Science AAAS

Irreversible Does Not Mean Unavoidable

H. Damon Matthews and Susan Solomon

Science **340**, 438 (2013);
DOI: 10.1126/science.1236372

potential factor. With a species that is not particularly suitable for controlled experiments, this is as close as we may ever get to proving that habits spread socially. Alternative hypotheses, such as genetic determination of the pattern or individual learning, were unsupported by the analysis.

Because of the neophobia of wild animals, field experiments are hard to conduct. Van de Waal *et al*. succeeded in inducing cultural transmission among wild vervet monkeys using a very elegant, controlled paradigm. They show that groups of wild monkeys can learn to distinguish between differently colored corn furnished by the experimenters. One color was palatable, the other highly distasteful. The two colors were counterbalanced across groups, so that corn of one color was palatable in some groups yet distasteful in others, and vice versa. All groups developed an exclusive preference for the untreated corn.

This by itself is just an example of individual learning, but then the investigators waited for new infants to be born in the groups and for new male immigrants to arrive from neighboring groups. When the researchers gave both groups of monkeys access to palatable corn of both colors, the original residents, showing great conservatism, stuck to their acquired preference (see the figure, panel B). Twenty-six of the 27 newborn infants also ate only the locally preferred food; the one exception was the infant of a female so low in rank that she had been forced to taste the alternative corn in her offspring's presence. The behavior of all infants supported the thesis that food preferences are acquired from mothers and not through individual exploration.

Male immigrants, too, adopted the local color preference, in most cases despite their arrival from groups that had developed the opposite preference. The only exception was an immigrant male who immediately achieved the top rank position in his new group, and who as a result may have been less sensitive to the behavior of the locals.

The two studies (*3*, *4*) show that cultural learning in animals is not a mere luxury that they occasionally engage in, but a common and widespread mechanism of behavioral acquisition. Conformism among animals—that is, the tendency to prefer behavioral options that are common in the local population despite familiarity with or the presence of alternative options—has been indicated by experiments on apes (*6*) and monkeys (*9*) and documented in behavioral field research (*10*). Its confirmation in field experiments suggests that the mechanism is robust, with a great potential to affect survival success.

References

1. J. Itani, A. Nishimura, in *Precultural Primate Behavior*, E. W. Menzel, Ed. (Karger, Basel, 1973), pp. 26–50.
2. F. B. M. de Waal, *The Ape and the Sushi Master* (Basic Books, New York, 2001).
3. J. Allen, W. Weinrich, W. Hoppitt, L. Rendell, *Science* **340**, 485 (2013).
4. E. van de Waal *et al.*, *Science* **340**, 483 (2013).
5. M. Tomasello, A. C. Kruger, H. H. Ratner, *Behav. Brain Sci.* **16**, 495 (1993).
6. A. Whiten *et al.*, *Nature* **437**, 737 (2005).
7. V. Horner, A. Whiten, E. Flynn, F. B. M. de Waal, *Proc. Natl. Acad. Sci. U.S.A.* **103**, 13878 (2006).
8. L. M. Hopper *et al.*, *Proc. Biol. Sci.* **275**, 835 (2008).
9. M. Dindo *et al.*, *PLoS ONE* **4**, e7858 (2009).
10. S. Perry, *Anim. Cogn.* **12**, 705 (2009).

10.1126/science.1237521

ATMOSPHERE

Irreversible Does Not Mean Unavoidable

Carbon dioxide emissions cuts implemented today would affect the rate of future global warming immediately.

H. Damon Matthews[1] and Susan Solomon[2]

Understanding how decreases in CO_2 emissions would affect global temperatures has been hampered in recent years by confusion regarding issues of committed warming and irreversibility. The notion that there will be additional future warming or "warming in the pipeline" if the atmospheric concentrations of carbon dioxide were to remain fixed at current levels (*1*) has been misinterpreted to mean that the rate of increase in Earth's global temperature is inevitable, regardless of how much or how quickly emissions decrease (*2*–*4*). Further misunderstanding may stem from recent studies showing that the warming that has already occurred as a result of past anthropogenic carbon dioxide increases is irreversible on a time scale of at least 1000 years (*5*, *6*). But irreversibility of past changes does not mean that further warming is unavoidable.

The climate responds to increases in atmospheric CO_2 concentrations by warming, but this warming is slowed by the long time scale of heat storage in the ocean, which represents the physical climate inertia. There would indeed be unrealized warming associated with current CO_2 concentrations, but only if they were held fixed at current levels (*1*). If emissions decrease enough, the CO_2 level in the atmosphere can also decrease. This potential for atmospheric CO_2 to decrease over time results from inertia in the carbon cycle associated with the slow uptake of anthropogenic CO_2 by the ocean. This carbon cycle inertia affects temperature in the opposite direction from the physical climate inertia and is of approximately the same magnitude (*2*, *6*).

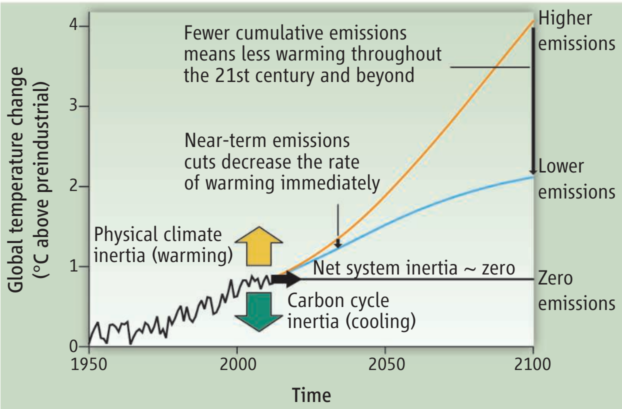
Because of these equal and opposing effects of physical climate inertia and carbon cycle inertia, there is almost no delayed warming from past CO_2 emissions. If emissions were to cease abruptly, global average temperatures would remain roughly constant for many centuries, but they would not increase very much, if at all. Similarly, if emissions were to decrease, temperatures would increase less than they otherwise would have (see the first figure).

Thus, although the CO_2-induced warming already present on our planet—the cumulative result of past emissions—is irreversible, any further increase in CO_2-induced warming is entirely the result of current CO_2 emissions. Warming at the end of this century and beyond will depend on the cumulative emissions we emit between now and then. But future warming is not unavoidable: CO_2 emissions reductions would lead to an immediate decrease in the rate of global warming.

Why, then, are many different near-term projections of CO_2-induced warming very similar? These modeled estimates are similar because even socioeconomic scenarios that produce very different cumulative emissions by the end of this century are not very differ-

[1]Department of Geography, Planning and Environment, Concordia University, Montreal, Quebec H3G 1M8, Canada. [2]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA. E-mail: damon.matthews@concordia.ca; solos@mit.edu

Published by AAAS

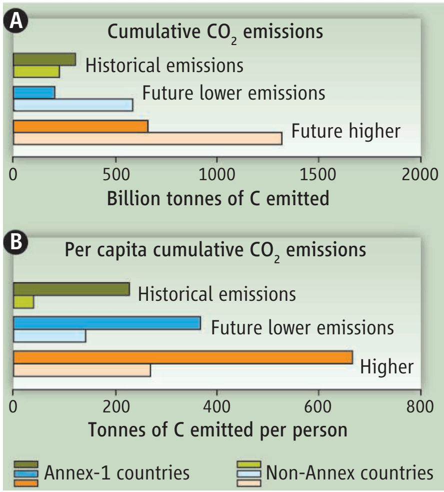


How the climate system responds. The climate response to CO_2 emissions is influenced by both physical climate and carbon cycle inertia, with the result that the net system inertia is close to zero. Therefore, future climate warming depends only on current and future CO_2 emissions, and the rate of warming will respond immediately to CO_2 emissions cuts. The illustrative future scenarios shown here are from SRES scenarios B1 (blue line) and A1FI (orange line). Idealized future warming is calculated as a linear function of cumulative CO_2 emissions. Observed historical temperatures are shown in black.

ent over the next two decades (figs. S1 and S2). The climate system physics implies that further increases in warming could in principle be stopped immediately, but human systems have longer time scales. Carbon-emitting infrastructure is designed to benefit humankind for many decades; each year's additional infrastructure implies added stock intended to last and emit CO_2 for many decades. It is this dependence on CO_2-emitting technology that generates a commitment to current and near-future emissions (*7*). Cleaner alternatives are being developed and carbon capture and storage technologies are being tested, but technological development and diffusion are subject to substantial inertia (*8*). Societal inertia, rather than the inertia of the climate system, is thus the critical challenge if we wish to begin to decrease the rate of CO_2-induced global warming in the near future.

The strong dependence of future warming on future cumulative carbon emissions implies that there is a quantifiable cumulative amount of CO_2 emissions that we must not exceed if we wish to keep global temperature below 2°C above preindustrial temperatures. Several recent analyses have suggested that total CO_2 emissions of ~1000 Pg C (~3700 Pg CO_2; 1 Pg = 10^{15} g) would give us about even odds of meeting the 2°C target (*9–12*). To meet such a target given historical emissions would mean that the world has roughly half of the allowable emissions budget remaining. This is equivalent to 50 years of emissions at current levels and carries the implication that the longer we delay before beginning to decrease emissions, the faster the rate of decrease must be to stay within this total allowable budget (*13*).

Emissions differ widely between countries, particularly between those in the developed and developing world (*14*). Cumulative carbon emissions from the developed world currently exceed those from developing countries, but rapid economic growth in emerging economies is expected to reverse this pattern within a few decades (fig. S2). Nonetheless, per capita cumulative emissions from developed countries are expected to remain far higher than those from developing nations throughout the 21st century (see the second figure). If technological investments and innovation increase the availability of reduced-carbon sources of energy that are competitive in price, development can continue to improve the lives of people in emerging economies without driving global climate change to increasingly dangerous levels. If reduced-carbon energy sources are not advanced rapidly, a great deal of carbon-intensive infrastructure



Development and emissions. Cumulative emissions from developed countries (Annex-1) currently exceed those from developing countries (non-Annex). This pattern is expected to reverse for future emissions scenarios (**A**), but per-capita cumulative emissions from developed countries are expected to remain much higher than those from developing countries (**B**). Historical emissions until 2012 are shown in green; future cumulative and per capita cumulative emissions are calculated at year 2100 for SRES B1 (blue) and A1FI (orange) emissions scenarios.

is likely to be put in place in the developing world, implying a large and ongoing societal commitment to further global CO_2 emissions and consequent climate warming (*7*).

Given the irreversibility of CO_2-induced warming (*5*, *6*), every increment of avoided temperature increase represents less warming that would otherwise persist for many centuries. Although emissions reductions cannot return global temperatures to preindustrial levels, they do have the power to avert additional warming on the same time scale as the emissions reductions themselves. Climate warming tomorrow, this year, this decade, or this century is not predetermined by past CO_2 emissions; it is yet to be determined by future emissions. The climate benefits of emissions reductions would thus occur on the same time scale as the political decisions that lead to the reductions.

References

1. J. Hansen *et al.*, *Science* **308**, 1431 (2005).
2. H. D. Matthews, A. J. Weaver, *Nat. Geosci.* **3**, 142 (2010).
3. See, for example, The Washington Post, 31 October 2012, www.washingtonpost.com/blogs/ezra-klein/wp/2012/10/31/why-the-united-states-is-so-unprepared-for-climate-disasters (accessed 10 November 2012).
4. For example, the IPCC's 2007 Summary for Policymakers from Working Group II (*15*) states that "Past emissions are estimated to involve some unavoidable warming…" with the consequence that "Adaptation will be necessary to address impacts resulting from the warming which is already unavoidable due to past emissions."
5. S. Solomon, G. K. Plattner, R. Knutti, P. Friedlingstein, *Proc. Natl. Acad. Sci. U.S.A.* **106**, 1704 (2009).
6. H. Matthews, K. Caldeira, *Geophys. Res. Lett.* **35**, L04705 (2008).
7. S. J. Davis, K. Caldeira, H. D. Matthews, *Science* **329**, 1330 (2010).
8. D. G. Victor, *Global Warming Gridlock* (Cambridge Univ. Press, Cambridge, 2011).
9. M. R. Allen *et al.*, *Nature* **458**, 1163 (2009).
10. H. D. Matthews, N. P. Gillett, P. A. Stott, K. Zickfeld, *Nature* **459**, 829 (2009).
11. S. Solomon *et al.*, *Climate Stabilization Targets* (National Academies Press, Washington, DC, 2011).
12. H. D. Matthews, S. Solomon, R. Pierrehumbert, *Philos. Trans. R. Soc. London Ser. A* **370**, 4365 (2012).
13. T. F. Stocker, *Science* **339**, 280 (2013).
14. B. Bolin, H. S. Kheshgi, *Proc. Natl. Acad. Sci. U.S.A.* **98**, 4850 (2001).
15. M. Parry, C. Hanson, P. van der Linden, J. Palutikof, O. Canziani, Eds., *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge Univ. Press, Cambridge, 2007), p. 19.

Acknowledgments: We thank S. Turner, A. Weaver, S. Lewis, N. Ramankutty, and members of the Concordia Climate Lab for helpful discussions. Supported by the Natural Sciences and Engineering Research Council of Canada and the Canadian Foundation for Climate and Atmospheric Sciences.

Supplementary Materials

www.sciencemag.org/cgi/content/full/science.1236372/DC1
Supplementary Text
Figs. S1 and S2
References

Published online 28 March 2013

10.1126/science.1236372