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Quantifying and ranking vulnerabilities in the carbon-climate-human system

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Definition and quantification of the concept of carbon-climate vulnerability is important for understanding the stresses on the earth system from anthropogenic forcing. We define "vulnerability" as the added risk to global wellbeing arising from a process or feedback in the earth system which amplifies anthropogenic forcing or stress. The risk may arise from both natural processes and those directly associated with human actions.

Hitherto, three different approaches have been taken to quantify carbon-climate vulnerability. First, positive feedbacks between climate and the carbon cycle have been studied in model experiments and in the C^4MIP intercomparison (Friedlingstein et al., 2006). Second, a heuristic, risk-based approach (Gruber et al., 2004) has been used to represent the vulnerability of various carbon pools on a plane with axes representing pool magnitude and likelihood of release, using literature-based judgements. Third, simple models have been used to assess the vulnerability to processes such as thawing of permafrost soils (eg Raupach and Canadell, 2008).

We develop a way of quantifying vulnerability which admits information both from all three of the above approaches. Working from the above definition of vulnerability, the measure of risk to global wellbeing is taken to be radiative forcing (RF) (IPCC, 2001). To identify the contribution of a particular process we consider the RF increase through given time interval in a reference case, RF(Ref), and a perturbed case, RF(Pert), where the perturbation is the addition or subtraction of a process, feedback or anthropogenic forcing relative to the reference case. The vulnerability of the perturbed case is RF(Pert)/RF(Ref). The reference case is defined by two attributes: (1) the total RF is the RF from CO_2 alone, and (2) the CO_2 airborne fraction with respect to total emissions is held constant at its average value over the last 5 decades of 0.45 (Canadell et al., 2007). These attributes are both approximately true for the earth system at present, though not necessarily in the future, and define a reference case which can be evaluated simply and unambiguously. There is no implication that future evolution of the real earth system will follow these simple reference assumptions.

We have applied this framework to quantify and thence to intercompare carbon-climate (and other related) vulnerabilities arising from four kinds of process:

1. Positive carbon-climate feedbacks in terrestrial and ocean systems as already captured by carbon-climate models such as those participating in C4MIP;
2. CO_2 and/or CH_4 releases from "additional" pools such as arctic and tropical peats and methane hydrates, presently not usually included in carbon-climate models;
3. Relaxing of the "aerosol brake" (Ramanathan and Feng, 2008) as anthropogenic aerosol loadings decrease in future through improvement of air quality and industrial cleanliness;
4. Political failure to define and implement global climate-change mitigation strategies, so that emissions remain near or above high-emission SRES scenarios (eg A1FI, A2) for several decades in the future.

Our methodology enables these sources of vulnerability to be compared systematically. It is found that the largest vulnerabilities arise from process groups 4 and 3, with significant additional vulnerability from groups 1 and 2.

These different kinds of vulnerability are additive only in a linear analysis about the present state of the earth system. As the earth system is progressively impacted by climate change and other anthropogenic forcings, nonlinear interactions among different kinds of vulnerability are likely.

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