean would become limited if atmospheric CO<sub>2</sub> dropped much below 10 ppm, which would result in an increase in the atmospheric fraction of industrial CO<sub>2</sub> from 50 % toward 100 %. This would make the



**Fig. 3** **a** Fossil carbon emission rate for all scenarios. **b** Atmospheric CO<sub>2</sub> trajectories of the scenarios, labeled as in Fig. 2. **c** Global mean temperatures from each scenario. **d** Lighting the fuse of climate change. **e** The evolving science of climate change. **f** Detection and attribution

lowest-CO<sub>2</sub> world even more climate-reactive than one would extrapolate from the buffered cases considered here.

### 1.4 Radiative forcing trajectories

The energy imbalance that results from releasing greenhouse gases, expressed as the radiative forcing, is the driving agent for climate change. Although the climate response is complicated

by the long time constant for warming the deep ocean, and by various feedbacks that operate on various time scales, the radiative forcing provides a first determinant for the severity of anthropogenic climate change.

Figure 3c shows the evolution of model radiative forcing from the scenarios. Since the airborne fractions of all the scenarios are about the same, the differences between the scenarios arise almost entirely from the radiative impact of the initial CO<sub>2</sub> concentration. Each trajectory consists of two phases. In the second, or terminal, phase, the temperature increases linearly with time. During this phase, the constant, initial CO<sub>2</sub> concentration is negligible compared to the exponentially growing part, and the radiative forcing, scaling as the log of the exponential, increases nearly linearly with time. In the initial ramp-up stage, the background, natural CO<sub>2</sub> concentration is not negligible, and the radiative forcing change is accelerating, until it reaches its maximum, terminal rate of change in the second stage.

For the actual case, in which pre-anthropogenic atmospheric CO<sub>2</sub> was near 280 ppm, the transition between these stages comes at about the year 2100, when the radiative forcing from CO<sub>2</sub> would be about 6 W/m<sup>2</sup>. At the present time (2016), the radiative forcing is only increasing half as quickly as it would be under business-as-usual in the terminal stage (assuming continued exponential growth). Our climate changes are moderated, for now, by the blanketing effect of the natural CO<sub>2</sub>.

The impact of varying the initial atmospheric CO<sub>2</sub> concentration is to create a family of radiative forcing trajectories that parallel each other, displaced from each other in time (Fig. 3c). The parallel trajectories of the scenarios arise from the mathematics of radiative forcing of exponentially growing CO<sub>2</sub> concentration, which is determined by the ratio of the background and the growing CO<sub>2</sub> concentrations, so that changing the natural concentration has the same impact as scaling the growing part would. A change in a pre-exponential constant (scaling the growing part) can be translated mathematically into an offset in the value of the exponent (time). A world with a lower natural CO<sub>2</sub> concentration reaches the terminal phase sooner, after less industrial carbon has been released, but otherwise the trajectories would be the same: the rate of change of the radiative forcing in the terminal stage, and the radiative forcing values at the transition between spin-up and terminal phases.

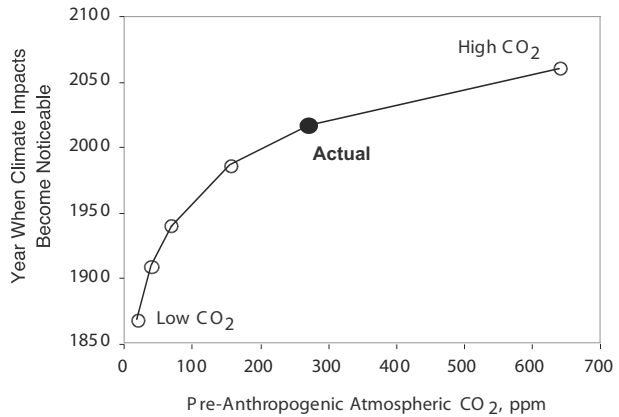
The greenhouse blanketing effect of the initial CO<sub>2</sub> concentration provides a fuse of some variable length, giving humanity time between when the match is lit and when the bomb goes off (Fig. 4a). If the initial atmospheric CO<sub>2</sub> concentration were half its actual value, we would currently be experiencing the actual business-as-usual climate expected for the year 2050. If there were only one tenth as much CO<sub>2</sub> in the atmosphere initially, the climate forcing we are experiencing today would have already happened, in the year 1900.

The scenario results are plotted as a function of the cumulative emission of carbon in Fig. 5. For the Actual scenario, there is a well-known linear temperature response to cumulative carbon emission (Allen et al. 2009) resulting from cancelling nonlinearities from band saturation and CO<sub>2</sub> solubility in the ocean. In a lower-CO<sub>2</sub> world, the temperature response is stronger, and less linear, because of the stronger nonlinearity of the radiative forcing (Fig. 5c) relative to the airborne fraction (Fig. 5b).

## 2 Historical context

The development of the steam engine can perhaps be credited with igniting the exponentially growing exploitation of fossil carbon as an energy source. The first “steam engine” was a

**Fig. 4 a** Impact of pre-anthropogenic atmospheric CO<sub>2</sub> on the timing of the onset of noticeable climate change

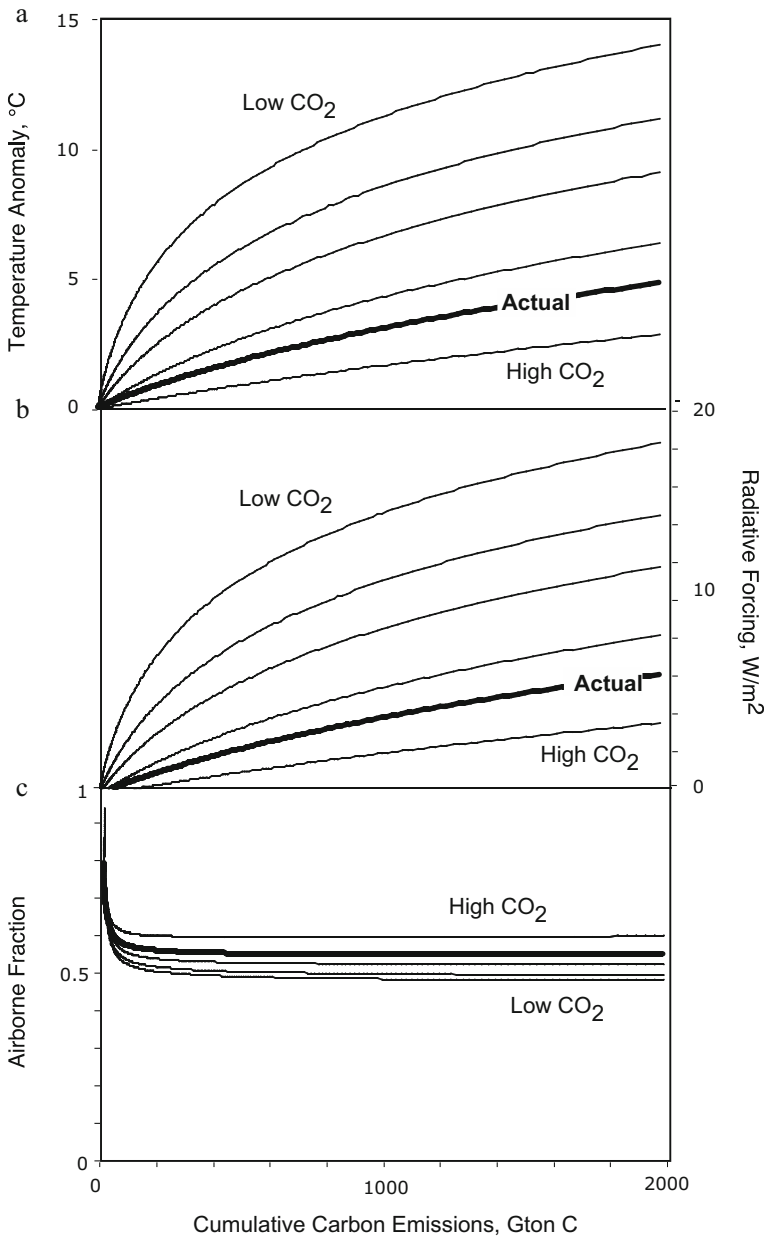


pump for draining water out of mines invented by Thomas Newcomen in 1712. If we are looking for the ingredients of a positive feedback, in which fossil energy use begets more fossil energy use, perhaps we can find it in this application, the extraction of metals from the Earth. A clearer breakthrough was the development of a rotary steam engine invented by James Watt in 1798, a source of more generic power that could accelerate the production of anything, including bigger steam engines or electricity. Thus the fuse was lit by about the year 1800.

How long did the fuse last, before it reached the bomb? Scientific analytical detection of the fingerprints of greenhouse gases on global climate came in about 1995 when the IPCC declared a “discernable human impact on Earth’s climate” (Houghton et al. 1995). This milestone did not suffice to motivate a significant change in fossil fuel emissions. We are only now reaching a stage of real pain, in which adverse effects such as droughts, and storm surges amplified by sea level rise, have arguably motivated the Paris Climate Agreement last year. Taking these as our end points, the background-CO<sub>2</sub> time-delay fuse lasted about two centuries.

While the fuse was burning, the growing scientific enterprise pieced together an understanding of Earth’s climate system. The first conception of radiative balance and the greenhouse effect came in 1827 from Fourier (1827). As a conceptual feat, this required a greater degree of abstraction and analytical sophistication than the development of steam power. Steam power motivated the development of thermodynamics and entropy (Carnot 1824), but the initial engine development required more engineering and plumbing than analytical theory. Describing Earth’s energy balance as a regulator of its surface temperature, on the other hand, required an understanding of light as an energy carrier, including the invisible infra-red radiation by which Earth sheds energy to space (which is half of the story). The greenhouse effect in particular operates entirely on the “dark” side of the energy budget.

The first, valiant stab at a quantitative prediction of the climate sensitivity due to CO<sub>2</sub> came another 75 years after that, in 1896, from Arrhenius (1896). He described the greenhouse-amplifying effect of condensable water vapor, the ice albedo feedback, and the roles of clouds and heat transport, on Earth’s climate. His prediction of a 4–6 °C global temperature change from doubling CO<sub>2</sub> seems prescient, but he was the beneficiary of a substantial amount of luck (Archer and Pierrehumbert 2011). The immensely complex IR absorption spectrum of CO<sub>2</sub> and water vapor were entirely uncharacterized in his day. His calculation was based on measurements of the intensity of IR from moonlight, made with the



**Fig. 5** Model scenario results plotted as a function of cumulative carbon emitted. Labeled as in Fig. 2. **a** Global mean temperature for all scenarios as a function of cumulative carbon emissions. **b** Radiative Forcing from CO<sub>2</sub>. **c** Cumulative airborne fraction of the fossil carbon

aim of determining the temperature of the moon. Arrhenius used the data to estimate the absorption of IR by CO<sub>2</sub> and H<sub>2</sub>O, by comparing measurements from times with different humidity and zenith angle. The element of luck comes in because the measurements only spanned about half of the relevant infrared spectrum. Doing the calculation better would have

to wait for detailed IR absorption spectra, requiring technology that would not be available for several decades (Dennison 1931).

Arrhenius proposed that human activity (“evaporating our coal mines”) might alter the climate, but thought it would take a thousand years for industry to double atmospheric CO<sub>2</sub>. Callendar (1938) showed measurements of atmospheric CO<sub>2</sub> through time that looked unreliable (only a few data points, made by different people and methods, of a quantity that fluctuates a lot in the atmospheric boundary layer in which we live), but turned out to capture the anthropogenic increase. Fifty years later, Revelle and Suise (1957) concluded that ocean uptake would buffer atmospheric CO<sub>2</sub>. Careful measurements of atmospheric CO<sub>2</sub> showing clearly the human impact begin at Moana Loa (Keeling 1961) in the mid 1950’s. These measurements also benefited from technological developments, in particular, gas chromatography (James and Martin 1952).

After Arrhenius, the literature fell into confusion about how the IR absorption would affect climate (Callendar 1938; Plass 1956). One factor is the increased IR shining down from the sky from thicker greenhouse gases, affecting the energy budget of the surface of the Earth, causing it to warm. A much bigger effect, missed by most of the literature of this time (after Arrhenius), is that the decrease in IR leaving the planet going to space decreases with thicker greenhouse gases, requiring the atmosphere and the ground to both warm up (driven by the top-of-atmosphere energy budget). In the end, quantitative understanding of the complex climate system seemed to require automatic computers as tools (relieving us of what Arrhenius called “these tedious calculations”). With a computer one attempts to capture in mathematics the behavior of a complex system as a sum of interacting, simpler pieces. Trying to build such a model, it becomes clear which preconceived notions of how things work actually pan out, and which are undermined by some hidden flaw in reasoning or unexpected connection in reality. The first weather model ran on a computer called UNIVAC (Mauchly 1948).

With all the pieces in place, an essentially modern quantitative understanding of the climate impact from fossil carbon use emerged (Manabe and Wetherald 1975) and matured to the extent of public warnings (Broecker 1975; Charney et al. 1979) by the 1970’s.

### 3 Alternate scenarios in the context of actual history

If the natural atmospheric CO<sub>2</sub> concentration had turned out to be lower than it actually turned out to be, the time line for anthropogenic climate change would have played out sooner. If CO<sub>2</sub> had been half its actual value, the climate would have started to change discernibly to the general public (parallel to today in actuality) in about the year 1980 (Fig. 4a). In actuality, our understanding of the potential impact of fossil fuel CO<sub>2</sub> on earth’s climate had essentially matured by this time. When the climate started changing, if scientific progress had been similar in that world, we would have understood semi-quantitatively what was going on. The atmospheric CO<sub>2</sub> concentration was known, and its significance understood well enough that, presumably, the earlier onset of warming could have been forecast. Although the cumulative emissions of carbon were much lower in 1980 (Fig. 4b), and the emission rates lower, the necessity to abate CO<sub>2</sub> emissions within a few decades would have been as strong then as it is now in actuality. In actuality we are in a better position, because alternative energy technologies are farther along in development now than they were in the 1980’s.

If atmospheric CO<sub>2</sub> had been a factor of 10 lower than it turned out to be, the changes we are now seeing in climate today would have occurred at about Arrhenius’ time (~1900).

Changing climate patterns would have been harder to discern, in a day without the global meteorological station network and communications of our world, and our longer historical record. Although Arrhenius had all the qualitative ingredients to explain a directed climate warming, a quantitative understanding was still decades out of reach. It is an interesting question to ponder, how much that might have mattered to impeding a social response to climate change. If real pain is mostly what it takes, Arrhenius would have had an explanation of how further pain could have been avoided. But to the extent that a thorough scientific understanding is also a requisite for making a decision to abandon fossil fuels, the outlook for humanity would have been considerably darker in this altered world than it turned out in actuality.

The first atomic bomb tests raised the question of whether the blast could ignite the atmosphere, fusing  $^{14}\text{N}$  into  $^{28}\text{Si}$  and extinguishing life on Earth. There are always uncertainties but the decision was made that the thermonuclear chemistry was well enough understood to safely trigger the explosion. When fossil carbon became a resource, the crucial parameter that would determine the future climate impacts was the natural, background atmospheric  $\text{CO}_2$  concentration. The people making the decision to burn coal had no idea what the atmospheric  $\text{CO}_2$  concentration was, or what significance it had in determining our fate. As it turns out, we were about a factor of two away from a much less forgiving world.

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