

## CLIMATE CHANGE IN CONTEXT

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Climate change is just one part of a larger change. We have entered a new geological epoch, the ‘Anthropocene’, in which the biosphere is heavily affected by human activities. This is not yet an official term in geology: textbooks still say we are in the Holocene, a geological epoch starting in 9750 B.C.. But the Holocene was always a parochial term—while it marks the end of a glacial period, there have been dozens of those, and there is nothing special about the last one *except* the rise of human civilization. From the perspective of the Earth as a whole, what matters is that our civilization has now expanded to the point of significantly affecting the atmosphere, the oceans, sedimentation, biodiversity, and more. There is no way to fully understand climate change, much less effectively ‘fight’ it or adapt to it, without some sense of this larger picture.

We can tentatively break the Anthropocene into phases. The ‘Early Anthropocene’, starting perhaps around the agricultural revolution, was characterized by exponential (or faster) growth of the human population and its impact on the biosphere [17, 27]. While local resource depletion has been a fact of life throughout this period, and might at times cause individual civilizations to collapse [6], by the time a world civilization was forged in the 20th century, exponential growth was perceived by many as a natural state of affairs. Indeed, many economists, particularly those with influence on government policy, seem still to be under the delusion that exponential growth of resource consumption can continue forever on a finite-sized planet.

However, this is impossible. It is true that ‘progress’, defined abstractly enough, can in principle continue for millions or billions of years. However, raw physical quantities associated to our impact on the planet cannot grow for centuries at their current annual percentage rate. More importantly, there are many indications that we are *now* approaching some limits set by the scale of our planet [25, 26]. Besides the limits related to fossil fuel consumption, which we discuss later, here are some examples:

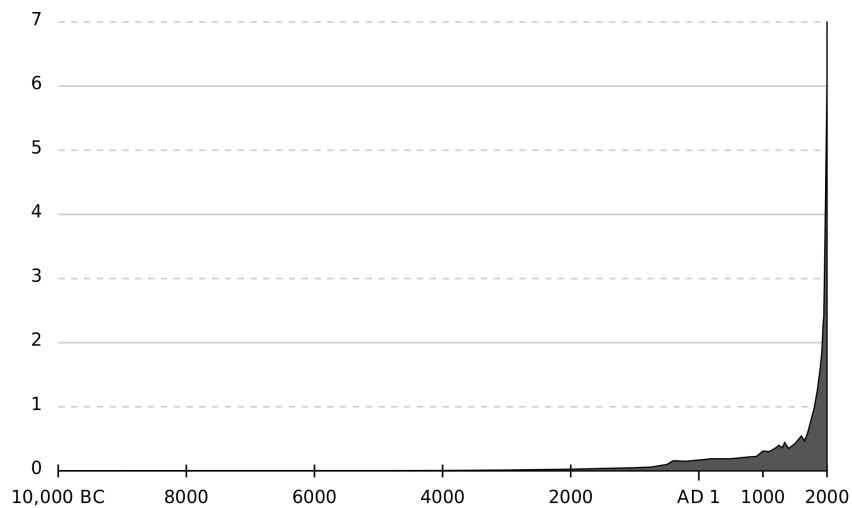
- About one quarter of all ‘net primary production’ is now used by humans [11]. Net primary production is the rate at which all the plants on Earth produce useful chemical energy, minus the amount they use themselves during respiration. Human use of net primary production doubled during the 20th century.
- The rate of species extinctions, while difficult to estimate precisely, is somewhere between 100 and 1000 times its usual background rate [15, 18].
- Humans now take more nitrogen from the atmosphere and convert it into reactive forms than all other terrestrial processes combined [8, 9]. Much of this reactive nitrogen is used in fertilizer and winds up in oceans, causing eutrophication and the formation of ‘dead zones’. A recent study counted

about 400 dead zones, ranging in area from 1 to 70,000 square kilometers [7].

- The amount of phosphorus flowing into the oceans is 8-9 times higher than its natural background rate [16]. This phosphorus is mined, used as fertilizer and runs off into the oceans. This is another cause of dead zones.
- Soil erosion from conventionally plowed agricultural fields is 10-100 times higher than the natural background rate of erosion or soil production [20].

So, we seem to be entering a new phase, the ‘Middle Anthropocene’, where the exponential growth of many physical quantities associated with human civilization comes to an end. This can happen in various ways. For example, a quantity can level off and approach an equilibrium value. It can begin to oscillate. Or, its growth can lead to a ‘tipping point’. This is a self-amplifying change which leads to a qualitatively different state of affairs. These are just some of many possibilities. Indeed, tipping points themselves come in many varieties, some of which have been classified mathematically [34].

Consider for example the population of humans on Earth, as shown in Figure 1. In the Early Anthropocene, say roughly from 10,000 BC to 1950 AD, the world population generally grew exponentially or faster, despite some setbacks.



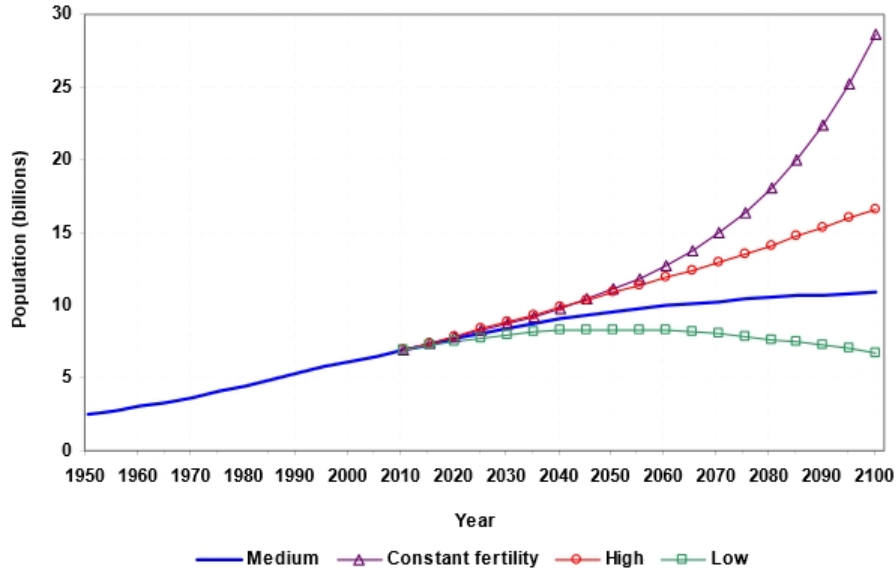
1. The Earth's population in billions

More recently, the annual percentage population growth rate has begun to drop. In 1970 it was growing at 2% per year. Now it is growing at about 1% per year. This is one sign among many that we are entering a new phase: the Middle Anthropocene.

The future, of course, remains open. We can imagine various scenarios. The population could level off at some new equilibrium. It could crash. It could level off and then slowly decline to a much lower level as birth rates drop worldwide below replacement rates, as they already have in Europe and Japan. Alternatively, it could level off but then crash when resources are depleted, or a nuclear world war occurs.

In their 2012 report [36], the UN projected that the world population will level off, growing to 9.6 billion by 2050 and 10.9 billion by 2100. This projection assumes

no dramatic developments, but still there is considerable uncertainty, as shown in Figure 2.

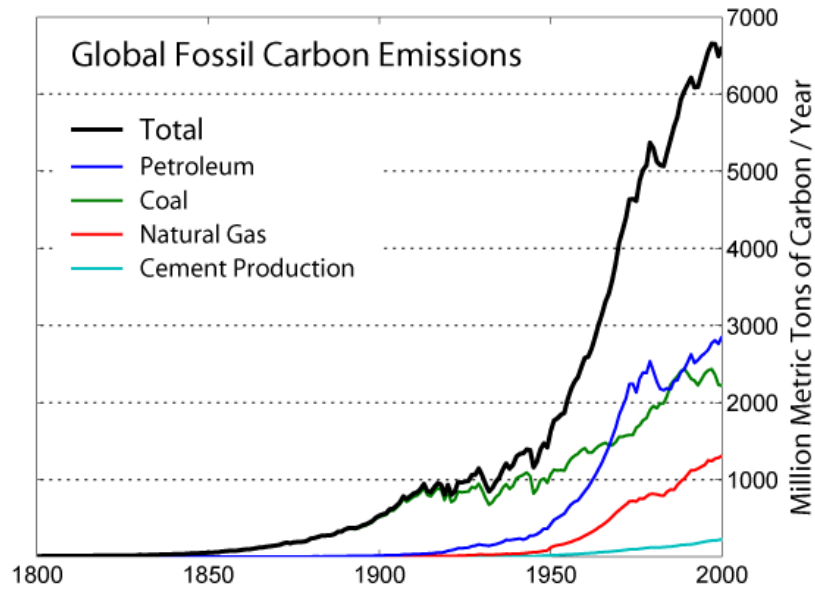


2. Population projections, *World Population Prospects: the 2012 Revision*, United Nations.

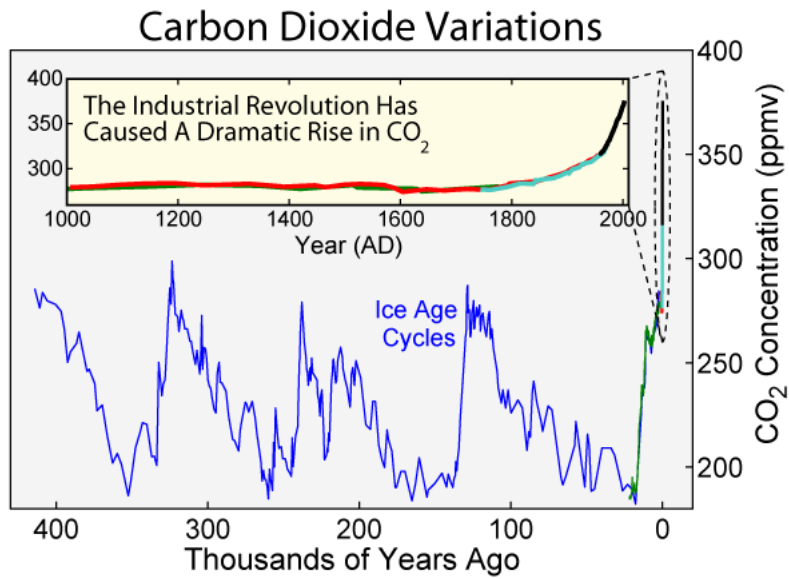
Of all the scenarios we can imagine, one of the most implausible is that the human population on Earth increases exponentially forever, in a continuation of the ‘constant fertility’ curve in Figure 2. Human civilization could expand into space, or replace itself with artificial intelligence, but these would count as ‘tipping points’, in which the whole meaning of population changes.

For another example of the shift from the Early to the Middle Anthropocene, consider carbon emissions and their effects. From 1800 until now, global carbon emissions grew in a roughly exponential way, as shown in Figure 3. In 2011, our use of fossil fuels and cement together with land-use change and deforestation put about 10.4 gigatonnes of carbon into the atmosphere [12]. This is a remarkable rate of increase, because the total amount of carbon in the atmosphere is only about 860 gigatonnes.

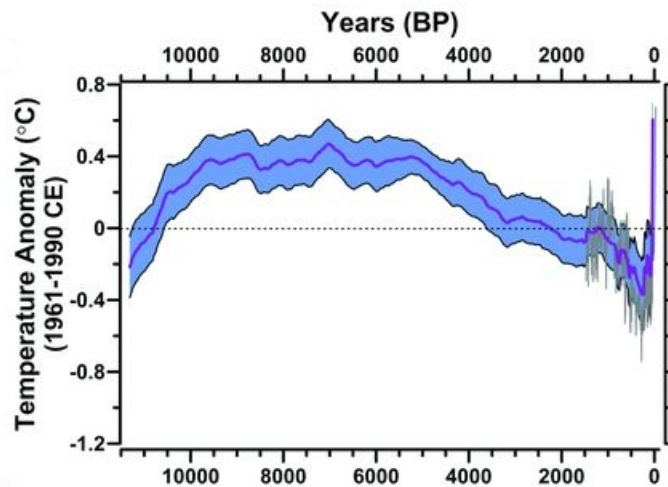
However, limiting factors are beginning to come into play. One is resource depletion. This is a hotly argued subject: clearly exponential growth of fossil fuel use must end eventually, but there is little consensus on when. Another is climate change. We have already pushed the  $\text{CO}_2$  concentration well above its previous peak values for many previous glacial cycles, as shown in Figure 4. This is driving temperatures upwards, breaking the natural cooling trend that began around 5000 BC, as shown in Figure 5. It seems we have already emitted enough  $\text{CO}_2$  to delay the start of the next glacial period by thousands or even hundreds of thousands of years [2, 5, 35]—another sign that we have entered a new geological epoch, the Anthropocene.



3. Carbon emissions due to fossil fuels, [Global Warming Art.](#)



4. CO<sub>2</sub> concentrations as measured from Antarctic ice cores and other sources, [Global Warming Art.](#)



5. Reconstruction of temperature from 73 different records, [Marcott et al.](#)

More importantly, the *rate of increase* of both CO<sub>2</sub> concentrations and global average temperature is unusually high. Ecosystems, and perhaps human civilization, can adapt to quite large temperature changes if these occur slowly enough. But adaptation takes time. The sudden changes we are imposing will almost certainly boost extinction rates beyond their already heightened level [33], and stress human civilization in ways we are just beginning to understand.

My main point, however, is that climate change is just one aspect of something much bigger: the transition from Early to Middle Anthropocene. It is not an isolated ‘problem’ of the sort routinely ‘solved’ by existing human institutions. It is part of a shift from the exponential growth phase of human impact on the biosphere to a new phase. Before, we might be tempted to treat ‘nature’ as distinct from ‘civilization’. Now, there is no nature separate from civilization. Before, exponential growth might be regarded as a natural state of human affairs. Now, every form of growth must be assessed for its effect on the biosphere.

In this new phase, we will be increasingly aware of possible tipping points. Only some of these are associated to carbon emissions. Here are some that are:

- **Loss of Arctic sea ice.** The summer minimum extent of Arctic sea ice has dropped from roughly 5 million square kilometers in 1980 to roughly half that in 2013. As sea ice melts, it reveals a much darker ocean surface, which absorbs more sunlight, warming the Arctic even more. This self-amplifying effect could lead to a tipping point, with the result being a permanently ice-free Arctic Ocean.
- **Melting of the Greenland ice sheet.** Between 2003 and 2010, ice on Greenland has been melting at an average rate of about 250 gigatonnes per year, but the melting has been accelerating at roughly 20 gigatonnes per year each year [24, 29, 37]. When ice melts to the point of revealing the darker rock beneath, a self-amplifying effect occurs. If all 3 million gigatonnes of ice in Greenland were to melt, it would cause a sea level rise of about 7 meters. However, this will take a long time, and the worst-case

scenario seems to give at most 2 meters of sea level rise by 2100 due to all causes, not just Greenland [23].

- **Melting of the West Antarctic ice sheet.** Between 2003 and 2009, the West Antarctic ice sheet has been melting at an average rate of about 170 gigatonnes per year, with an acceleration of roughly 13 gigatonnes/year<sup>2</sup> [24, 29, 37]. If the ice melts to the point where ocean water undercuts the ice sheet and separates it from the bedrock, a self-amplifying effect arises that could lead to a collapse of the ice sheet. If all 2 million gigatonnes of this ice were to melt or drift into the ocean, it would cause a sea level rise of about 5 meters.
- **Permafrost and tundra loss.** Permafrost in the northern hemisphere is starting to melt, releasing carbon dioxide and methane, which are greenhouse gases [30]. Again, this is potentially a self-amplifying mechanism [38]. Roughly 1500 gigatonnes of carbon is stored in permafrost worldwide [32, 40]. This is a huge amount, since there only 860 gigatonnes of carbon in the atmosphere now, and the amount burnt so far by humans is about 570 gigatonnes. Furthermore, methane causes about 72 times as much global warming as an equal mass of carbon dioxide for its first 20 years in the atmosphere, and about 25 times as much for the first 100 years [10].
- **The clathrate gun hypothesis.** Increases in ocean temperature may sometimes trigger the sudden release of large amounts of methane from ‘clathrates’ buried in sea beds. These clathrates consist of methane trapped in ice crystals. The total amount of carbon in these deposits is quite difficult to determine, but recent estimates suggest it could be between 500 and 3000 gigatonnes [4, 19, 21]. A release of methane from clathrates may have been involved in the Paleocene-Eocene Thermal Maximum [22, 39], when perhaps 2500-7000 gigatonnes of carbon entered the oceans and atmosphere, the temperature rose about 6°, and there was a mass extinction of microscopic deep-sea organisms—along with the rise of mammals. There is some controversy over whether a large release of methane from clathrates could occur in the next century or two due to global warming [2, 30].

For more on tipping points in the Earth’s climate system, see the 2007 paper by Lenton *et al* [14].

Tipping points of sufficient magnitude, perhaps interacting with each other, could cause an global ‘state shift’ [3]. In other words, the climate and biosphere could shift to a significantly different state. This would probably be less hospitable to human life and most existing species, simply because we are adapted to the current state, and adaptation takes time.

The likelihood and timing of a global state shift are difficult to estimate ahead of time, because of the complexity of the systems involved. Even predicting individual tipping points is difficult, though techniques for doing this are under study [13, 28, 34]. However, we can be sure of this: if we continue to affect many aspects of the Earth ever more drastically, we will push parts of the biosphere to their tipping points.

This means, among other things, that taking measures to limit carbon emissions while still pursuing exponential economic growth will at best postpone the

time when we meet tipping points, *unless* we decouple economic growth from the growth of raw physical quantities such as exploitation of net primary production, production of runoff containing reactive nitrogen and phosphorus, and so on. Thus, an important question is whether we can ‘virtualize’ the economy, making it less dependent on these physical quantities. The much-vaunted ‘information economy’ could be a step towards this, by reducing the need for travel and shipping. However, we need to go further before we can lighten our footprint on the Earth enough to make the Middle Anthropocene a pleasant time for humanity.

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## REFERENCES

- [1] D. Archer, Methane hydrate stability and anthropogenic climate change, *Biogeosciences* **4** (2004), 521–544. Also available as [doi:10.5194/bg-4-521-2007](https://doi.org/10.5194/bg-4-521-2007).
- [2] D. Archer and A. Ganopolski, A movable trigger: Fossil fuel CO<sub>2</sub> and the onset of the next glaciation, *Geochemistry Geophysics Geosystems* **6** (2005), Q05003. Also available at [doi:10.1029/2004GC000891](https://doi.org/10.1029/2004GC000891).
- [3] A. D. Barnosky *et al*, Approaching a state shift in Earth’s biosphere, *Nature* **486** (2012), 52–58. Also available at [doi:10.1038/nature11018](https://doi.org/10.1038/nature11018).
- [4] B. Buffett, D. Archer, Global inventory of methane clathrate: sensitivity to changes in the deep ocean, *Earth and Planetary Science Letters* **227** (2004), 185–199. Also available at <http://geosci.uchicago.edu/archer/reprints/buffett.2004.clathrates.pdf>.
- [5] A. B. Cochelin, L. A. Mysak and Z. Wang, Simulation of long-term future climate changes with the green McGill paleoclimate model: the next glacial inception, *Climatic Change* **79** (2006), 381–401. Also available at [doi:10.1007/s10584-006-9099-1](https://doi.org/10.1007/s10584-006-9099-1).
- [6] J. Diamond, *Collapse: How Societies Choose to Fail or Succeed*, Viking, 2005.
- [7] R. J. Diaz and R. Rosenberg, Spreading dead zones and consequences for marine ecosystems, *Science* **321** (5891), 926–9. Also available at [doi:10.1126/science.1156401](https://doi.org/10.1126/science.1156401).
- [8] J. N. Galloway and E. B. Cowling, Reactive nitrogen and the world: two hundred years of change, *Ambio* **31** (2002), 64–71.
- [9] N. Gruber and J. N. Galloway, An earth system perspective of the global nitrogen cycle, *Nature* **451** (2008), 293–296.
- [10] S. Solomon *et al*, *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Chapter 2, United Nations, 2007. Also available as <http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf>.
- [11] F. Krausmann *et al*, Global human appropriation of net primary production doubled in the 20th century, *PNAS* (2013). Available at [doi:10.1073/pnas.1211349110](https://doi.org/10.1073/pnas.1211349110).
- [12] C. LeQuéré, The global carbon budget 1959–2011, *Earth Syst. Sci. Data* **5** (2013), 165–185. Also available at [doi:10.5194/essd-5-165-2013](https://doi.org/10.5194/essd-5-165-2013).
- [13] T. M. Lenton, Early warning of climate tipping points, *Nature Climate Change* **1** (2011), 201–209. Also available at [doi:10.1038/nclimate1143](https://doi.org/10.1038/nclimate1143).
- [14] T. M. Lenton *et al*, Tipping elements in the Earth’s climate system, *PNAS* **105** (2008), 1786–1793. Also available at [doi:10.1073/pnas.0705414105](https://doi.org/10.1073/pnas.0705414105).
- [15] G. Mace, H. Masundire and J. Baillie, Biodiversity, in *Ecosystems and Human Well-Being: Current State and Trends*, eds. H. Hassan, R. Scholes and N. J. Ash, Island Press, Washington D.C., 2005, pp. 79–115.
- [16] F. T. Mackenzie, L. M. Ver and A. Lerman, Century-scale nitrogen and phosphorus controls of the carbon cycle, *Chemical Geology* **190** (2002), 13–32.
- [17] B. Mason, Man has been changing climate for 8,000 years, *Nature News*, 2003. Also available at [doi:10.1038/news031208-7](https://doi.org/10.1038/news031208-7).
- [18] R. M. May, Ecological science and tomorrow’s world, *Phil. Trans. Roy. Soc. B* **365** (2010), 41–47. Available at [doi:10.1098/rstb.2009.0164](https://doi.org/10.1098/rstb.2009.0164).

- [19] A. V. Milkov, Global estimates of hydrate-bound gas in marine sediments: how much is really out there?, *Earth Science Reviews* **66** (2004), 183–197. Also available at [doi:10.1016/j.earscirev.2003.11.002](https://doi.org/10.1016/j.earscirev.2003.11.002).
- [20] D. Montgomery, Soil erosion and agricultural sustainability, *PNAS* **104** (2007), 13268–13272. Also available at [doi:10.1073/pnas.0611508104](https://doi.org/10.1073/pnas.0611508104).
- [21] E. Piñero *et al*, Estimation of the global inventory of methane hydrates in marine sediments using transfer functions, *Biogeosciences* **10** (2013), 959–975. Also available at [doi:10.5194/bg-10-959-2013](https://doi.org/10.5194/bg-10-959-2013).
- [22] K. Panchuk, A. Ridgwell and L. R. Lump, Sedimentary response to Paleocene-Eocene Thermal Maximum carbon release: a model-data comparison, *Geology* **36** (2008), 315–318. Also available at [doi:10.1130/G24474A.1](https://doi.org/10.1130/G24474A.1).
- [23] W. T. Pfeffer, J. T. Harper and S. O’Neel, Kinematic constraints on glacier contributions to 21st-century sea-level rise, *Science* **321** (2008), 1340–1343.
- [24] Eric Rignot *et al*, Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise, *Geophysical Research Letters* **38** (2011), L05503. Also available at [doi:10.1029/2011GL046583](https://doi.org/10.1029/2011GL046583).
- [25] J. Rockström *et al*, Planetary boundaries: exploring the safe operating space for humanity, *Ecology and Society* **14** (2009), 32. Also available at <http://www.ecologyandsociety.org/vol14/iss2/art32/>.
- [26] J. Rockström *et al*, A safe operating space for humanity, *Nature* **461** (2009), 472–475.
- [27] W. F. Ruddiman, The anthropogenic greenhouse era began thousands of years ago, *Climatic Change* **61** (2003), 261–293. Also available at [doi:10.1023/B:CLIM.0000004577.17928.fa](https://doi.org/10.1023/B:CLIM.0000004577.17928.fa).
- [28] M. Scheffer *et al*, Early-warning signals for critical transitions, *Nature* **461** (2009), 53–59. Also available as [doi:10.1038/nature08227](https://doi.org/10.1038/nature08227).
- [29] E. J. O. Schrama, Revisiting Greenland ice sheet mass loss observed by GRACE, *Journal of Geophysical Research* **116** (2011), ???
- [30] N. Shakhova, Methane release on the Arctic East Siberian shelf, *Geophysical Research Abstracts* **9** (2007), 01071. Also available as <http://www.cosis.net/abstracts/EGU2007/01071/EGU2007-J-01071.pdf>.
- [31] N. Shakhova *et al*, Anomalies of methane in the atmosphere over the East Siberian shelf: Is there any sign of methane leakage from shallow shelf hydrates?, *Geophysical Research Abstracts* **10** (2008), 01526. Also available as <http://www.cosis.net/abstracts/EGU2008/01526/EGU2008-A-01526.pdf>.
- [32] C. Tarnocai *et al*, Soil organic carbon pools in the northern circumpolar permafrost region, *Global Biogeochemical Cycles* **23** (2009), GB2023. Also available at [doi:10.1029/2008GB003327](https://doi.org/10.1029/2008GB003327).
- [33] C. D. Thomas *et al*, Extinction risk from climate change, *Nature* **42** (2004), 145–148. Also available at [doi:10.1038/nature02121](https://doi.org/10.1038/nature02121).
- [34] J. M. T. Thompson and J. Sieber, Predicting climate tipping points as a noisy bifurcation: a review, *International Journal of Chaos and Bifurcation* **21** (2010), 399–423. Also available at [doi:10.1142/S0218127411028519](https://doi.org/10.1142/S0218127411028519).
- [35] P. C. Tzedakis *et al*, Determining the natural length of the current interglacial, *Nature Geoscience* **5** (2012), 138–141. Also available at [doi:10.1038/ngeo1358](https://doi.org/10.1038/ngeo1358).
- [36] United Nations, *World Population Prospects: the 2012 Revision*, available at <http://esa.un.org/unpd/wpp/>.
- [37] I. Velicogna, Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE, *Geophysical Research Letters* **36** (2009) L19503. Also available at [doi:10.1029/2009GL040222](https://doi.org/10.1029/2009GL040222).
- [38] K. M. Walter, Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming, *Nature* **443** (2006), 71–75. Also available at [doi:10.1038/nature05040](https://doi.org/10.1038/nature05040).
- [39] J. D. Wright and M. F. Schaller, Evidence for a rapid release of carbon at the Paleocene-Eocene thermal maximum, *PNAS* **110** (2013), 15908–15913. Also available at [doi:10.1073/pnas.1309188110](https://doi.org/10.1073/pnas.1309188110).
- [40] S. A. Zimov, Permafrost and the global carbon budget, *Science* **312** (2006), 1612–1613.