What surprises lurk within the climate system?

2016 Environ. Res. Lett. 11 120202

(http://iopscience.iop.org/1748-9326/11/12/120202)

Environmental Research Letters

OPEN ACCESS

PUBLISHED
7 December 2016

EDITORIAL

What surprises lurk within the climate system?

Katharine Hayhoe[1] **and Robert E Kopp**[2]

[1] Climate Science Center and Department of Political Science, Texas Tech University, Lubbock TX, USA
[2] Department of Earth & Planetary Sciences, Rutgers Energy Institute, and Institute of Earth, Ocean & Atmospheric Sciences, Rutgers University, New Brunswick, NJ, USA

Aristotle might argue that humans were not responsible for the choices made at the beginning of the Industrial Era, when collective scientific and societal knowledge limited our capacity to choose wisely and well [1]. Regardless of our original ignorance, however, over the last few centuries we have been conducting an unprecedented experiment with the Earth's climate system.

Human society is built on the implicit assumption that climate is largely stationary: that historical records can be used with confidence to determine the energy loads of our buildings, the hundred-year floodplains of our cities, and the growing zones for the crops that power our economy and feed our world. What happens when that assumption is no longer valid?

For generations, our civilization has been building a climate debt, borrowing from the stability of the future to power the economic growth of the present. Through the combustion of fossil fuels, as well as agriculture, deforestation, land use change, and waste, human activities have disrupted the natural carbon cycle, increasing atmospheric carbon dioxide (CO_2) by almost 50% and methane (CH_4) by 250% relative to pre-industrial levels [2]. Even as this climate debt continues to grow, it is now coming due: the heat trapped by these and other greenhouse gases is raising global temperature, affecting heat and cold extremes, heavy precipitation and drought, sea ice and ice sheet melt, sea level rise and coastal flooding, and many other aspects of the climate system [3] that can harm human health, the economy, food supply, water availability, and even national security [4–6].

As climate scientists, we look to both the future and the past to understand what's happening in a world in which global temperatures are changing approximately 10 times faster than between the last glacial maximum and the current Holocene epoch [7], and are hurtling towards levels never before experienced in the relatively brief history of human civilization [8]. Looking forward, we force increasingly complex mathematical representations of the climate system—Earth System Models (ESMs)—with a range of future scenarios, representing everything from continued reliance on fossil fuels to the sharp emission cuts required to achieve global mean temperature targets such as the 'well below 2 °C' goal of the Paris Agreement [9]. These simulations provide invaluable insights into the probability, severity, and magnitude of human-induced climate change and its associated impacts: yet they are still imperfect. Some known processes likely to accelerate the rate of change and/or its impacts, such as methane release from thawing permafrost and sea level rise from ice sheet melt, are not included in most standard simulations. Incomplete representation of interactions between components that *are* included may be just as important. For example, models that underestimate the rate of Arctic sea ice melt will also underestimate the rate of Arctic warming; and models that inaccurately capture the response of ecosystems to climate change will also miss their effects on the carbon cycle and albedo.

Looking back, paleoclimate records provide evidence that self-reinforcing cycles (technically but potentially confusingly referred to as *positive feedbacks*) can accelerate climate change and even shift the Earth's climate system into new states very different from those experienced in the recent past [10–12]—for example, states in which the Arctic Ocean is ice-free in summer [13, 14], in which the Atlantic Meridional Overturning Circulation is greatly weakened [15], or in which ice sheets are dramatically shrunken [16, 17]. Some of these potential state shifts can be captured by climate models [18], but others arise from feedbacks or processes that are missing.

Paleoclimate analyses also reveal a broader limitation of global models. Compared to geological reconstructions of temperature and CO_2 from the past warm periods [19, 20], global climate models have a tendency to underestimate—both in the global mean and especially at the poles—the magnitude of warming in response to higher CO_2 levels. This underestimation hints at potential shifts in the state of the climate system that could increase climate sensitivity in a warmer world [21]. A bias towards underestimation is evident in predicting more recent rates of sea level rise, and other physical changes in the climate system [22, 23], while scientific assessments over the past few decades have demonstrated a systematic tendency towards 'erring on the side of least drama [24]'. Together, these limitations emphasize the need to stress-test ESMs against the paleoclimate record, and to build models and conduct simulations that explore potential catastrophic events and states of the world with low or unknown probability but profound consequences.

What other surprises might the climate system hold? Less dramatic but more imminent—and with the potential for serious physical and/or socio-economic harm—is the risk of the 'perfect storm' of multiple extreme events occurring in rapid sequence, or in tandem. On its own, a prolonged drought, record-breaking flood, or killer heat wave may be devastating but not surprising [25]. Together, however, the impact of simultaneous droughts and heat waves occurring in multiple breadbaskets around the world, or a recurring pattern of droughts that together add up to the type of 'mega-drought' seen in paleoclimate records for the US Southwest [26], can be far greater than the sum of each individual part [27]. Simultaneous stressors may increase the odds of climate-driven socio-economic tipping points, both beneficial (such as more active climate policy) and detrimental (such as an increase in civil conflict) [12]. These risks and uncertainties emphasize the need for large initial condition ensembles from multiple ESMs, analyses of extremes within those ensembles over multiple spatial and temporal scales, and integration of projected changes in physical climate with drivers of socioeconomic impacts and policies.

Regardless of our ignorance when humans first began this planetary experiment centuries ago, we are now cognizant of the climate debt that we have incurred and which we will be paying for centuries and even millennia to come. Over 150 years of scientific research—including the last 10 years of publications in *Environmental Research Letters*—have established that human activities are primarily responsible for both the changes we are seeing today as well as for the surprises that tomorrow may hold. Inhabitants of Arctic villages and low-lying coastal areas will soon become the world's first climate refugees; for many of them, it is too late to preserve their homelands [28–30]. For many more of us, the time to act is now—because the further and the faster the Earth's climate system is pushed, the greater the risk of surprise.

References

[1] Aristotle *Ethica Nicomachea*, III.1, trans. Jowell

[2] Blasing T J 2016 Recent greenhouse gas concentrations *CDIAC* (doi:10.3334/CDIAC/atg.032)

[3] USGCRP 2014 Our changing climate *Climate Change Impacts in the United States: The Third National Climate Assessment* pp 19–67 ch 2

[4] Crimmins A, Balbus J, Gamble J L, Beard C B, Bell J E, Dodgen D, Eisen R J, Fann N, Hawkins M D and Herring S C 2016 *The Impacts of Climate Change on Human Health in the United States: a Scientific Assessment* (US Global Change Research Program) (doi:10.7930/J0VX0DFW)

[5] Houser T, Hsiang S, Kopp R and Larsen K 2015 *Economic Risks of Climate Change: An American Prospectus* (New York: Columbia University Press)

[6] IPCC 2014 Summary for policymakers *Climate Change 2014: Impacts, Adaptation, and Vulnerability Part A: Global and Sectoral Aspects Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed C B Field *et al* (Cambridge: Cambridge University Press) pp 1–32

[7] Snyder C W 2016 Evolution of global temperature over the past two million years *Nature* **538** 226–8

[8] Collins M 2013 Long-term climate change: projections, commitments and irreversibility *Climate Change 2013: The Physical Science Basis Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed T F Stocker *et al* (Cambridge: Cambridge University Press)

[9] United Nations 2015 *Paris Agreement* (https://treaties.un.org/doc/Treaties/2016/02/20160215%2006-03%20PM/Ch_XXVII-7-d.pdf)

[10] Lenton T M, Held H, Kriegler E, Hall J W, Lucht W, Rahmstorf S and Schellnhuber H J 2008 Tipping elements in the earth's climate system *Proc. Natl Acad. Sci.* **105** 1786–93

[11] Lenton T M 2013 Environmental tipping points *Annu. Rev. Environ. Resour.* **38** 1–29

[12] Kopp R E, Shwom R, Wagner G and Yuan J 2016 Tipping elements and climate-economic shocks: pathways toward integrated assessment *Earth's Future* **4** 346–72

[13] Polyak L *et al* 2010 History of sea ice in the Arctic *Quat. Sci. Rev.* **29** 1757–78

[14] Li C, Notz D, Tietsche S and Marotzke J 2013 The transient versus the equilibrium response of sea ice to global warming *J. Clim.* **26** 5624–36

[15] Barker S and Knorr G 2016 A paleo-perspective on the AMOC as a tipping element *PAGES Mag.* **24** 14–5

[16] Dutton A, Carlson A, Long A, Milne G, Clark P, DeConto R, Horton B, Rahmstorf S and Raymo M 2015 Sea-level rise due to polar ice-sheet mass loss during past warm periods *Science* **349**

[17] DeConto R and Pollard D 2016 Contribution of Antarctica to past and future sea-level rise *Nature* **531** 591–7

[18] Drijfhout S, Bathiany S, Beaulieu C, Brovkin V, Claussen M, Huntingford C, Scheffer M, Sgubin G and Swingedouw D 2015 Catalogue of abrupt shifts in intergovernmental panel on climate change climate models *Proc. Natl Acad. Sci.* **112** E5777–86

[19] Salzmann U *et al* 2013 Challenges in quantifying pliocene terrestrial warming revealed by data-model discord *Nat. Clim. Change* **3** 969–74

[20] Goldner A, Herold N and Huber M 2014 The challenge of simulating the warmth of the mid-Miocene climatic optimum in CESM1 *Clim. Past* **10** 523–36

[21] Caballero R and Huber M 2013 State-dependent climate sensitivity in past warm climates and its implications for future climate projections *Proc. Natl Acad. Sci.* **110** 14162–7

[22] Hansen J 2007 Scientific reticence and sea level rise *Environ. Res. Lett.* **2** 024002

[23] Rahmstorf S, Foster G and Cazenave A 2012 Comparing climate projections to observations up to 2011 *Environ. Res. Lett.* **7** 044035

[24] Brysse K, Oreskes N, O'Reilly J and Oppenheimer M 2013 Climate change prediction: erring on the side of least drama? *Glob. Environ. Change* **23** 327–37

[25] IPCC 2012 Managing the risks of extreme events and disasters to advance climate change adaptation *A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* ed C B Field *et al* (Cambridge: Cambridge University Press) p 582

[26] Cook E, Seager R, Heim R, Vose R, Herweijer C and Woodhouse C 2009 Megadroughts in North America: placing IPCC projections of hydroclimatic change in a long-term palaeoclimate context *J. Quat. Sci.* **25** 48–61
[27] Lunt T, Jones A, Mulhern W, Lezaks D and Jahn M 2016 Vulnerabilities to agricultural production shocks: an extreme, plausible scenario for assessment of risk for the insurance sector *Clim. Risk Manage.* **13** 1–9
[28] Hamilton L, Saito K, Loring P, Lammers R and Huntington H 2016 Climigration? Population and climate change in Arctic Alaska *Population Environ.* **38** 115–33
[29] Davenport C and Robertson C 2016 Resettling the first American 'climate refugees' *New York Times* (http://nytimes.com/2016/05/03/us/resettling-the-first-american-climate-refugees.html)
[30] Constable A 2016 Climate change and migration in the Pacific: options for Tuvalu and the Marshall Islands *Reg. Environ. Change* in press (doi:10.1007/s10113-016-1004-5)