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The Anthropocene equation

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Abstract

The dominant external forces influencing the rate of change of the Earth System have been astronomical and geophysical during the planet's 4.5-billion-year existence. In the last six decades, anthropogenic forcings have driven exceptionally rapid rates of change in the Earth System. This new regime can be represented by an 'Anthropocene equation', where other forcings tend to zero, and the rate of change under human influence can be estimated. Reducing the risk of leaving the glacial–interglacial limit cycle of the late Quaternary for an uncertain future will require, in the first instance, the rate of change of the Earth System to become approximately zero.

Keywords

Earth System, globalisation, rate of change

Human activities now rival the great forces of nature in driving changes to the Earth System (Steffen et al., 2007). This has led to the proposal that Earth has entered a new geological epoch – the Anthropocene (Crutzen, 2002; Crutzen and Stoermer, 2000). While substantial data have been gathered in support of the Anthropocene proposal (Waters et al., 2016), what has been missing is a high-order conceptual framework of the Earth System's evolution within which the Anthropocene can be compared with other changes in Earth history. We propose that in terms of the rate of change of the Earth System, the current regime can be represented by an 'Anthropocene equation'.

Earth is approximately 4.54 billion years old (Dalrymple, 2001). The Earth System is a single, planetary-level complex system composed of the biosphere, defined here as the sum of all biota living at any one time and their interactions, including interactions and feedbacks with the geosphere defined here as the atmosphere, hydrosphere, cryosphere and upper part of the lithosphere (Steffen et al, 2016). The age of Earth's biosphere has been estimated at 3.7–4.1 billion years old (Bell et al., 2015; Nutman et al., 2016). Astronomical and geophysical forces have been the dominant external drivers of Earth System change during this period (McGregor et al., 2015; Petit et al., 1999). Astronomical forces that affect insolation and relate to solar irradiance include orbital eccentricity, obliquity and precession driven by gravitational effects of the sun and other planets

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(Milanković, 1941), and impact events. Geophysical forces include volcanic activity, weathering and tectonic movement.

Under the influence of these external forcings, the rate of change of the Earth System (E) at the highest order of abstraction can be given by (after Schellnhuber, 1998, 1999, 2001):

$$\frac{dE}{dt} = f\left(A, G\right) \tag{1}$$

where A is astronomical forcing, G is geophysical forcing.

While astronomical and geophysical forcings have been dominant drivers pulling the Earth System into new states (i.e. 'basins of attraction'), internal dynamics, including biospheric evolutionary processes, interacting with these drivers, can also drive major Earth System change, for example, the Great Oxygenation Event 2.4 billion years BP that took place over hundreds of millions of years (Konhauser et al., 2009). Throughout Earth's past, strong negative feedbacks arising from the internal dynamics of the Earth System, often involving the biosphere, have assured long periods – hundreds of millions of years at times – of relative stability (Lenton and Williams, 2013). Internal dynamics are particularly important because of their influence on the atmospheric concentration of greenhouse gases such as carbon dioxide, which in turn significantly influence the climate (Lenton, 2016).

Therefore, for completeness, an equation for the rate of change of the Earth System can be given as:

$$\frac{dE}{dt} = f\left(A, G, I\right) \tag{2}$$

where I is internal dynamics of the Earth System.

In the recent past, subdivisions of the Quaternary (2.588 Myr to present) have been defined by climate forcing related to cyclical variation in Earth's orbit coupled with other astronomical forcings, changes in solar irradiance, and irregular events such as volcanic eruptions (Berger et al., 2006). At present, the Earth System of the Quaternary is typified by saw-tooth oscillations of glacial–interglacial cycling initially with 40,000-year periodicity until ~1.2 Myr BP, then switching to 100,000-year periodicity. *Homo sapiens* evolved during a rather unusual state of potential instability in Earth's history (Lenton and Williams, 2013). While astronomical forcing (A) has been the overriding external trigger of change in the Quaternary, relatively small astronomical forcings have resulted in distinctly different states of the Earth System because of the strong influence of internal dynamics (I), with bifurcation points influenced by small changes in atmospheric concentrations of carbon dioxide (Berger et al., 2006; Ganopolski et al., 2016). Under current astronomical forcing and atmospheric levels of carbon dioxide of about 280 ppm, Holocene-like conditions could have been expected for probably another 50,000 years (Ganopolski et al., 2016).

However, an entirely new forcing is now driving change in the Earth System: human activity (H). Although H is a subset of I (internal dynamics), here we argue that the magnitude, the unique nature of the forcing in the history of the planet, and the rate have now become so profound that H deserves to be considered in its own right in the context of Earth System dynamics. After Schellnhuber (1999), we write:

$$\frac{\mathrm{d}E}{\mathrm{d}t} = f\left(A, G, I, H\right) \tag{3}$$

How significant is H as a driver of the rate of change of the Earth System? Steffen et al. (2004, 2011, 2015b) identified trends in socio-economic activities representative of H over the past 2.5 centuries and found a broad correlation with Earth System changes, as measured by the rates of change of biodiversity, atmospheric chemistry, marine biogeochemistry and land-use change amongst others. The authors noted a very sharp increase in the rate of change of both H and E since 1950 and a strong coupling between the two, a phenomenon now known as the Great Acceleration (Hibbard et al., 2006; Steffen et al., 2007).

Examination of individual Earth System processes show the remarkable domination of H over the other three factors in equation (3). For example, in one century, the Haber-Bosch process has doubled the amount of reactive nitrogen in the Earth System relative to the pre-industrial baseline, arguably the largest and most rapid impact on the nitrogen cycle for some ~2.5 Ga (Canfield et al., 2010). The rate of change of ocean carbonate chemistry – ocean acidification – is potentially unparalleled in at least the last ~300 Ma (Hönisch et al., 2012). The rate of carbon emissions to the atmosphere (~10 Pg/yr) are probably the highest they have been in ~66 Ma, since the start of the Cenozoic (Cui et al., 2011; Zeebe et al., 2016) (Table 1).

For biodiversity, typical rates of background extinction are estimated to be around 0.1 extinctions/million species years (De Vos et al., 2015). Current extinction rates are estimated to be tens to hundreds of times higher than natural background rates of extinction (Barnosky et al., 2012; Ceballos et al., 2015). Humans have now modified the structure and functioning of the biosphere to such an extent that the Anthropocene may mark the beginning of a third stage in the evolution of Earth's biosphere, following the microbial stage from ~3.5 Ga BP and the metazoan from ~650 Ma (Williams et al., 2015).

In the last 7000 years, ice volumes on Earth stabilised and carbon dioxide (CO_2) levels have changed only slowly over that period. This provides a Holocene baseline for assessment of the Anthropocene rate of change of the climate system (Waters et al., 2016). Atmospheric CO_2, now above 400 parts per million (ppm) is 120 ppm higher than the Holocene baseline, and has increased ~100 times as fast as the most rapid rise during the last glacial termination (Loulergue et al., 2008). Atmospheric CH_4 concentration has risen rapidly to 1810 ppb in 2012, a level 2.5 times the level in 1750 (722 ppb) (Saunois et al., 2016). The rate of change appears extraordinary compared with natural changes and is more than double any observed value in the past 800,000 years (Loulergue et al., 2008; Wolff, 2011).

From 9500 to 5500 years BP global average temperature plateaued, followed by a very slight cooling trend (Marcott et al., 2013). Over the last 7000 years the rate of change of temperature was approximately −0.01°C/century. Over the last hundred years, the rate of change is about 0.7°C/century (Intergovernmental Panel on Climate Change (IPCC), 2013), 70 times the baseline – and in the opposite direction. Over the past 45 years (i.e. since 1970, when human influence on the climate has been most evident), the rate of the temperature rise is about 1.7°C/century (NOAA, 2016), 170 times the Holocene baseline rate.

We deduce, therefore, that astronomical and geophysical forcings in the Holocene, and perhaps even through the entire Quaternary, approximate to zero compared with the impact of current human pressures on the rate of change of the Earth System (Ganopolski et al., 2016; McGregor et al., 2015; Steffen et al., 2004, 2015a; Waters et al., 2016; Williams et al., 2015). We also note from the rates of change described above that I now is also significantly less than H. Therefore, following from Schellnhuber (1999), but more directly based on Steffen et al. (2004, 2011, 2015b), the current rate of change of the Earth System at the highest level of abstraction can be represented as:

$$\frac{dE}{dt} = \underset{\mathrm{A,\,G,\,I} \rightarrow 0}{f\left(H\right)} \tag{4}$$

which might be termed the 'Anthropocene equation'.

Table 1. Rates of change of the Earth System.

	Holocene baseline rate of change	Current rate of change	Magnitude/scale of change	References
Earth System parameter-climate				
Atmospheric CO_2 concentration	~0.17 ppm/century decrease between c. 11k and 7k BP; ~0.30 ppm/century increase between c. 7k BP and 1750	166 ppm/century (average 1970–2015)	~550 times faster than Holocene baseline rate ~100 times faster than the most rapid rise during the last glacial termination. ~10 times faster than the maximum rate of carbon outgassing during the Paleocene-Eocene Thermal Maximum	Ciais et al. (2013) Wolff (2011) Zeebe et al. (2016)
Atmospheric CH_4 concentration	2 ppb/century	575 ppb/century (1984–2015 average)	~285 times faster than Holocene baseline rate. From 1750 to 2012 CH_4 increased by 150% from 722 ppb to 1810 ppb	http://www.esrl.noaa.gov/gmd/ccgg/trends_ch4/#global_data Saunois et al. (2016) Singarayer et al. (2011)
Global average surface temperature	−0.01°C/century	1.7°C/ century (average 1970–2015)	170 times faster than the Holocene baseline rate	Marcott et al. (2013) NOAA (2016)
Sea-level rise	~0 mm/yr from c. 3000 BP to pre-industrial	3.2±0.4 mm/yr (1993–2010)	Average global sea level is currently higher than at any other time within the past ~115,000 years	Church et al. (2013) IPCC (2013)
ES parameter-biosphere				
Extinction rate	0.1 extinctions per million species years	1–10 extinctions per million-species years	10–100 times background rate	Ceballos et al. (2015) De Vos et al. (2015)
Terrestrial biosphere modification	Up to 1700, ~50% of global ice-free land cover was wild; ~5% was intensively used	By 2000, only 25% was wild and 55% was intensively used by humans		Ellis et al. (2010)
Climate-triggered species range shifts	Small compared with range shift during Pleistocene –Holocene transition	Similar or greater than range shifts at beginning and end of the Pleistocene	Future range shifts may be ~10 times greater than during Pleistocene –Holocene transition	Diffenbaugh and Field (2013)
ES parameter-biogeochemical cycles				
Ocean acidity	~0 pH unit/year	−0.0014–0.0024 pH unit/year in surface waters	pH of seawater has decreased by ~0.1 since beginning of industrial era, equivalent to a 26% increase in H^+ ion concentration. Surface-ocean chemistry changes during the Anthropocene are projected to be three to seven times larger and 70 times faster than during a deglaciation. Current OA rate of change is highest in possibly 300 million years	Elsig et al. (2009) Hönisch et al. (2012) Rhein et al. (2013) Zeebe (2012)
N cycle	Biological nitrogen fixation on land: 58 Tg/yr, in the ocean: 140 Tg/hr, and fixation by lightning: 5 Tg/yr	~180 Tg N per year from industrial and intended biological fixation, and 30 Tg N per year from human combustion processes.	Humans now fix as much N as all natural processes combined. This is possibly the largest and most rapid change to the global N cycle in 2.5 billion years.	Fowler et al. (2013) Gruber and Galloway (2008)
P cycle	10–15 Tg P/yr input to soil (pre-industrial weathering)	28–33 Tg P/yr input to soil (from enhanced weather and mining of P for fertilizers)	Up to 3 times more P per year released to environment from human activities compared with Holocene baseline	Carpenter and Bennett (2011)
Sedimentary fluxes		~57,000 Tg/yr of sediments displaced by mineral extraction	Sediment displacement by mineral extraction nearly 3 times greater than global river sediment transport. Human processes have increased sediment flow by erosive processes and reduced sediment flow by dam building	Douglas and Lawson (2000) Steffen et al. (2007, 2015) Syvitski et al. (2009) Zalasiewicz et al. (2014b)

Notes: Current rates of change of key Earth System processes (climate, biosphere and biogeochemical cycles) relative to various time intervals in the geological and historical past. Ranges are included where significant uncertainty exists, for example, extinction rates.

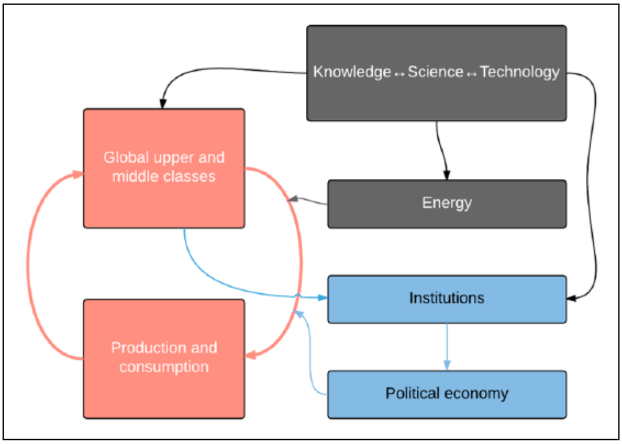

Figure 1. A systems approach to understand the linkages, interactions and feedbacks driving the Great Acceleration and emergent behaviour affecting the rate of change of the Earth System (modified from Hibbard et al., 2006: figure 18.2).

When did H come to dominate the astronomical and geophysical forcings and the internal dynamics of the Earth System? Although there have been several proposed start dates for the Anthropocene, including the Neolithic revolution (Ruddiman, 2013), the rise of European empires and subsequent colonialisation (Lewis and Maslin, 2015), and the Industrial Revolution (Crutzen, 2002), none can match the mid-20th-century, global-level, synchronous step change in human enterprise and the simultaneous human-driven change in many features of Earth System structure and functioning. That is, anthropogenic impact crossed a critical threshold around 1950 with the beginning of the Great Acceleration, when H moved from being a force of similar or smaller magnitude to A and G, to usurping them entirely (Steffen, 2004, 2007, 2011; Waters, 2016).

An obvious, and critical, next step is to represent H as a sub-system of the Earth System because it is now the prime forcing driving the rate of change of the Earth System. Although a full analysis of H is beyond the scope of this paper (see McNeill and Engelke, 2016, for an analysis of the Great Acceleration), we note one attempt at describing the system dynamics of H that is particularly relevant here because it attempted to describe the dynamics of the Great Acceleration (Figure 1; adapted after Hibbard et al., 2006).

Based on Figure 1, we can represent H as:

$$H = f(P, C, T) \tag{5}$$

where P is population (more specifically the global ‘consumers’: the upper and middle classes as defined by income on a national basis), C is consumption (and by definition production), and T is the Technosphere (Haff, 2014), a concept particularly well-suited to Earth System analysis (Zalasiewicz et al., 2014a). Note that equation (5) has similarities to the IPAT identity of Holdren and Ehrlich (1974).

The Technosphere can be further broken down as follows:

$$T = f(En, K, Pe) \tag{6}$$

where En is the energy system, K is knowledge and Pe is political economy, which relates to economic systems bound by political decisions, now overwhelmingly dominated by globalisation (it

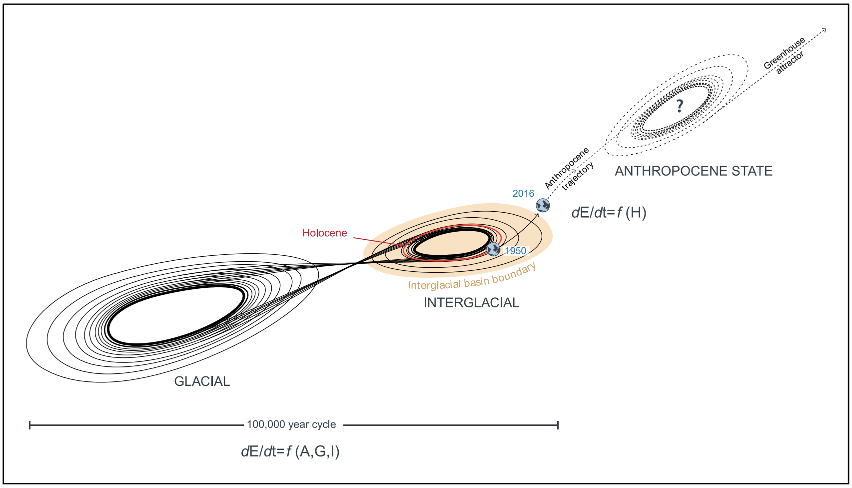

Figure 2. Saw-tooth oscillations of Earth's recent glacial–interglacial cycles represented as contour lines around basins of attraction (each cycle is unique), and the trajectory of the Anthropocene. The trajectory beyond 2016 indicates a significant departure from the glacial–interglacial limit cycle of the late Quaternary, and a unique event in Earth's history. A stable Anthropocene basin of attraction is speculative. Beyond it lies a greenhouse attractor. It remains unclear whether anthropogenic forcing is significant enough to drive the Earth System into a greenhouse state.

is worth noting that not all individuals or groups of people are equally responsible for the impacts of *H* on d*E*/d*t* (Malm and Hornborg, 2015)), as shown in Figure 1. However the term *H* is characterised in detail, the Anthropocene equation shows the domination of natural forcings by human forcings, particularly since the mid-20th century (Hamilton and Grinevald, 2015).

Figure 2 shows a potential future trajectory of the Earth System in the Anthropocene, with the system in 2016 poised at a critical position. Remaining within the interglacial conditions of the late Quaternary will require the exceptionally rapid rate of change of the Earth System to return to close to zero, with human forcings reduced to levels less than, or at least comparable to, astronomical and geophysical forcings and the internal dynamics of the Earth System. Sustained human pressures risk abrupt exiting of the glacial–interglacial limit cycle of the late Quaternary (Clark et al., 2016; Ganopolski et al., 2016), and ushering in Earth's sixth great extinction event (Barnosky et al., 2012).

While the next few decades are crucial in setting the trajectory of *H*, and hence of the Earth System, over the next tens of thousands of years (Clark et al., 2016; Ganopolski et al., 2016), in the longer term the domination of *H* over *A, G* and *I* is very likely to be a transient condition, perhaps similar to the Paleocene-Eocene Thermal Maximum (PETM) 56 million years ago (Hönisch, et al. 2012). In that event, a massive release of carbon (between 3000 and 7000 PgC), possibly from methane hydrates in the sea floor, drove a temperature spike of 4–8°C over a few thousand years (Steffen et al., 2016; Zeebe et al., 2016). During the PETM, a sharp perturbation in *G* over a few thousand years drove the instability in the Earth System, but it was short-lived with the system returning to its long-term trajectory 100,000–200,000 years after the carbon release as *A, G* and *I* restored their long-term control of the system.

In the case of the Anthropocene, efforts to achieve the long-term viability of a global civilisation – global sustainability – implies that *Homo sapiens* will deliberately and rapidly reduce its impacts on the Earth System so that they are more comparable in magnitude and more synergistic with *A,* *G* and particularly *I*. Alternatively, continued increases in *H* could well lead to abrupt changes in the Earth System that could trigger societal collapse, forcibly reducing *H* dramatically and returning control of the system to *A, G* and *I*. The legacy of the impacts of *H* on *I* through changes in the biosphere could, however, be discernible in the internal dynamics of the Earth System for millions of years (Williams et al., 2015).

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