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Perspective

Complexity and determining dangerous levels of climate impacts

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Abstract
A recent paper (Gerten *et al* 2013 Environ. Res. Lett. **8** 034032) finds very different global warming thresholds of concern between water scarcity and ecosystem changes. This may at first appear surprising, as each process is controlled to some extent by functioning of the land surface. Hence this analysis reflects the fundamentally different character of what constitutes water scarcity among people, compared to water stress for ecosystems. Gerten *et al* (2013 Environ. Res. Lett. **8** 034032) find both responses to warming are highly nonlinear, but in opposite senses. Water scarcity could affect multiple millions of people for even low levels of warming, but that number would almost stabilize should warming continue. In contrast, ecosystem changes become massively more responsive to climate change at higher warming levels. This re-iterates how complex the Earth system is, making it difficult to determine what constitutes overall single thresholds of climate change society may choose to consider avoiding. However, it is argued here that such targets are still much needed, providing a focal point for discussion, and complexity should not be used as an excuse to prevent setting them.

1. Main paper

It is difficult to imagine any other scientific endeavour that has been subjected to so much public scrutiny as climate change. As research underpins climate prediction and associated impacts, it might be expected that this should lead to concise answers. What, precisely, constitutes safe levels of altered atmospheric greenhouse concentrations? Then any broader debate is free to concentrate solely on what level of warming might be deemed unacceptable based on projected impacts—and ask the question: how can the global economy implement emissions reductions to avoid crossing a dangerous threshold? However, in many respects this has not yet happened. The argument is made here that this lack of progress is because, despite vigorous efforts to explain the enormous complexity of the Earth system, there remain major uncertainties. The recent paper by Gerten *et al* (2013) is particularly important in this context, as it additionally highlights how the impacts responses to climate change are also highly complex.

There have been two decades of comprehensive high-resolution modelling of the climate system, aided through (a) step changes in computational availability and (b) much better and longer measurement datasets to inform process parameterization. Major advances have occurred in understanding functioning of the atmosphere, oceans, terrestrial ecosystems, cryosphere and all interactions between them. Yet the uncertainty bounds on climate sensitivity, the amount of warming for a doubling of atmospheric carbon dioxide concentrations, remains stubbornly large (IPCC 2013). Although it is totally correct to disclose in full this uncertainty in current knowledge, unfortunately it has the side-effect of forcing a polarization in the debate. Some green pressure groups may select the upper predictions of change, and give a potentially overly pessimistic and thus alarmist assessment of the evolution of the human–climate system. Other pressure groups do the opposite, and equate uncertainty as meaning the science is simply wrong. The latter attempt to debunk everything to do with climate change, including attributes we do know with more certainty, such as an almost certain human fingerprint on the general warming record to date (Stott *et al* 2006). This polarization, preventing informed and inclusive debate, in itself constitutes a real threat. It makes it more difficult for society to assess and discuss the risks of global warming and prepare for any related impacts.

In wondering as to how we have ended up in this situation, a recent paper in this journal (Gerten *et al* 2013) provides an excellent microcosm of the competing and differential factors that control the full human–climate-impacts system. They combine projections by different climate models with the LPGmL vegetation model (Bondeau *et al* 2007, Sitch *et al* 2003), discovering that global warming of 2 °C, 3.5 °C and 5 °C would expose an extra 8%, 11% and 13%, respectively, of the world population to new or enhanced water scarcity. This suggests that even two degrees of global warming could affect a very large fraction of society, and is arguably a threshold too high. Yet warming levels beyond that, in relative terms, do not add substantially to the population affected, indicating nonlinear saturation. The authors then consider projections of habitat transformation. Again for warming levels 2 °C, 3.5 °C and 5 °C, they now find major ecosystem changes reaching levels of 1%, 10% and 74% adjustment to 'present endemism-weighted vascular plant species'. First this suggests in this context, two degrees of warming might be acceptable. Second, it again points to highly nonlinear features, but in the opposite way, with an acceleration of change for increasing warming levels—in broad terms is one characteristic of environmental tipping points (Lenton *et al* 2008). Add to this differential responses of terrestrial ecosystems to the mix of any raised atmospheric greenhouse gas concentrations (Huntingford *et al* 2011), that only recently are geochemical cycle influences on vegetation being routinely considered, e.g. nitrogen cycle (Thomas *et al* 2013) and phosphorous cycle (Mercado *et al* 2011), and that physiological acclimation effects need to be included in modelling studies (Huntingford *et al* 2013), then the overall situation becomes even more convoluted to understand.

So what to do? First, we need to assess further the finding of Gerten *et al* (2013) that the number affected by water scarcity increases quickly in warming level before flattening off. Is this because a large fraction of the population already suffers water scarcity (their figure 3(a), red and dark orange histogram components)? How large a section of society is sufficiently developed with appropriate infrastructure that they can cope with almost any change to the hydrological cycle—and can this be made to increase in to the future, which would further flatten the responses? What is the influence on projections of using a single metric for defining chronic water scarcity of 1000 m^3 per capita per year (Falkenmark and Widstrand 1992)? However, this work also suggests something more fundamental is also needed. Paradoxically, given so much complexity, there emerges a desperate requirement for simple-to-understand specifications of what might constitute generally safe bounds. Hence there is a very persuasive argument—and one this author believes—that even if the current values of such bounds are not precisely known, target specification does provide a quantity to focus thinking in policy circles. It also focuses research, allowing the implications of new findings to be routinely translated into refining any such climate targets, and keeps the pressure on to reduce model parameter uncertainty. The two-degrees limit is now the most widely used threshold, emerging in part from the 'burning embers' diagrams that featured in the 3rd IPCC assessment (IPCC 2001). And as an example of reassessment, Smith *et al* (2009) argue such burning embers diagrams were overly optimistic. Even to limit global warming to two degrees will require major ongoing emissions reductions, and soon (Huntingford *et al* 2012). However, here too there is complexity, as there is some flexibility between slightly later deeper cuts, or slower emissions decreases but starting almost immediately. Fortunately, therefore, a second summary threshold is emerging that encapsulates this degree of freedom. The long atmospheric lifetime of carbon dioxide allows a single cumulative remaining total of 'allowable' CO_2 emissions to be specified, leaving easier specification of emissions pathways that meet that total. Allen *et al* (2009) find that the burning of a trillion tonnes of carbon since pre-industrial times, across climate sensitivities, ocean diffusivities and carbon cycle feedbacks, corresponds to a most likely warming of two degrees. So far we are already over 50% of the way to that cumulative emission total.

Emerging assessments of how the Earth system functions and including climate feedbacks on the carbon cycle (e.g. Piao *et al* 2013), or new projections of expected climate impacts provided by analyses such as Gerten *et al* (2013), matter. These may refine the total remaining 'allowable' emissions to stay below two degrees, or potentially demand re-assessment of the two-degrees limit itself as an appropriate upper level to warming. Exploring of safe planetary boundaries must continue across a broad range of environmental thresholds (Rockstrom *et al* 2009), with translation back to warming or total emissions targets. Setting simple targets remains key to facilitate emission negotiations, even if for the time being and despite the best research efforts, these are based to some extent on incomplete knowledge.

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