Some implications of the bomb-test curve

John Reid
P.O. Box 279
Cygnet
Tasmania 7112
Australia
johnsinclairreid@gmail.com

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Abstract

The bomb-test curve showing the decay of $^{14}CO_2$ in the atmosphere following the cessation of nuclear weapons testing provides valuable information about the carbon cyle. The bomb-test curve has an exponential decay with a single time constant, tending over 50 years to the pre-bomb-test equilibrium. These facts imply that CO_2 diffuses rapidly from the atmosphere where it has a residence time of only ten years. The system can be modelled with simple first-order differential equation whereby CO_2 diffuses from the atmosphere and is replacd by CO_2 from the deep ocean brought to the surface by ocean currents. The model indicates that less than twenty percent of recent CO_2 increases are anthropogenic in origin.

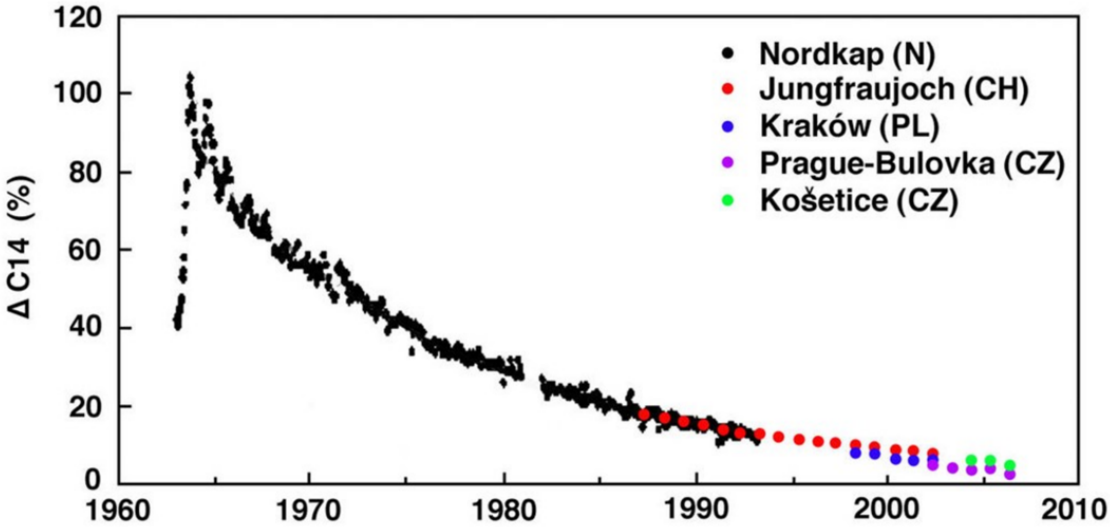

Figure 1: Atmospheric concentration of ^{14}C

1 Introduction

The concentration of CO_2 in the atmosphere has been monitored continuously since 1958 when Charles Keeling established a monitoring station on Mauna Loa in Hawaii. Since that time a number of other, similar stations have been established. All such stations show a steady increase in atmospheric CO_2 from year to year once seasonal variations are excluded. It is widely believed that this is due to human activities such as the combustion of fossil fuels and that emissions from natural sources such as the ocean and volcanoes play a relatively minor role. Increases in global average surface temperature observed during the 20th century have been attributed to this increase because, as a triatomic molecule, CO_2 is a strong absorber of infrared radiation. A number of complex computer models predict the degree of global warming according to various atmospheric CO_2 scenarios. As a prerequisite, these CO_2 scenarios are themselves modelled. Such models are based on an agglomeration of theories and facts known generically as the Carbon Cycle. Perhaps the single most important aspect of the Carbon Cycle is the length of time for which anthropogenic CO_2 remains in the atmosphere. Over the previous half century an experiment has been under way which illuminates the relationship between CO_2 stored in the atmosphere and its interchange with other potential reservoirs. That experiment involved the injection of a pulse of radioactive carbon, ^{14}C, into the atmosphere was an unintended consequence of nuclear weapons testing which took place in the 1950s and 60s. The circumstances were entirely serendipitous but it would be difficult to design a better experiment with which to investigate the carbon cycle as it pertains to the atmosphere. The observed decay in atmospheric concentrations of ^{14}C which followed the cessation of the tests, is known as the bomb-test curve.

2 The Carbon Cycle and the bomb-test curve

The bomb-test curve is shown in Figure 1. The following facts are immediately evident:

1. Atmospheric 14C exhibits exponential decay
2. The exponential decay has a single time constant of 14.3 years giving a residence time of 10 years
3. After 50 years the curve has returned to its pre-bomb-test background value.

The bomb-test curve is a direct measurement of the impulse-response of the atmospheric reservoir to a perturbation in its CO_2 content. The above listed facts lead, respectively, to the following conclusions:

1. The exponential decay implies that the removal of atmospheric CO2 from the atmosphere is dominated by a first order differential equation, the diffusion equation, whereby the rate of diffusion from the atmosphere reservoir is proportional to the concentration.
2. The single time constant implies that the CO_2 diffuses into a single reservoir (or multiple reservoirs with similar time constants).
3. The asymptotic approach to a new equilibrium which is indistinguishable from the pre-bomb background value implies that the second reservoir into which the atmospheric $^{14}CO_2$ has diffused, must be very much larger than the atmospheric reservoir itself.

3 A deep-ocean reservoir model

These facts and deductions form the basis for our model. We further assume that there are regions of the ocean surface where atmospheric CO_2 diffuses into the deep ocean which constitutes the second reservoir and that there are other regions of the ocean surface where CO_2 outgasses from the ocean into the atmosphere. This outgassing occurs, not by a diffusion process, but by pumping. Deep ocean CO_2 at 4°C is brought into the surface layer by upwelling ocean currents. As the upwelled seawater from beneath the thermocline is warmed by sunlight it becomes supersaturated with CO_2 which comes out of solution. This happens because, like most gases, the solubility of CO_2 is inversely related to temperature.

The simplest mathematical description is the following first order differential equation:

$$\frac{\mathrm{d}K}{\mathrm{d}t} + \frac{K}{\tau} = a(t) + p(t) \tag{1}$$

where $K = K(t)$ is the atmospheric concentration of CO_2 at time t, τ is the diffusion time constant estimated from the bomb-test curve, $a(t)$ is the production rate of anthropogenic CO_2 and $p(t)$ is the rate at which CO_2 is being pumped out of the ocean. Three out of four of the terms in (1) can be measured or calculated. Only $p(t)$ is not known and it can be calculated from the other three terms, viz,:

$$p(t) = \frac{\mathrm{d}K}{\mathrm{d}t} + \frac{K}{\tau} - a(t) \tag{2}$$

The solution is shown in Figure 2. The rapid rate of diffusion, which leads to a surprisingly small value of τ, means that the rate of diffusion into the ocean dominates the process. Since concentration in the atmosphere is not diminished as a result implies, in turn, that atmospheric CO_2 is replenished by a comparably high rate of pumping, $p(t)$, of approximately 50 Gt/year in 2010, so dwarfing the anthropogenic production rate, $a(t)$, of 10 Gt/year.

4 Conclusions

Utilising the bomb-test curve as a measure of the impulse response function of the atmospheric CO_2 reservoir, and assuming this reservoir is replenished by pumping rather than diffusion, leads to the conclusions that the residence time of CO_2 in the atmosphere is 10 years and that less than twenty percent of observed recent increase in atmospheric CO2 concentration is anthropogenic in origin.

5 References

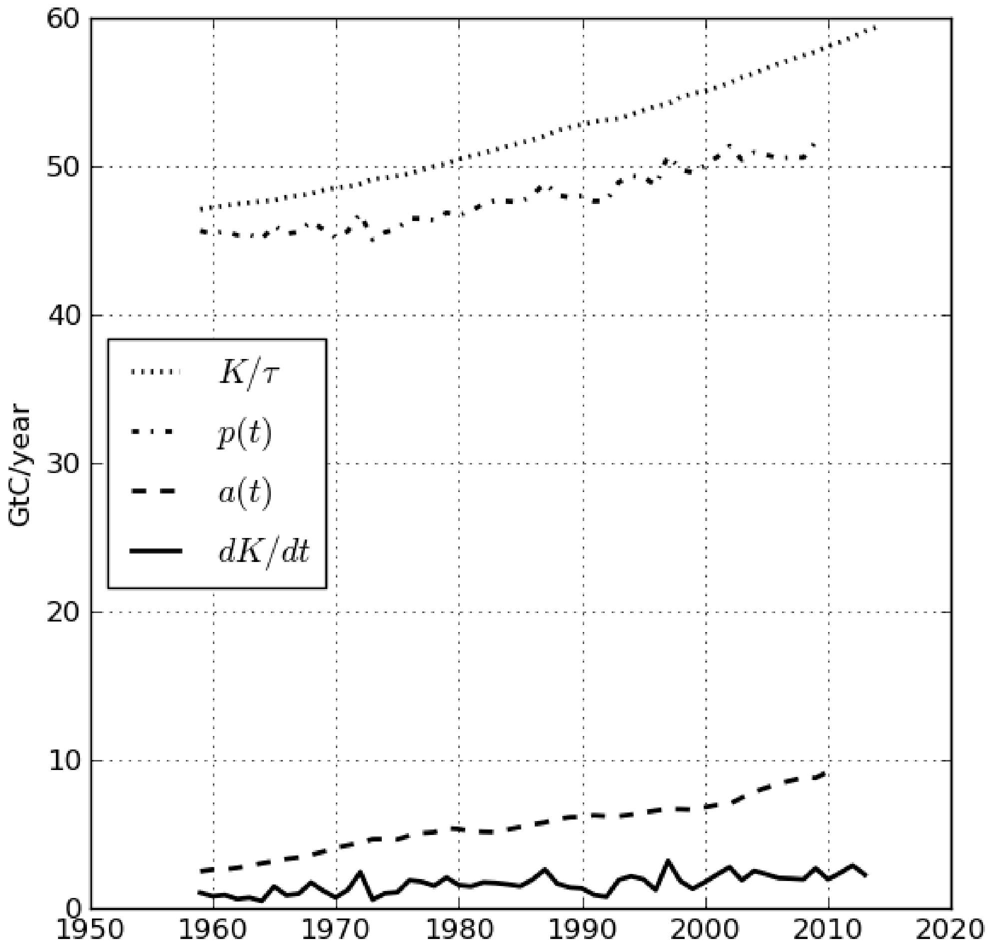

Figure 2: Solution of equation (2) for $p(t)$, the rate at which CO_2 is pumped from the ocean (dot-dash). Also shown are K/τ, the atmosphere to ocean diffusion rate, (dots), $a(t)$, the anthropogenic production rate, (dashes), and $\mathrm{d}K/\mathrm{d}t$, the measured rate of increase of atmospheric CO_2 concentration, (solid).