

NONLINEAR MODEL FOR NATURAL CARBON CYCLE PROCESS

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Abstract: It was in 1896 when S. Arrhenius first noticed the potential effect of human activities on the carbon cycle and the implications for climate change. He put forward the theory that CO₂ in the atmosphere was an important greenhouse gas and that it was a by-product of burning fossil fuels. In 1958, Charles Keeling began the observations at Mauna Loa Observatory, 3650 m up a mountain in Hawaii, regarded as far enough away from any carbon dioxide source to be a reliable measuring point. Measurements of CO₂ in the atmosphere have been continuous for almost 50 years. In recent decades, CO₂ increased on average by 1.4 parts per million (ppm) a year because of the amount of fossil fuels burnt.

Keywords: carbon cycle, model, atmosphere, projection.

1. INTRODUCTION AND HISTORY

Carbon (C) is unquestionably one of the most important elements on Earth. It is the principal building block for the organic compounds that make up life. Carbon's electron structure gives it a ⁺⁴ charge, which means that it can readily form bonds with itself, leading to a great diversity in the chemical compounds that can be formed around carbon; hence the diversity and complexity of life. Carbon occurs in many other forms and places on Earth; it is a major constituent of limestone, occurring as calcium carbonate (CaCO₃); it is dissolved in ocean water and fresh water; and it is present in the atmosphere as carbon dioxide (CO₂), the second most important greenhouse gas. The flow of carbon throughout the biosphere, atmosphere, hydrosphere, and geosphere is one of the most complex, interesting, and important of the global cycles. More than any other global cycle, the carbon cycle challenges us to draw together information from biology, chemistry, oceanography, and geology in order to understand how it works and what causes it to change.

1.1 Kyoto Protocol

There is growing concern about the impact that increased emissions of the "greenhouse gases" are having on the global climate. Because of this, the Kyoto Protocol has been established to limit emissions of greenhouse gases. Under the Kyoto Protocol, industrialised countries and those in transition to a market economy (the so-called "Annex I countries", among them being also Romania) have agreed to limit or reduce their emissions of these greenhouse gases. The "Annex I Countries" are those that have taken on emission reduction or limitation targets under the Kyoto Protocol.

The Protocol sets quantified emission limitations and reduction obligations with respect to a basket of six gases. Of these, carbon dioxide (CO₂), which derives from the burning of fossil fuels such as coal, oil and gas, is the most important. Methane (CH₄) and nitrous oxide (N₂O) emissions are also substantial contributors to the problem.

The targets define the amount of greenhouse gases that the countries are allowed to emit in the 'commitment period' of 2008 to 2012, relative to the amount emitted in 1990. These targets represent either a cut in emissions or a lower rate of increase in emissions.

1.2 Mauna Loa

In the late 1950's, Roger Revelle, an American oceanographer, and a colleague, Charles Keeling, began monitoring atmospheric CO₂ at an observatory on Mauna Loa, on the big island of Hawaii. The record from Mauna Loa, shown in Figure 1 below, is a dramatic sign of global change that captured the attention of the whole world because it shows that this "experiment" we are conducting is apparently having a significant effect on the global carbon cycle. The climatologically consequences of this change are potentially of great importance to the future of the global population.

The Mauna Loa atmospheric CO₂ measurements constitute the longest continuous record of atmospheric CO₂ concentrations available in the world. The Mauna Loa site is considered one of the most favourable locations for measuring undisturbed air because possible local influences of vegetation or human activities on atmospheric CO₂ concentrations are minimal and any influences from volcanic vents may be excluded from the records. The methods and equipment used to obtain these measurements have remained essentially unchanged during the 47-year monitoring program.

Because of the favourable site location, continuous monitoring, and careful selection and scrutiny of the data, the Mauna Loa record is considered to be a precise record and a reliable indicator of the regional trend in the concentrations of atmospheric CO₂ in the middle layers of the troposphere. The Mauna Loa record shows a 19.4% increase in the mean annual concentration, from 315.98 parts per million by volume (ppmv) of dry air in 1959 to 377.38 ppmv in 2004. The 1997-1998 increase in the annual growth rate of 2.87 ppmv represents the largest single yearly jump since the Mauna Loa record began in 1958. This represents an average annual increase of 1.4 ppmv per year.

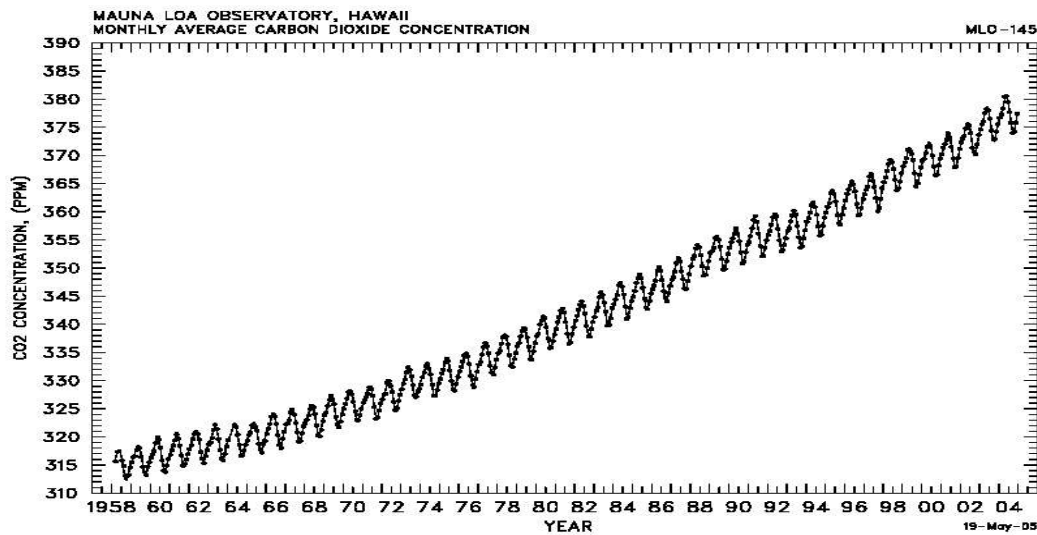


Fig. 1.

2. CARBON CYCLE MODELLING

We modified the C.free model of carbon cycle (Fiddaman, 1997), which is an eddy diffusion model with stocks of carbon in the atmosphere, biosphere, mixed ocean layer, and 10 deep ocean layers.

In the C.free model, all emissions initially accumulate in the atmosphere. As the atmospheric concentration of CO₂ rises, the uptake of CO₂ by the ocean and biosphere increases, and carbon is gradually stored. The atmospheric flux to the biosphere consists of net primary production (NPP). Net primary production grows logarithmically as the atmospheric concentration of CO₂ increases according to:

$$NPP = NPP_0 \left(1 + \beta_b \ln \left(\frac{C_a}{C_{a,0}} \right) \right) \quad (1)$$

NPP = net primary production
 NPP₀ = reference net primary production
 β_b = biostimulation coefficient
 C_a = CO₂ in atmosphere
 $C_{a,0}$ = reference CO₂ in atmosphere

Because the relationship is logarithmic, the uptake of CO₂ by the biosphere is less than proportional to the increase in atmospheric CO₂ concentration. Effects of the current biomass stock, temperature, and human disturbance are neglected.

It is worth noting that this formulation is not robust to large deviations in the atmospheric concentration of CO₂. As the atmospheric concentration of CO₂ approaches zero, net primary production approaches minus infinity, which is not possible given the finite positive stock of biomass. As the concentration of CO₂ becomes very high, net primary production can grow arbitrarily large, which is also not possible in reality. Neither of these constraints is a problem for reasonable model trajectories, though.

To simplify the model, detailed biospheres are aggregated into stocks of biomass (leaves, branches, stems, roots) and humus (litter, humus).

$$C_b(t) = \int NPP(t) - \frac{C_b(t)}{\tau_b} dt \quad (2)$$

C_b = carbon in biomass
 τ_b = biomass residence time

$$C_h(t) = \int \frac{\Phi C_b(t)}{\tau_b} - \frac{C_h(t)}{\tau_h} dt \quad (3)$$

C_h = carbon in humus
 τ_h = humus residence time
 Φ = humification fraction

The interaction between the atmosphere and mixed ocean layer involves a shift in chemical equilibrium. CO₂ in the ocean reacts to produce HCO₃⁻ and CO₃⁻². In equilibrium,

$$C_m = C_{m,0} \left(\frac{C_a}{C_{a,0}} \right)^{\left(\frac{1}{\zeta}\right)} \quad (4)$$

C_m = CO₂ in mixed ocean layer
 $C_{m,0}$ = reference CO₂ in mixed ocean layer
 C_a = CO₂ in atmosphere
 $C_{a,0}$ = reference CO₂ in atmosphere
 ζ = buffer factor

The atmosphere and mixed ocean adjust to this equilibrium with a time constant of 9.5 years.

The buffer or Revelle factor, z , is typically about 10. As a result, the partial pressure of CO₂ in the ocean rises about 10 times faster than the total concentration of carbon.

This means that the ocean, while it initially contains about 60 times as much carbon as the preindustrial atmosphere, behaves as if it were only 6 times as large.

The buffer factor itself rises with the atmospheric concentration of CO₂ and temperature. This means that the ocean's capacity to absorb CO₂ diminishes as the atmospheric concentration rises. The temperature effect (which is omitted in this model) is one of several possible feedback mechanisms between the climate and carbon cycle.

$$\xi = \xi_0 + \delta_b \ln \left(\frac{C_a}{C_{a,0}} \right) \quad (5)$$

ξ = buffer factor

ξ_0 = reference buffer factor

δ_b = buffer CO₂ coefficient

C_a = CO₂ in atmosphere

$C_{a,0}$ = reference CO₂ in atmosphere

The deep ocean is represented by a simple eddy-diffusion structure similar to that in the Oeschger model, but with fewer layers. Effects of ocean circulation and carbon precipitation, present in more complex models, are neglected. Within the ocean, transport of carbon among ocean layers operates linearly. The flux of carbon between two layers of identical thickness is expressed by:

$$F_{m,n} = \frac{(C_m - C_n)^e}{d^2} \quad (6)$$

$F_{m,n}$ = carbon flux from layer m to layer n

C_k = carbon in layer k

e = eddy diffusion coefficient

d = depth of layers

The effective time constant for this interaction, e/d^2 , varies with d , the thickness of the ocean layers. This model employs a 75 meter mixed layer, five 200 meter middle layers, and five 560 meter deep ocean layers with the time constants of 1.4 years, 10.0 years and, respectively, 78.4 years. Models with fewer ocean layers underestimate the short term participation of the ocean in carbon uptake and must increase uptake by other means to compensate.

3. MODEL RESULTS

The historical carbon emissions summarize two main components: from fossil fuels burnt and from land use, since 1850. This data provides estimates of global net carbon fluxes, on a year-by-year basis from 1850 through 2000, resulting from fossil fuels burnt and changes in land use (such as harvesting of forest products and clearing for agriculture), taking into account not only the initial removal and oxidation of the carbon in the vegetation, but also subsequent regrowth and changes in soil carbon. We used a five years mean of the total historical carbon emissions as an input lookup for the C.free model.

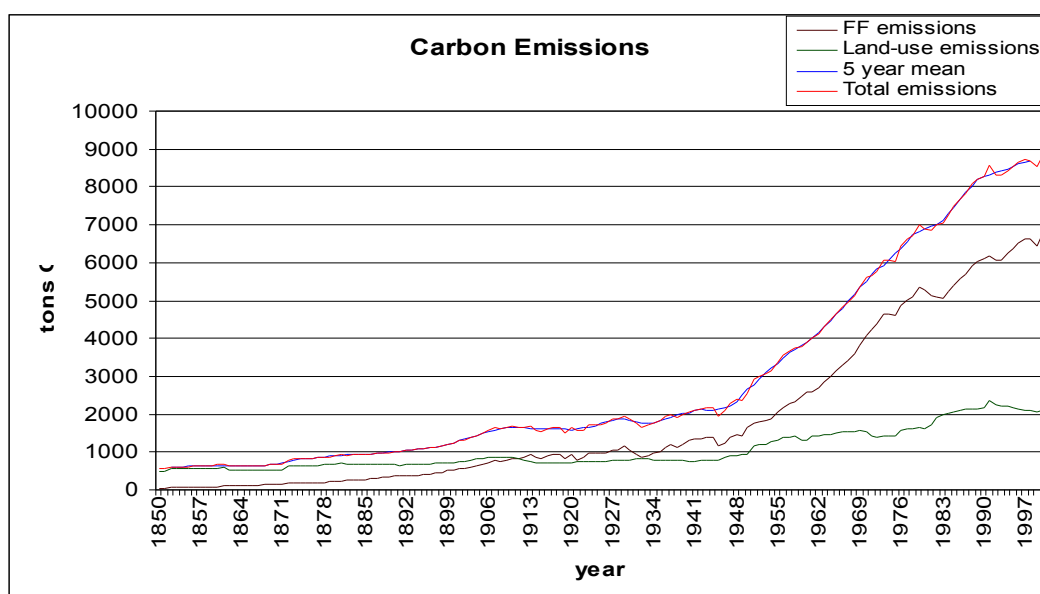


Fig. 2.

After 2004, we proposed different scenarios for carbon emissions, according with some IPCC emissions scenarios, with Kyoto Protocol and even the utopist scenario of complete emissions cut-off after 2005.

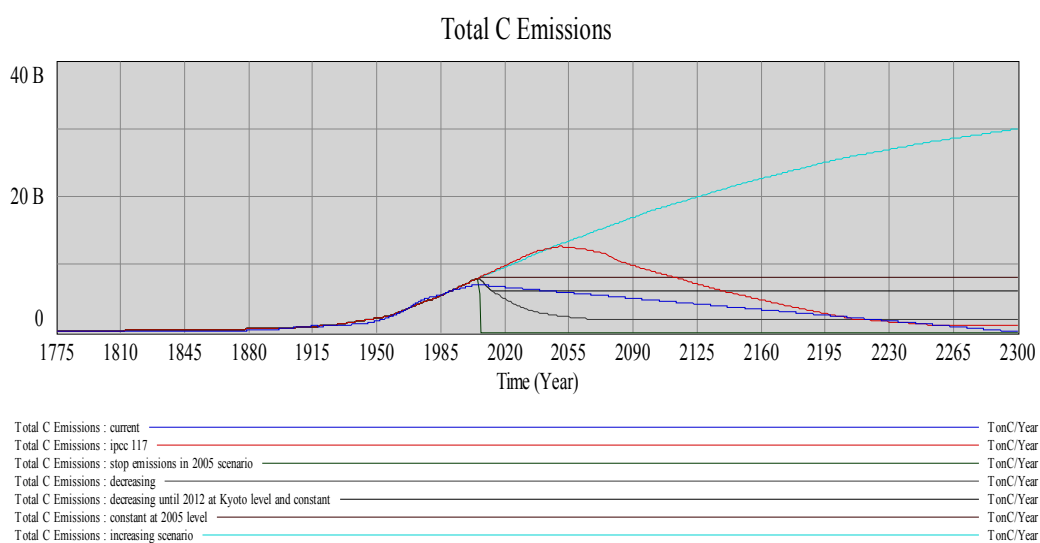
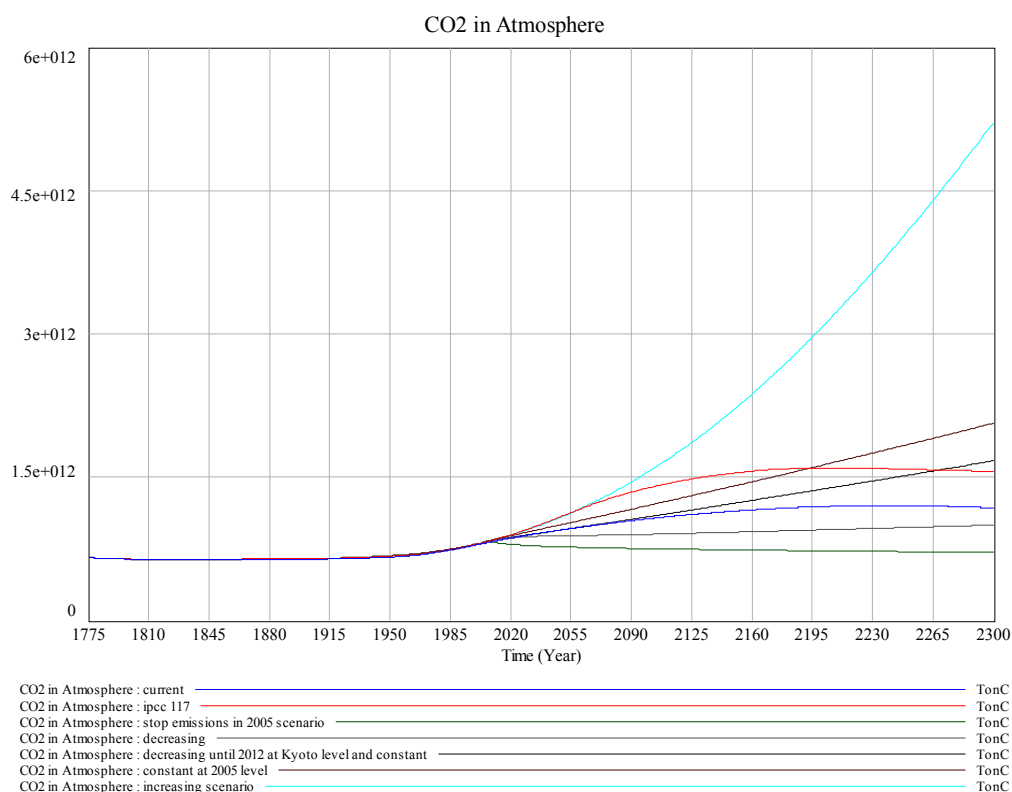


Fig. 3.

After running the model with these different scenarios, the results were in accordance with IPCC models results. We can clearly see that even if we will stabilize the emissions, the amount of CO₂ in atmosphere will continue to rise.

Fig. 4.



4. CONCLUSIONS

At the 1997 Kyoto conference, 38 industrialized nations agreed to reduce emissions to about 95% of 1990 rates by 2012. While the agreement is better than business as usual, rapidly developing nations like China are not signatories, and their emissions continue to grow. The policy debate has become a fight over whether to stabilize the emission rate, not the stocks of greenhouse gases that drive the climate. Even if Kyoto were fully implemented, emissions would continue to exceed removal and GHG concentrations would continue to rise. The fight over implementation of the Kyoto Protocol, therefore, has become a debate about how much more GHG concentrations in the atmosphere will rise, and how much faster the global climate will warm. Halting warming, much less reversing it, is not even on the table.

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