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EDITORIAL

What surprises lurk within the climate system?

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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 What happens when that assumption is no longer valid?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.

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