A Carbon Balance Model of Atmospheric CO_2
11 September 2020
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The increasing concentration of carbon dioxide (CO_2) gas in the atmosphere is the result of a steadily increasing rate of anthropogenic (human-caused) emissions of that gas since the dawn of industrialization (~1750). Our growing stream of CO_2 emissions has perturbed the natural balance of Earth's Carbon Cycle.

I have constructed two analytical models (based on math formulas instead of computer numerics) of Global Warming: the first is based on the heat balance of the Biosphere (thermodynamics), and the second is based on the shifting balance of the Carbon Cycle (a rate equation for CO_2 concentration). This report is about a new and improved version of the latter, my Carbon Balance Model.

I will show a comparison between the Carbon Balance Model and historical data (by NOAA) on atmospheric CO_2 concentration over time (1980-2020); and between my Carbon Balance and Heat Balance models for the global temperature rise in recent decades (1980-2125). Also, future trends in CO_2 concentration and average global temperature are projected.

This Carbon Balance Model includes the simultaneous operation of these three effects:

— continuously changing anthropogenic CO_2 emissions over time (3 cases),

— an increase or decrease in the rate of CO_2 capture by the 'fast' processes of photosynthesis and absorption by the surface waters of the oceans, in proportion to shifts in the atmospheric concentration of CO_2,

— the 'slow' (or long-term) CO_2 absorption ascribed to rock weathering and deep ocean effects (the treatment of this effect being improved over my previous work).

All of these effects have been treated for years, and in greater detail, in the super-computer climate models constructed by the professionals. My ‘simple’ models are aimed at improving my non-specialist’s quantitative understanding of Global Warming, and to be able to give a reasonable description of it.

GENERAL FORM OF THE RATE EQUATION

The general rate equation for the changing concentration of CO2 in the atmosphere is:

$$dC/dy = [E_f + E_l] - [S_b + S_o] + I$$

The rate of change of the concentration (C) of atmospheric CO2 with respect to time in units of years (y) is equal to the net imbalance of:

E_f = annual emissions rate of fossil CO2 from energy generation and industry,

E_l = annual emissions rate of naturally stored CO2 from land use changes,

S_b = annual sink/absorption rate of CO2 by photosynthesis on land,

S_o = annual sink/absorption rate of CO2 by the oceans,

I = apparent annual source or sink of CO2 that results from unknowns and the limits on the accuracy of the data. The slow absorption rate will be included in this term.

The data used in the above is that given by the Global Climate Project (GCP, published on 4 December 2019). However, the IPCC2007 data on “sinks” is used to assist in estimating how those sinks increase or decrease in capacity in response to changes in the atmospheric concentration of CO_2.

The above quantities *do not* include the unperturbed (background or “ancestral”) emission rates by respiration and ocean releases, nor absorption rates by photosynthesis and ocean absorption, because those rates are in perfect balance (both in the GCP and IPCC sets of data); and they do not contribute to CO_2 accumulation in the atmosphere.

ANTHROPOGENIC CO2 EMISSIONS

The rates of fossil CO_2 emission from human industry were:

E_f = 20 GtCO2/y, in 1990,

E_f = 36.6 GtCO2/y, in 2020.

The unit GtCO2/y is giga-metric-tonnes of CO_2 per year; and 1 tonne = 1000 kilograms.

The rates of fossil CO_2 emission from land use (or misuse) were:

E_l = 4±2 GtCO2/y, in 1998,

E_l = 6±2 GtCO2/y, in 2018.

Linear time-dependent models of $E_f(y)$ and $E_l(y)$ are constructed as follows:

$E_f(y) = 0.533*(y-1990) + 20$GtCO2/y,

$E_I(y) = 0.1*(y-1998) + 4GtCO2/y.$

Adding these into a combined anthropogenic CO_2 emissions rate over time, E(y), produces the expression:

$E(y) = 0.633*(y-1953.35)$, GtCO2/y.

This formula produces the following numbers for annual emissions:

E(1953.35) = 0, GtCO2
E(1960) = 4.21
E(1970) = 10.5
E(1980) = 16.8
E(1990) = 23.2
E(1998) = 28.3
E(2000) = 29.5
E(2010) = 35.9
E(2018) = 40.9
E(2019) = 41.6
E(2020) = 42.2
E(2050) = 61.8
E(2060) = 67.5
E(2120) = 105.5
E(2125) = 108.7.

TABLE 1 shows a comparison of the E(y) model to published data.

TABLE 1, Annual Anthropogenic CO2 Emissions (GtCO2)

YEAR	E_f DATA (GCP)	E_l model	Sum E_f+E_l	E model
1960	9.6	0.2	9.8	4.2
1970	14.8	1.2	16	10.5
1980	19.4	2.2	21.6	16.8
1990	22.6	3.2	25.8	23.2
2000	25.2	4.2	29.4	29.5
2010	33.2	5.2	38.4	35.9
2019	36.8	6.1	42.9	41.6

The E(y) model agrees quite well with the data (for E_f, with the addition of estimated land use emissions, E_l, for the corresponding years) for the last three decades.

GIGA-TONNES OF CO2 PER PPM

An Atomic Mass Unit (AMU) is defined as $1.660539*10^{-27}$ kilograms (kg).

The AMU masses of individual diatomic nitrogen (N2), diatomic oxygen (O2), and carbon dioxide (CO2) molecules are: 28.014AMU for N2, 31.998AMU for O2, and 44AMU for CO2.

The masses of these molecules in kg are:

N2: $4.6518*10^{-26}$

O2: $5.3134*10^{-26}$

CO2: $7.3064*10^{-26}$.

The atmosphere is essentially 79% N2, and 21% O2. The quantities of all the other gas species in the atmosphere, combined, are less than 1% of the atmosphere. So, it is convenient to define a fictitious “air” molecule, which is 79% N_2 and 21% O_2, and as a result has a mass of 28.85AMU, and an individual molecule weight of $4.65183*10^{-26}$ kg.

The total mass of the atmosphere is $5.2*10^{18}$ kg (CRC Handbook of Chemistry and Physics, 1967-1968). The total number of molecules in the atmosphere is given by the ratio

$(5.2*10^{18}$ kg)/($4.65183*10^{-26}$ kg) = $1.1178*10^{44}$ molecules.

Thus, one part-per-million (1 ppm) of the atmosphere represents $1.1178*10^{38}$ molecules.

Therefore, 1 ppm of CO_2 has a mass of $8.16903*10^{12}$ kg = 8.16903GtCO_2.

The 277ppm of CO_2 in the atmosphere in pre-industrial times represents a mass of 2,262.8GtCO_2.

At 417ppm, the present mass of CO_2 in the atmosphere is 3,406.5GtCO_2.

The additional 140ppm of accumulated anthropogenic CO_2 emissions stored by the atmosphere has a mass of 1,143.7GtCO_2.

The anthropogenic emission rate model, E(y), can be restated in terms of ppm-per-year (ppm/y) by dividing its formula given in units of GtCO_2/y, by the ratio:

8.16903GtCO_2/ppm.

$E(y) = (7.7488*10^{-2})*(y-1953.35)$, ppm/y

$E(y) = {}^{(y-1953.35)}/_{12.905}$, ppm/y.

SINKS

Here, S_b is the label for the absorption rate of atmospheric CO2 by the biosphere (photosynthesis), and S_o is the label for the absorption rate of atmospheric CO2 by the surface waters of the ocean (recall, these are only the fluxes created by the anthropogenic perturbation of the Carbon Cycle).

From GCP2019 data:

S_b = 1.47ppm/y
S_o = 1.10ppm/y.

Therefore

$S = S_b + S_o$ = 2.57ppm/y,

and at the end of 2018, the atmospheric CO2 concentration was C=407.4ppm.

From IPCC2007 data:

S_b = 1.22ppm/y
S_o = 1.22ppm/y.

Therefore

$S = S_b + S_o$ = 2.44ppm/y,

and at the end of 2004, the atmospheric CO2 concentration was C=375ppm.

The above shows a growth in the capacity of the total Sink (S) as the atmospheric concentration of CO2 (C) was increased. This probably reflects an added stimulation for CO2 absorption by photosynthesis and the oceans because of a larger concentration of CO2 in the air. Will this 'growth of CO2 appetite' by the composite sink continue with increasing C indefinitely, or will this effect saturate at some higher level of CO2 concentration? Unknown.

The simplest quantification of this 'sink growth' effect is a linear relationship between S and C:

The slope of that linear equation is given by

$$^{\Delta S}/_{\Delta C} = {}^{(2.57\text{-}2.44,\ ppm/y)}/_{(407.4\text{-}375,\ ppm)} =$$

$$= 4.012*10^{-3}\ y^{-1} = (249.23y)^{-1},$$

so that S as a function of C is given by

$$S = {}^{[C\text{-}407.4,\ ppm]}/_{249.23y} + 2.57ppm/y.$$

For later convenience, I define the following parameter (delta-time-1, in years):

$$\Delta t_1 = 249.23y.$$

The relationship S(C) gives the following numerical results:

S = 0.94 ppm/y at C = 0 ppm
S = 2.05 ppm/y at C = 277 ppm
S = 2.44 ppm/y at C = 375 ppm
S = 2.57 ppm/y at C = 407.4 ppm
S = 10.97 ppm/y at C = 2500 ppm.

In reality, I would expect S equal to 0 when C is zero, and to saturate at a capacity below 10.97ppm/y (when C=2500ppm), at some as-yet to be reached high level of concentration. Nevertheless, I will use this model of sink capacity as a function of atmospheric CO2 concentration, for all levels of C.

LONG TERM CO2 SWEEPERS AND THE PETM

The "fast" processes, which initially scavenge atmospheric CO2, are photosynthesis and absorption by the surface waters of the oceans. Each of these processes can saturate if there is too much atmospheric CO2, and if the emission fluxes (both their magnitude and speed) are higher that the total sink capacity (scavenging rate).

The long-term, or "slow," processes of scavenging atmospheric CO2 are the chemical reactions of weathering of rocks (carbonate and silicate) and soils.

Somewhere between 14,000GtCO2 and 26,000GtCO2 was injected into the atmosphere 55.5 million years ago (55.5mya) over a geologically short span of perhaps 1000 to 3000 years, most likely by a combination of volcanic activity, magmatic heating of seafloor carbonate sediments, wildfires and the burning of peat deposits. The time of this event is now classified by geologists as the transition from the Paleocene Epoch to the Eocene Epoch, and is known as the Paleocene-Eocene Thermal Maximum (PETM).

As noted by the PETM's name, the Earth's average global temperature reached its highest point since the extinction of the dinosaurs 66mya, during the 200,000 years of the PETM. After the relative cooling off of the PETM, the global temperature during the Eocene rose steadily for ~5my, peaking ~50mya at nearly the level of the highest temperature during the PETM excursion, and then fell steadily for ~15my, when the global temperature plummeted at the start of the Oligocene Epoch and

Antarctic Glaciation began. The ~20my span after the PETM is known to geologists as the Eocene Optimum, a long period of high global temperature with an ice-free Earth; with swamps, ferns and Redwood forests in the Arctic, and jungles in the Antarctic.

I gave a detailed description of the PETM, and pointed out two major expositions on it: a 2014 video-recorded presentation by Dr. Scott Wing (Curator of Fossil Plants, Smithsonian Museum of Natural History, Washington, DC), and a major publication on Climate Change by the National Research Council of National Academies of Science in 2011. See the report posted with the following web-link (in particular, see Note 11 in that report).

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Ye Cannot Swerve Me: Moby-Dick and Climate Change
15 July 2019
https://manuelgarciajr.com/2019/07/15/ye-cannot-swerve-me-moby-dick-and-climate-change/

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The first 1,000 years of the decay of CO2 concentration from its peak level during the PETM (C_{PETM}) can be characterized by the following exponential function

$C(y) = C_{PETM}*e^{-(y-y_1)/\Delta t_2}$, (at year "y" after year y_1),

for the parameter Δt_2 defined as

$\Delta t_2 = 1442.7y.$

The rate of decay for this C(y) function is

$$dC/_{dy} = -(^{C_1}/_{\Delta t_2})*e^{-(y-y_1)/\Delta t_2},$$

and I use this function to model the slow (long-term) processes that scavenge CO2 from the atmosphere (replacing the label "I" in the general rate equation, and with C_1 as the starting value of C in calculated projections of trends beyond 'starting' years y_1).

RATE EQUATION FOR THE ACCUMULATION OF ATMOSPHERIC CO2

Given all the above, a rate equation for the accumulation of atmospheric CO2 can be written as follows

$$dC/_{dy} = R*(y-y_e) - ^{[C-C_1]}/_{\Delta t_1} - S_1 - (^{C_1}/_{\Delta t_2})*e^{-\Delta y/\Delta t_2},$$

where:

$\Delta y = (y-y_1)$, (years),

$\Delta t_1 = 249.23y$,

$\Delta t_2 = 1442.7y$,

$S_1 = 2.57ppm/y$,

$R = (7.7488*10^{-2}) = (^1/_{12.905})$, ppm/y^2,

$y_e = 1953.35y$.

To solve this equation, I first substitute the variable name "x" for Δy, the independent variable,

$$^{dC}/_{dx} = R*(x+y_1-y_e) - {}^{[C-C_1]}/_{\Delta t_1} - S_1 - ({}^{C_1}/_{\Delta t_2})*e^{-x/\Delta t_2},$$

and define the parameter, x_0, for convenience,

$x_0 = (y_1-y_e)$. Continuing with algebra produces

$$^{dC}/_{dx} + ({}^{C}/_{\Delta t_1}) = R*x + [R*x_0 + {}^{C_1}/_{\Delta t_1} - S_1] +$$

$$- ({}^{C_1}/_{\Delta t_2})*e^{-x/\Delta t_2},$$

and the following constants (N and D), for a given particular numerical example, can be defined:

$$N = [R*x_0 + {}^{C_1}/_{\Delta t_1} - S_1], \text{ ppm/y},$$

$$D = ({}^{C_1}/_{\Delta t_2}), \text{ ppm/y}.$$

Using all the above, the rate equation for C(x) now appears as

$$^{dC}/_{dx} + ({}^{C}/_{\Delta t_1}) = R*x + N - D*e^{-x/\Delta t_2}.$$

This is a first order, linear differential equation and is solved by a standard technique of integration to yield (after a bit of algebra)

$$C(x) = C_1 * e^{-x/\Delta t_1} + R * x * \Delta t_1 +$$

$$+ [N - {}^{D}/_{a} - R * \Delta t_1] * \Delta t_1 * [1 - e^{-x/\Delta t_1}] +$$

$$+ ({}^{D}/_{a}) * \Delta t_1 * [1 - e^{-(a*x)/\Delta t_2}],$$

for constant “a” defined as

$$a = (1 - {}^{\Delta t_1}/_{\Delta t_2}).$$

Using the parameter values specified previously, the CO2 concentration C(x) for x being a time span in number of years after year 2020, for the rising trend of anthropogenic emissions given by the E(y) model, is

$$C(x) = (417ppm) * e^{-x/(249.2y)} + (19.31ppm/y) * x +$$

$$- [3{,}824ppm] * [1 - e^{-x/(249.2y)}] +$$

$$+ (87.06ppm) * [1 - e^{-x/(1{,}743.93y)}].$$

Since the average global temperature had increased by 1°C with the accumulation of an additional 130ppm of CO2 above the pre-industrial concentration of 277ppm, I take the following ratio as a convenient scale constant,

+130ppm CO2 above C=277ppm <—> +1°C.

The temperature rise as a function of x follows from

[C(x)-277ppm], scaled by this factor, and for this specific case is

$$\Delta T(x) = (3.21°C)*e^{-x/(249.2y)} + ({}^{x}/_{6.73}, °C) +$$

$$- [29.42°C]*[1 - e^{-x/(249.2y)}] +$$

$$+ ({}^{1}/_{1.49})*[1 - e^{-x/(1,743.93y)}] - 2.132°C.$$

In reality, there is a lag between a pulse of added CO2 into the atmosphere and a rise in global temperature; ΔT does not adjust instantaneously to C. Nevertheless, I consider the scaling factor shown to produce temperature histories from examples of C(x), of sufficient accuracy for this simplified Carbon Balance Model.

Note that the specific C(x) and ΔT(x) histories shown above are for a continuous growth of anthropogenic emissions (the "E-growth" case).

C AND ΔT FOR "FLAT" EMISSIONS FROM YEAR 2020

The development of this case proceeds from the rate equation in the form

$$^{dC}/_{dy} = E(2020) - {}^{[C-C_1]}/_{\Delta t_1} - S_1 - ({}^{C_1}/_{\Delta t_2})*e^{-\Delta y/\Delta t_2}.$$

By a similar mathematical exercise, the histories C(x) and ΔT(x) are found to be

$$C(x) = (417ppm)*e^{-x/(249.2y)} +$$

$$+ [1061.6ppm]*[1 - e^{-x/(249.2y)}] +$$

$$+ (87.06ppm)*[1 - e^{-x/(1{,}743.93y)}],$$

and

$$\Delta T(x) = (3.21°C)*e^{-x/(249.2y)} +$$

$$+ [8.17°C]*[1 - e^{-x/(249.2y)}] +$$

$$+ ({}^{1}/_{1.49})*[1 - e^{-x/(1{,}743.93y)}] - 2.13°C.$$

This last example is labeled the “E-flat” case.

C AND ΔT FOR EMISSIONS DIMINISHING TO 0 BY YEAR 2060

Using the relationship

$$E(y) = E(2020) - (0.129ppm/y)*(y-2020),$$

for $E(2020)=5.17ppm/y$,

and restricting attention to the time span between 2020 and 2060, produces the histories:

$$C(x) = (417ppm)*e^{-x/(249.2y)} - 32.15*x +$$

$$+ [8,988.8ppm]*[1 - e^{-x/(249.2y)}] +$$

$$+ (87.06ppm)*[1 - e^{-x/(1,743.93y)}], \text{ and}$$

$$\Delta T(x) = (3.21°C)*e^{-x/(249.2y)} - (^{x}/_{4.044}, °C) +$$

$$+ [69.15°C]*[1 - e^{-x/(249.2y)}] +$$

$$+ (^{1}/_{1.493})*[1 - e^{-x/(1,743.93y)}] - 2.13°C.$$

The continuation of these histories after year 2060 would be

$$C(x) = C(2060)*e^{-x/(249.2y)} +$$

$$+ [C(2060) - 553.39]*[1 - e^{-x/(249.2y)}] +$$

$$+ (87.06ppm)*[1 - e^{-x/(1,743.93y)}], \text{ and}$$

$$\Delta T(x) = [^{C(2020)}/_{130}]*e^{-x/(249.2y)} +$$

$$+ [^{C(2020)}/_{130} - 4.26°C]*[1 - e^{-x/(249.2y)}] +$$

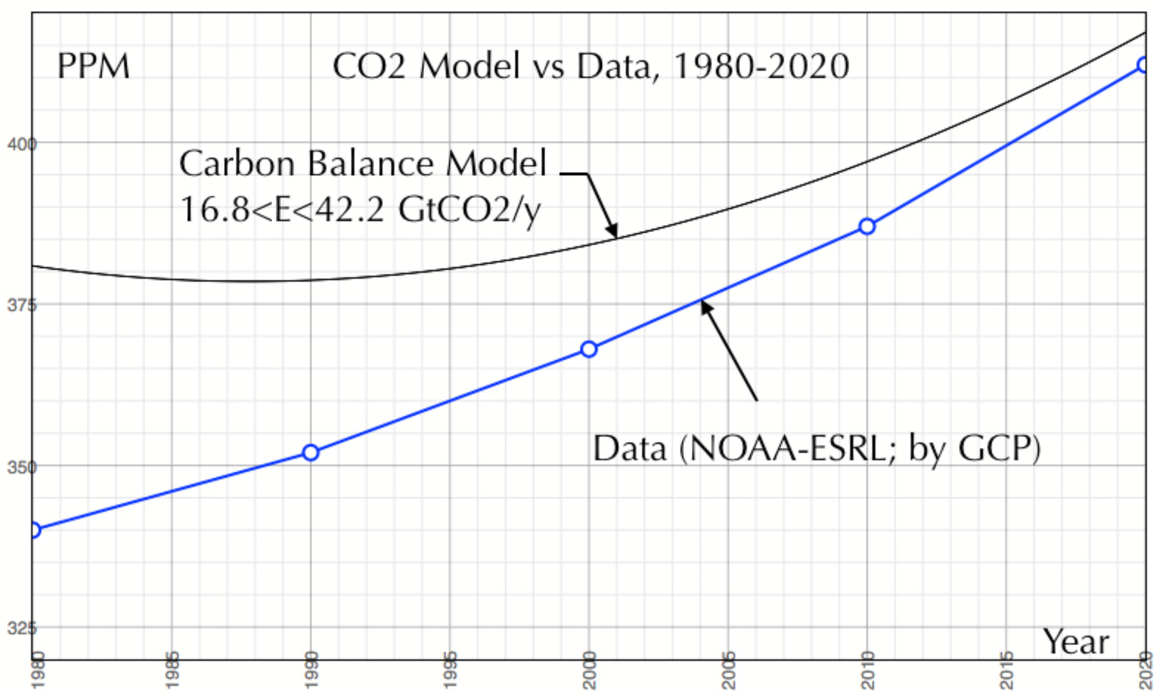
$$+ (^{1}/_{1.49})*[1 - e^{-x/(1,743.93y)}] - 2.13°C.$$

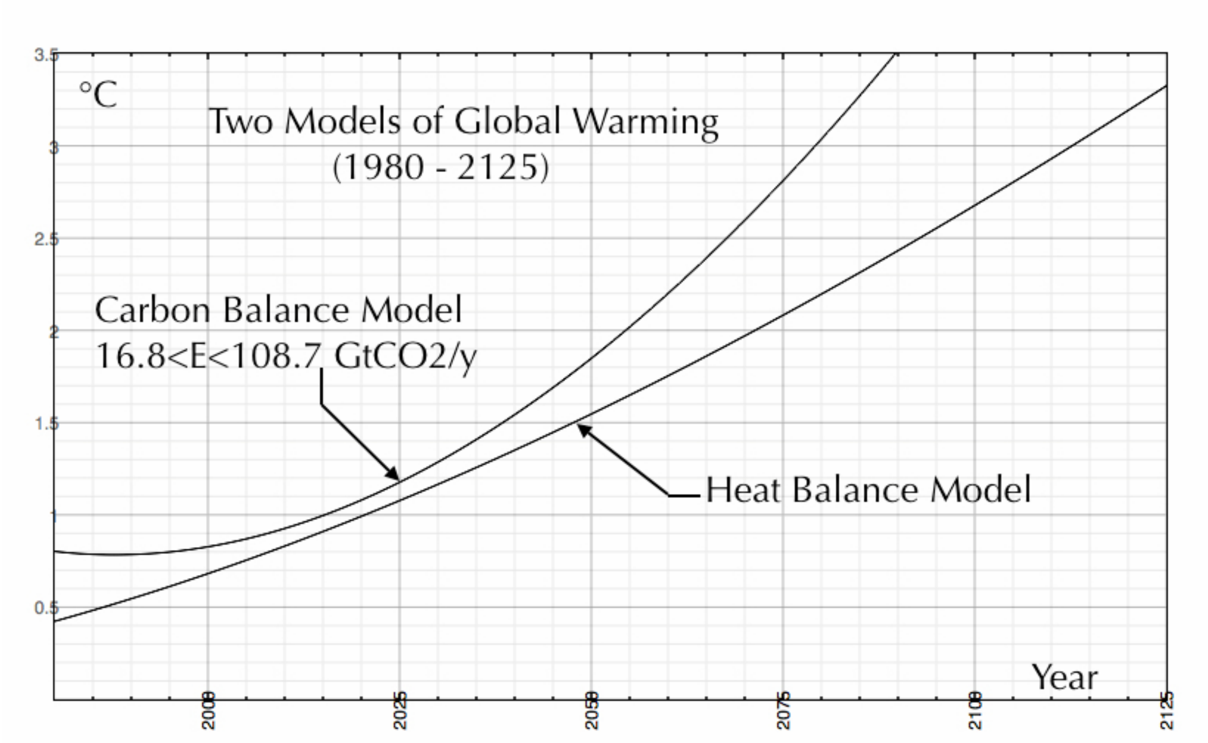
For this example C(2060)=404.12ppm.

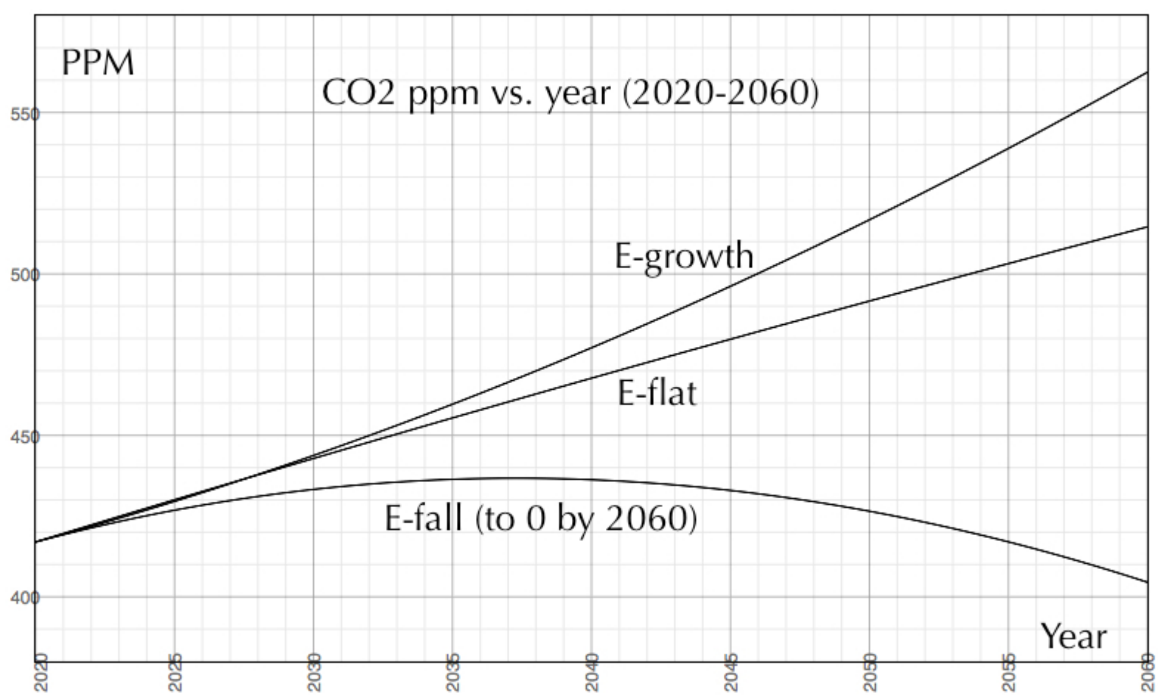
This example is labeled the “E-Fall” case (before year 2060), and the “No E” case (after year 2060).

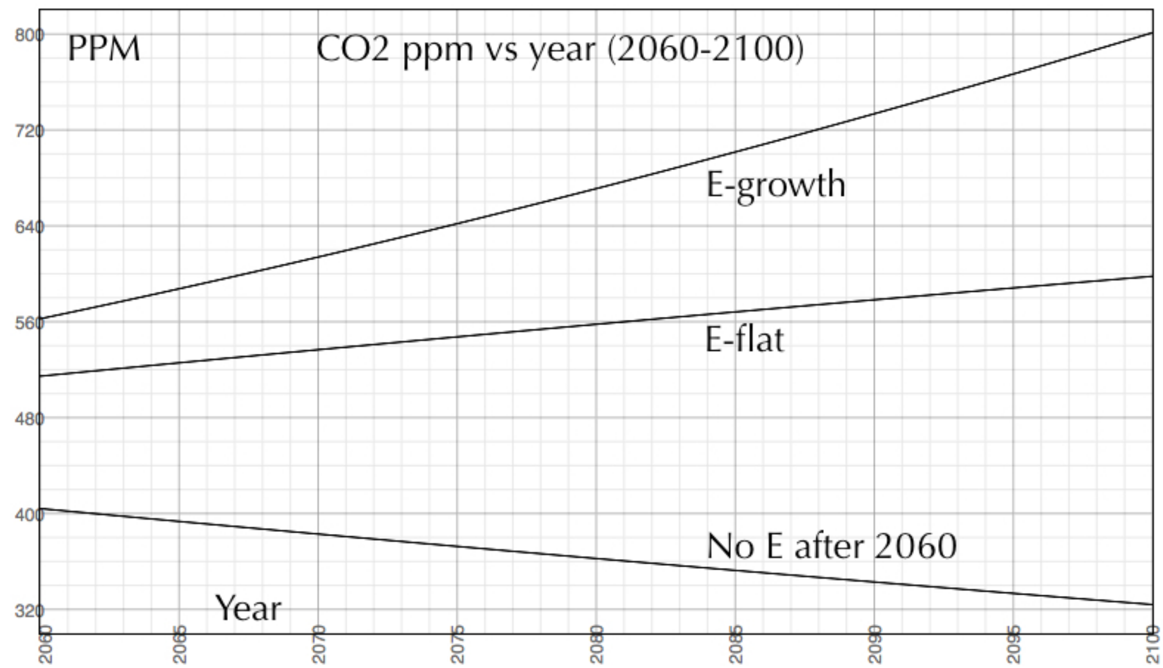
GRAPHS

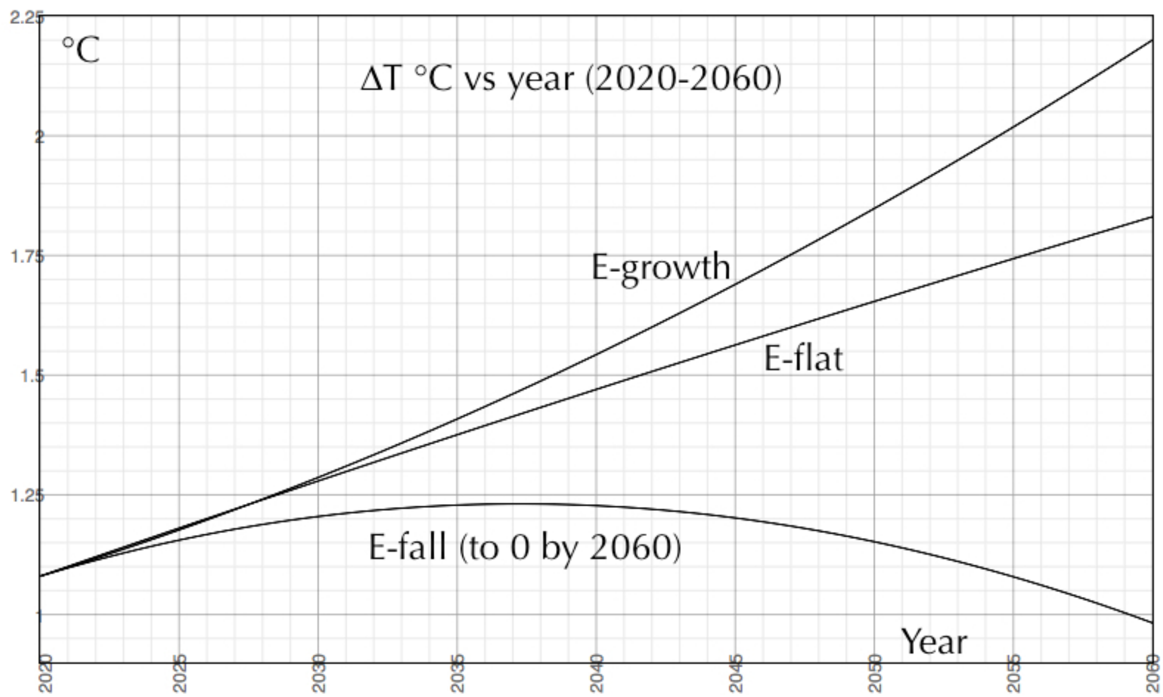
The examples presented above are shown in the following graphs.

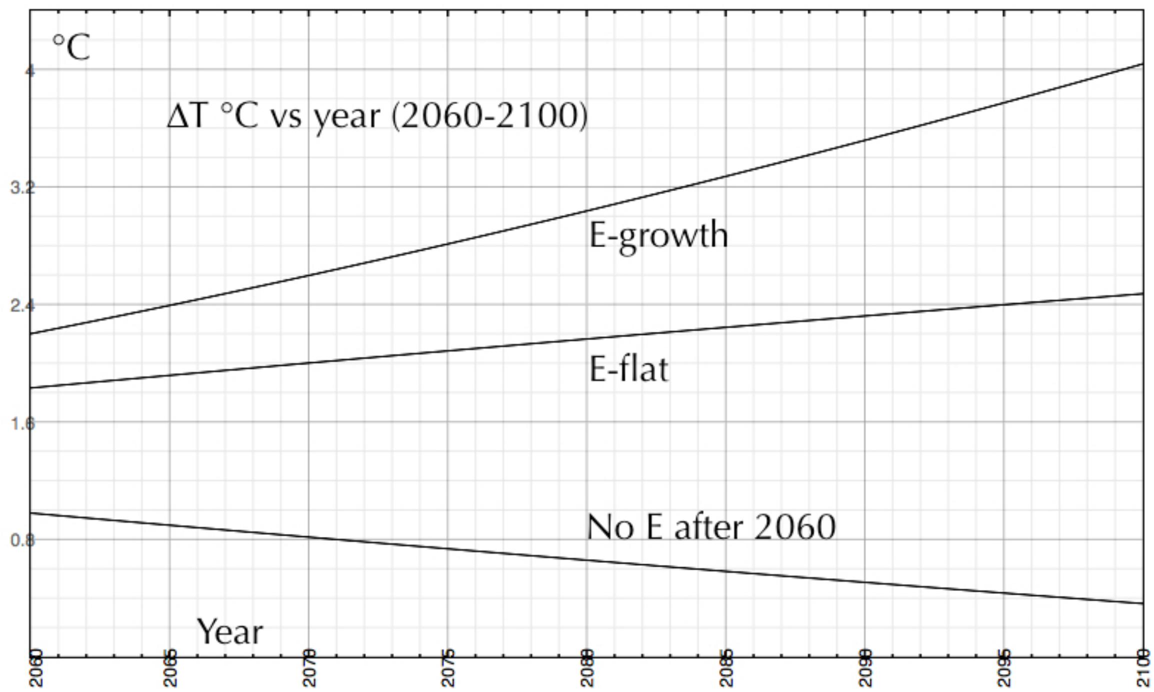



°C
Two Models of Global Warming
(1980 - 2125)
Carbon Balance Model
16.8<E<108.7 GtCO2/y
Heat Balance Model
Year
3.5
3
2.5
2
1.5
1
0.5
2000
2025
2050
2075
2100
2125


PPM
CO2 ppm vs. year (2020-2060)
E-growth
E-flat
E-fall (to 0 by 2060)
Year
550
500
450
400
2020
2025
2030
2035
2040
2045
2050
2055
2060


PPM
CO2 ppm vs year (2060-2100)
E-growth
E-flat
No E after 2060
Year
800
720
640
560
480
400
320
2060
2065
2070
2075
2080
2085
2090
2095
2100


°C
ΔT °C vs year (2020-2060)
E-growth
E-flat
E-fall (to 0 by 2060)
Year
2.25
2
1.75
1.5
1.25
1
2020
2025
2030
2035
2040
2045
2050
2055
2060



CARBON CYCLE DATA

TABLE 1

ITEM	GCP, Sources 2009-2018 GtCO2/y	GCP, Sinks 2009-2018 GtCO2/y	IPCC, Sources 1958-2004 GtCO2/y	IPCC, Sinks 1958-2004 GtCO2/y
MODERN				
Fossil CO2	35		26	
Land CO2	6		6	
Volcanoes			0.3	
Weathering				0.7
Biosphere/ Photosynthesis		12		10
Ocean releases			70 (* or 0)	
Ocean absorbs		9		80 (* or 10)
BACKGROUND				
Respiration	440		440	
Photosynthesis		440		440
Ocean releases	330		260 (* or 330)	
Ocean absorbs		330		260 (* or 330)
Imbalance/ unknowns/ error bounds	unknown accumulation/ loss —>	-2	+3.4	<— unknown source
Annual Atmospheric CO2 accumulation	+18		+15	
1750, ppm	~277			
1958, ppm			315	
2004, ppm			375	
Jan. 2018, ppm	407.4			
Jan. 2019, ppm	411			

TABLE 2

ITEM	GCP, Sources 2009-2018 ppm/y	GCP, Sinks 2009-2018 ppm/y	IPCC, Sources 1958-2004 ppm/y	IPCC, Sinks 1958-2004 ppm/y
MODERN				
Fossil CO2	4.28		3.18	
Land CO2	0.73		0.73	
Volcanoes			0.037	
Weathering				0.086
Biosphere/ Photosynthesis		1.47		1.22
Ocean releases			8.57 (* or 0)	
Ocean absorbs		1.10		9.79 (* or 1.22)
BACKGROUND				
Respiration	53.8		53.8	
Photosynthesis		53.8		53.8
Ocean releases	40.4		31.8 (* or 40.4)	
Ocean absorbs		40.4		31.8 (* or 40.4)
Imbalance/ unknowns/ error bounds	unknown accumulation/ loss —>	-0.25	+0.42	<— unknown source
Annual Atmospheric CO2 accumulation	+2.20		+1.84	
1750, ppm	~277			
1958, ppm			315	
2004, ppm			375	
Jan. 2018, ppm	407.4			
Jan. 2019, ppm	411			

CONCLUSION

I think this model can offer moderately accurate projections of CO2 concentration (C) and the consequent average global temperature perturbation (ΔT), dependent on the magnitude and linear evolution (up, down, or absent) of the anthropogenic emissions.

Because this model is so extremely simplified in comparison to the immense complexity of the Global Warming reality, I think that the inaccuracies that exist are tolerable since the entire purpose of the model is to provide reasonable insights into potential trends driven by our CO2 emissions.

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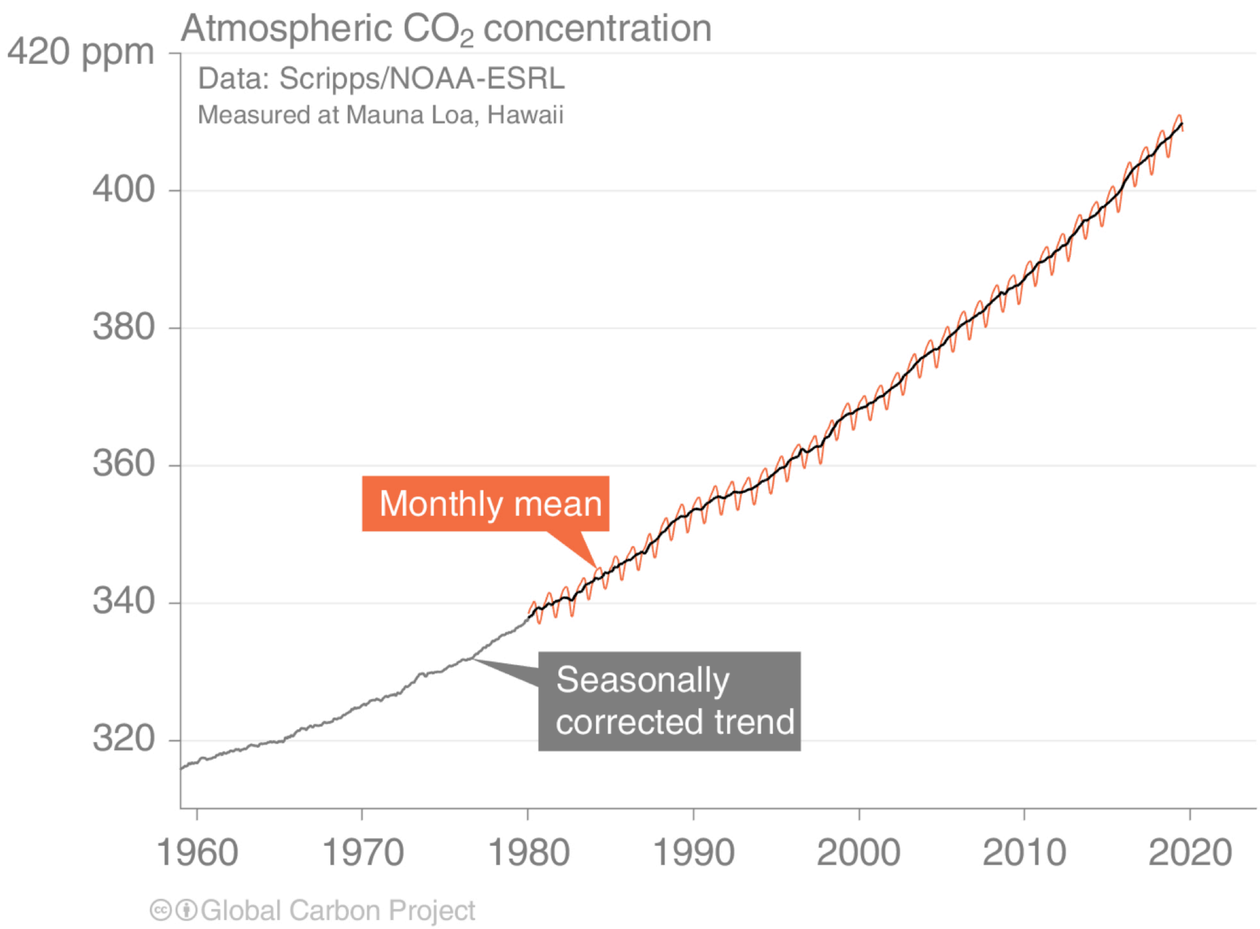
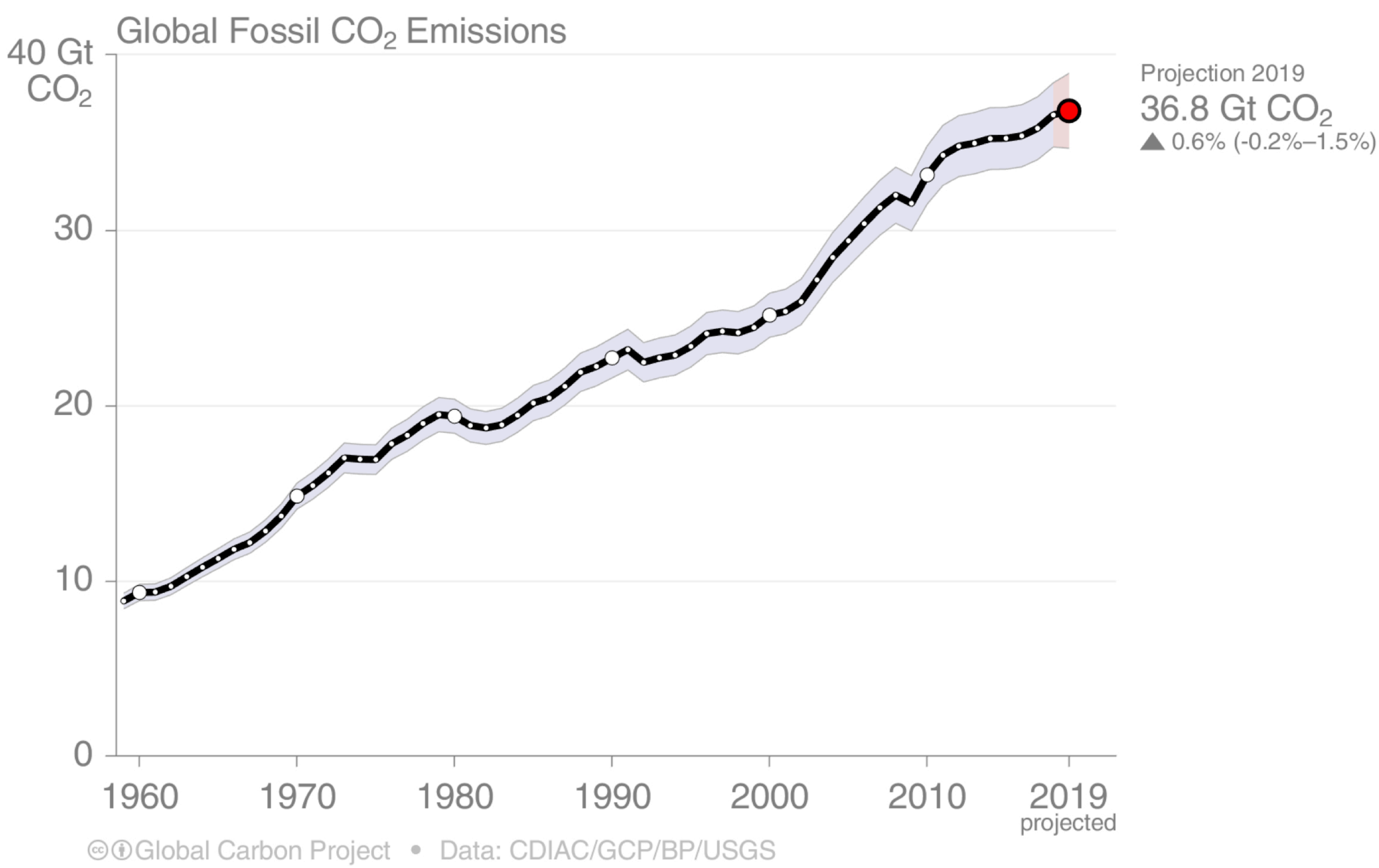
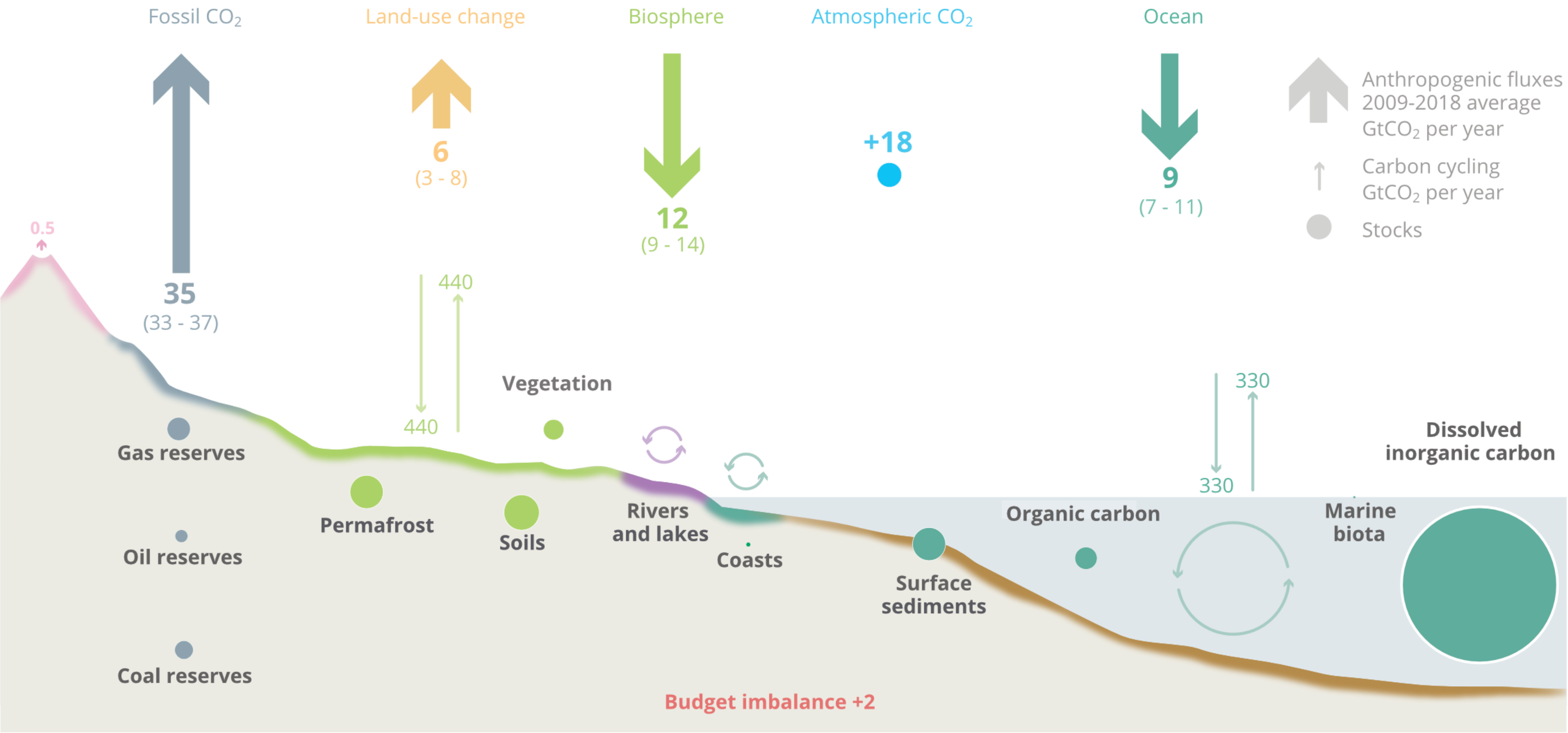

Atmospheric CO_2 concentration
420 ppm
Data: Scripps/NOAA-ESRL
Measured at Mauna Loa, Hawaii
400
380
360
340
320
Monthly mean
Seasonally corrected trend
1960
1970
1980
1990
2000
2010
2020
Global Carbon Project



Global Fossil CO2 Emissions
40 Gt CO2
30
20
10
0
1960
1970
1980
1990
2000
2010
2019 projected
Projection 2019
36.8 Gt CO2
▲ 0.6% (-0.2%–1.5%)
Global Carbon Project • Data: CDIAC/GCP/BP/USGS

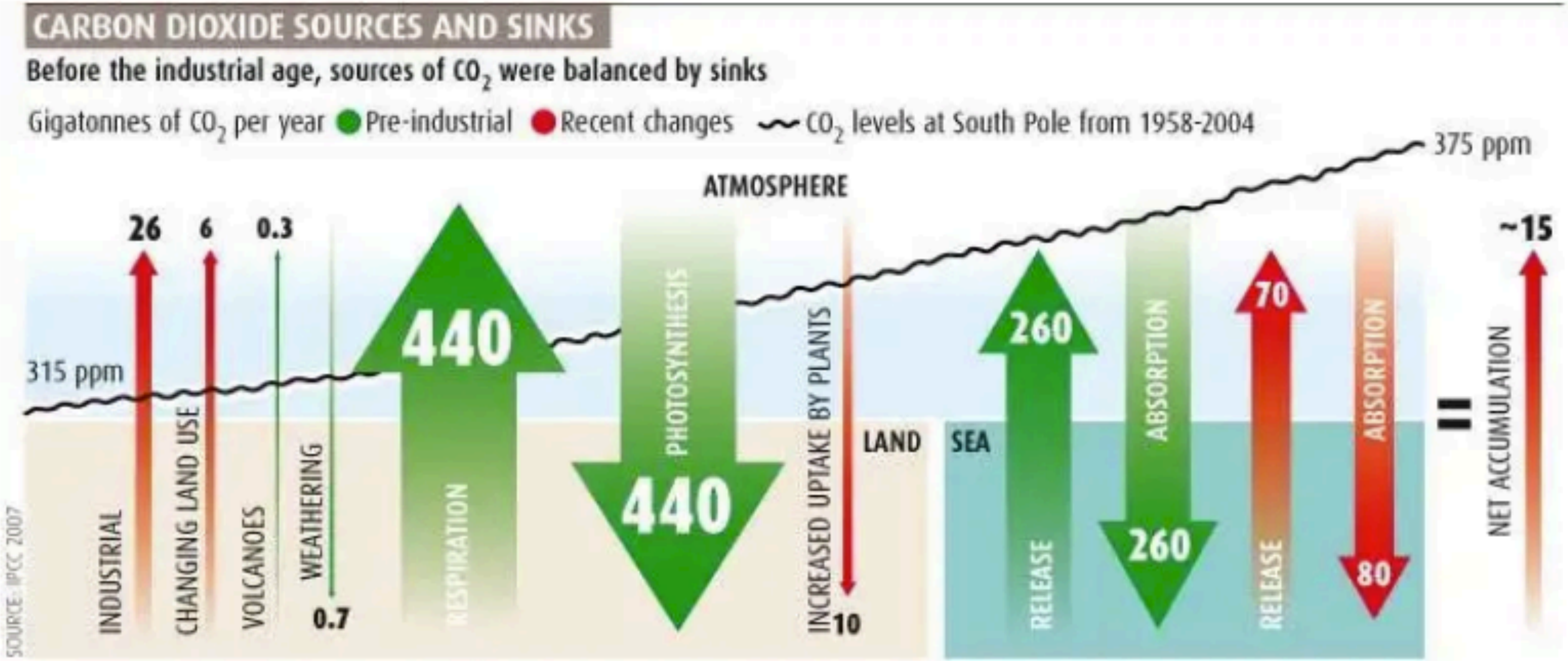
Anthropogenic perturbation of the global carbon cycle

Perturbation of the global carbon cycle caused by anthropogenic activities, averaged globally for the decade 2009–2018 ($GtCO_2$/yr)



The budget imbalance is the difference between the estimated emissions and sinks.

Source: CDIAC; NOAA-ESRL; Friedlingstein et al 2019; Ciais et al. 2013; Global Carbon Budget 2019



Carbon dioxide sources and sinks

CO2 Sweepers and Sinks in the Earth System

The carbon fluxes in and out of the surface and sedimentary reservoirs over geological timescales are finely balanced, providing a planetary thermostat that regulates Earth's surface temperature. Initially, newly released CO2 (e.g., from the combustion of hydrocarbons) interacts and equilibrates with Earth's surface reservoirs of carbon on human timescales (decades to centuries). However, natural "sinks" for anthropogenic CO2 exist only on much longer timescales, and it is therefore possible to perturb climate for tens to hundreds of thousands of years (Figure 3.5). Transient (annual to century-scale) uptake by the terrestrial biosphere (including soils) is easily saturated within decades of the CO2 increase, and therefore this component can switch from a sink to a source of atmospheric CO2 (Friedlingstein et al., 2006). Most (60 to 80 percent) CO2 is ultimately absorbed by the surface ocean, because of its efficiency as a sweeper of atmospheric CO2, and is neutralized by reactions with calcium carbonate in the deep sea at timescales of oceanic mixing (1,000 to 1,500 years). The ocean's ability to sequester CO2 decreases as it is acidified and the oceanic carbon buffer is depleted. The remaining CO2 in the atmosphere is sufficient to impact climate for thousands of years longer while awaiting sweeping by the "ultimate" CO2 sink of the rock weathering cycle at timescales of tens to hundreds of thousands of years (Zeebe and Caldeira, 2008; Archer et al., 2009). Lessons from past hyperthermals suggest that the removal of greenhouse gases by weathering may be intensified in a warmer world but will still take more than 100,000 years to return to background values for an event the size of the **Paleocene-Eocene Thermal Maximum (PETM)**.

In the context of the timescales of interaction with these carbon sinks, the mean lifetime of fossil fuel CO2 in the atmosphere is calculated to be 12,000 to 14,000 years (Archer et al., 1997, 2009), which is in marked contrast to the two to three orders of magnitude shorter lifetimes commonly cited by other studies (e.g., IPCC, 1995, 2001). In addition, the equilibration timescale for a pulse of CO2 emission to the atmosphere, such as the current release by fossil fuel burning, scales up with the magnitude of the CO2 release. "The result has been an erroneous conclusion, throughout much of the popular treatment of the issue of climate change, that global warming will be a century-timescale phenomenon" (Archer et al., 2009, p. 121).

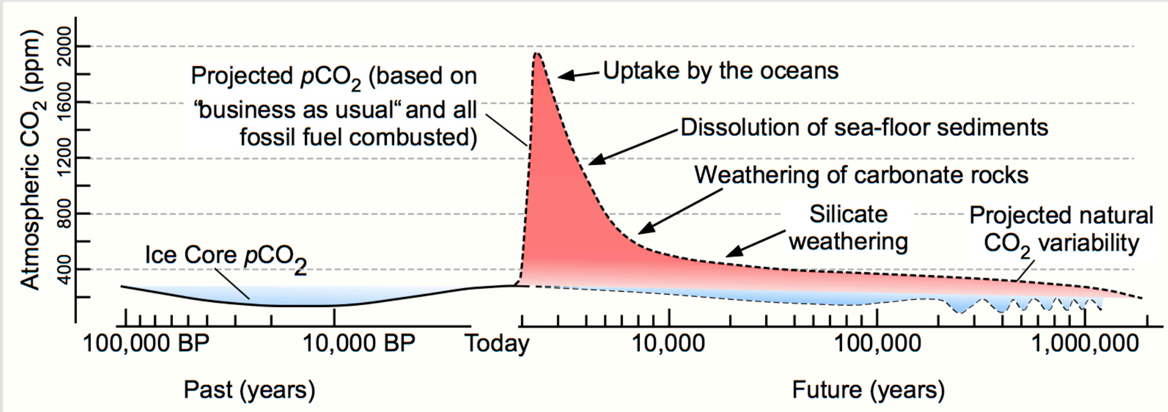


FIGURE 3.5 Graphic portrayal of the CO_2 "lifetime" assuming nonlinear CO_2 uptake kinetics by various short (decades to millennia) and long-term (10^4 to 10^5 y) surface and sedimentary carbon reservoirs. Projected natural CO_2 variability assumes 100 ky orbital control.
SOURCE: Modified from Walker and Kasting (1992); B.B. Sageman, personal communication.

CO2 "lifetime" in the atmosphere
National Research Council 2011. *Understanding Earth's Deep Past: Lessons for Our Climate Future*. Washington, DC: The National Academies Press. Figure 3.5, page 93 of the PDF file, page numbered 78 in the text.
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Ye Cannot Swerve Me: Moby-Dick and Climate Change
15 July 2019
https://manuelgarciajr.com/2019/07/15/ye-cannot-swerve-me-moby-dick-and-climate-change/

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Oakland, California, 10:15am, 9 September 2020
"Burning Land Eclipse"