On the Anthropocene Equation

Bill Menke, April 25, 2017

I paraphrase a correspondent's email:

> *... my friends and I spotted the Anthropocene Equation[1] in some online article. If says that the rate of change of earth's destruction is a function of human activity:*
>
> $$\frac{dE}{dt} = f(H) \quad \text{when} \quad A, G, I \to 0$$
>
> *Here E is the earth system, H is human activity, and A, G, I are astronomical, geological and internal dynamical factors, respectively. Astronomical and geophysical forces, the authors argue, are grossly outweighed by human activity and are irrelevant in the equation. (Personally, I would have a hard time asserting such a thing). My friends insist on calling it a "mathematical equation" while I tend to think of math equations (especially something that claims to model earth's health) to be much more involved and have some math operators and a bunch of variables. I see in it as nothing more than author's theory written out using mathematical notation ...*

I would like to start with what might at first appear to be a digression.

The idea that the total mass of carbon on the earth is constant with time is a simple but powerful idea. We can express this idea as reservoir equation that says that the sum of the mass of carbon in the atmosphere, C_A, in the biosphere, C_B, in the ocean, C_O, and in geological formations C_G is a constant that is independent of time t:

$$C_A(t) + C_B(t) + C_O(t) + C_G(t) = constant \tag{1}$$

This equation is based on the very strong physical principle of conservation of mass and is very nearly correct, although it does omit some minor processes such as the in-fall of carbonaceous meteorites from space and the production carbon-14 from cosmic rays interacting with nitrogen in the atmosphere (and it subsequent decay). It is a simple equation, yet one that is surprisingly useful.

The constant on the right hand side of Equation (1) can be eliminated by differentiating the equation with respect to time. The resulting equation expresses the rate of change of the masses:

$$\frac{dC_A}{dt} = -\frac{dC_B}{dt} - \frac{dC_O}{dt} - \frac{dC_G}{dt} \tag{2}$$

This equation says that any increase in carbon in the atmosphere is accompanied by a draw-down of the carbon stored in the biosphere, ocean and/or in geological formations, and vice versa. For example, coal mining removes carbon from geological formations and must be accompanied by an increase of carbon in the atmosphere, oceans and/or biosphere.

The terms in Equation (2) can be studied individually. Carbon dioxide is a trace gas in the atmosphere; furthermore the atmosphere is well-mixed by winds so that its concentration $X(t)$ does not vary much with position on the globe. These properties allow us express the change in the mass of atmospheric carbon as a change in its concentration:

$$\frac{dC_A}{dt} \approx M_A \frac{dX}{dt} \tag{3}$$

Here M_A is the mass of the atmosphere, which is approximately constant. Equation (3) is useful because the concentration X is the quantity that is most easily measured and the one that best quantifies the greenhouse warming effect of atmospheric carbon dioxide.

The biosphere term in Equation (2) can be divided into terms that represent different species, such as elephants:

$$\frac{dC_B}{dt} = \frac{dC_E}{dt} + \cdots \tag{4}$$

Here C_E is the mass of carbon in the world's elephant herds. Furthermore, elephant carbon increases due to reproduction $R(t)$ and decreases due to poaching $P(t)$:

$$\frac{dC_E}{dt} = R - P \tag{5}$$

Elephant reproduction depends primarily upon the number of elephants - the more adults, the more babies. Hence, we can write, at least approximately:

$$\frac{dC_E}{dt} = \frac{p}{100} C_E - P \tag{6}$$

where p expresses reproduction as a percentage of the mass of elephants. We know that elephants reproduce only slowly, so when time is measured in years, we expect p to be just a few percent.

While the annual reproduction rate R does not exceed a few percent, poaching P can be conducted at an arbitrarily high rate. Human beings have the technological means to poach every elephant on the planet in just a few months. In a poaching-dominated era, the reproduction term in Equation (6) can be ignored:

$$\frac{dC_F}{dt} \approx -P \tag{7}$$

The elephants are being poached so fast that their slow reproduction cannot keep up; it is irrelevant. If we understand the carbon in the world's elephant herds C_F to be a measure of their health, we can recognize Equation (7) as an Anthropocene Equation. It says:

> While both reproduction and poaching affect the health of elephant herds, only poaching is important when it is so intense that elephants do not have time to reproduce.

(8)

Part of Garrney and Steffen's (2017) motivation for developing the Anthropocene Equation was to define the Anthropocene era. We should turn Equation 8 around:

> When poaching, and not reproduction, is the primary factor affecting the size of elephant herds, elephants are experiencing Anthropocene conditions.

(9)

Now back to my correspondent's question. The Anthropocene Equation is an attempt to quantify the notion that the intensity of human activities is so high that it needs to considered alongside, geological and internal dynamical factors and may be the *dominant* source of change in some earth system processes. This assertion is clearly true for some measures of the health of the earth system, such as the elephant herds that I discuss above, as well as their obvious analogues, such as rhino herds, whale pods and maybe even forests and some fisheries. These are cases where we can write an equation analogous to Equation (7) in which we can:

(A) Clearly define a earth system variable that is changing;
(B) Enumerate the factors that cause it to change; and
(C) Plausibly argue that the anthropogenic factor is the dominant one.

However, performing one of more of these analytical steps is problematical for many aspects of the earth system, because detailed knowledge of many parts of the system is lacking. The evolution of new infectious diseases may be an example. On the one hand, we have the sense that changes in human patterns of interacting with the environment may be increasing the rate of their emergence. On the other hand, our knowledge of even the natural processes involved in their evolution (let along the anthropogenic ones) is sufficiently fuzzy that even qualitative descriptions of the important processes are controversial.

The notion that *all* earth system processes are dominated by anthropogenic processes does not seem to be true, at least for the time being. Australian droughts may be a counter example, for their pattern is known to be heavily influenced by the El Nino Southern Oscillation (ENSO), which is a type of natural dynamical instability in the climate system (the I in the Anthropocene Equation). Furthermore, should the time come when anthropogenic factors do dominate, they might very well do so by modulating the strength of ENSO, rather than through a completely independent mechanism. This brings out the problem that the ideal of distinguishing causes of change is more complicated than is presented in Equation (6). In actuality, the global circulation models (GCM's) that are the real-world analogues to Equation (6) embody extremely complicated physics with many interactions and feedbacks. Cause and effect is difficult to discern in their predictions, except to the extent that the GCM's can be run many times, both with and without particular anthropogenic forcings, and the different ensembles of predictions compared. One anthropogenic forcing may weaken ENSO (and thus reduced the severity of Australian droughts) while another may have the opposite effect, so the role of human beings in bringing on droughts may well depend upon the details of the scenarios.

To merely assert than an Anthropocene Equation holds for a poorly understood process is misleading; to assert that it hold for all earth system processes, even more so.

Garrney and Steffen (2017) also argue that the change from a regime in which the natural factors A, G, I dominate to one in which human activity H dominates may lead to radically different mean state of the earth system – as different from the pre-industrial world as was the Ice Age. This is essentially an argument by analogy, and draws upon our understanding of simple systems of equations that bear some resemblance to the Anthropocene Equation and that that are known to have "basins of attractions" (depicted in the author's Figure 2) that represent frequently-experienced conditions. However, these analogies lack specificity; the specific earth system variables are not identified and so the difference between the basins cannot be assessed. Saying that the growing importance of anthropogenic forcing is likely to cause the earth system to experience new patterns of behavior is almost a truism. The key issue is whether these new patterns are radically different from those we currently experience, or are only marginally so.

I would characterize the Anthropocene Equation as an "intellectual sketch" that is neither a hoax nor an environmental science breakthrough. It uses the language of mathematics to set forth and clarify an agenda, but none of its equations significantly contribute to that agenda. Its key contribution is to focus attention on the importance of the relative sizes of natural and anthropogenic sources of earth system change, and to point out that, at least in some cases, the anthropogenic sources may be the dominant ones.

[1]Garrney, O. and Steffen, W., The Anthropocene Equation, The Anthropocene Review 4, 53-61, 2017.