CLIMATE RESPONSE

Strong warming at high emissions

The ratio of global temperature change to cumulative emissions is relatively constant up to two trillion tonnes of carbon emissions. Now a new modelling study suggests that the concept of a constant ratio is even applicable to higher cumulative carbon emissions, with important implications for future warming.

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At the 2015 Paris Conference, the global community agreed to limit global warming to below 2 °C relative to pre-industrial levels and to pursue further efforts for limiting temperature increase to below 1.5 °C. Given that current trends in fossil fuel emissions would result in temperatures above those targets, policymakers need to have a clear view of what is at stake both on decadal and centennial timescales if no meaningful climate policies are put in place. In the absence of mitigation, cumulative carbon emissions will probably exceed two trillion tonnes of carbon (2,000 GtC) before the end of this century, and the burning of the total fossil fuel resource would lead to cumulative emissions of about 5,000 GtC. Now, writing in *Nature Climate Change*, Katarzyna Tokarska and colleagues[1] suggest that the CO_2-attributable warming continues to increase approximately linearly with such high emissions and will be larger than previously thought if no actions to reduce emissions are taken.

The peak global mean temperature reached under certain cumulative carbon emissions increases approximately linearly for emissions up to 2,000 GtC[2,3] (red and blue lines in Fig. 1). The concept of such a constant relationship suggests that a given range of CO_2 emissions, regardless of the rate of release[4], will ultimately lead to a given warming. For example, if 1,000 GtC are emitted, the IPCC[5] reports that the committed warming is likely to lie between 0.8 and 2.5 °C. But simulations with simple models suggest that this relationship might be lower for cumulative carbon emissions exceeding 2,000 GtC (ref. 2). However, this remains unconfirmed in comprehensive Earth system models (ESMs) due to limited simulations available.

To address this knowledge gap, Tokarska and co-workers[1] used simulations from four comprehensive Earth system models from the Coupled Model Intercomparison Project Phase 5 (CMIP5-ESMs) and from seven Earth system models of intermediate complexity (EMICs) to explore the robustness of this concept for cumulative carbon emissions larger than 2,000 GtC. All models were forced with prescribed CO_2 concentrations that assumed little or no mitigation in CO_2 emissions up to the year 2300, corresponding to total cumulative carbon emissions of around 5,000 GtC. The authors found that the simulated global mean warming in response to 5,000 GtC ranges from 6.4 to 9.5 °C in the four comprehensive CMIP5-ESMs analysed (red shading in Fig. 1). This is more warming than simulated by the seven EMICs that carried out the same simulation (4.3 to 8.4 °C; blue shading in Fig. 1). Additionally, mean Arctic warming is projected to increase in the CMIP5-ESMs by more than twice the global mean (14.7 to 19.5 °C) and regional precipitation is set to increase by more than a factor of four.

Even more importantly, the authors report that the ratio of warming to cumulative carbon emissions continues to be approximately constant, even up

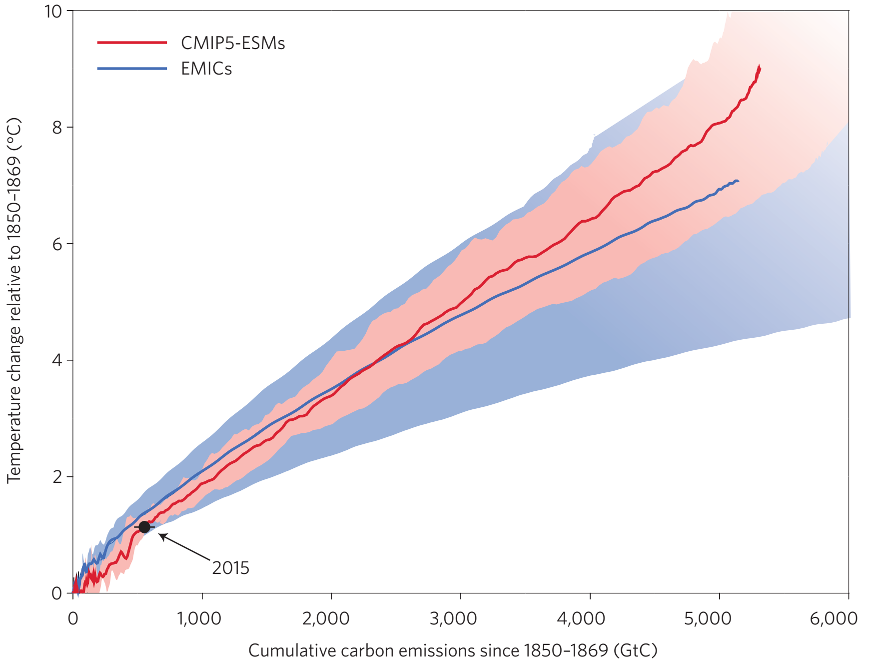

Figure 1 | Global annual mean surface temperature changes as a function of cumulative carbon emissions based on the RCP8.5-extension scenarios over the period 1850 to 2300 as simulated with four CMIP5-ESMs (red line) and seven EMICs (blue line). The red and blue lines indicate the multi-model mean changes and the shaded ranges illustrate the model spread over all CMIP5-ESMs and EMICs. The shaded ranges are filled as long as data of all models is available and are faded out for illustrative purposes afterward. Data are taken from ref. 1 and are smoothed with a five-year running mean. The simulated temperature data are scaled by the ratio of CO_2 radiative forcing to total radiative forcing to show the CO_2-attributable warming only. The CMIP5-ESM multi-model mean is only shown for the period 1850 to 2280. The black point indicates observational-based estimates for the year 2015. Observed cumulative carbon emissions from 1870 to 2015 are 555 ± 55 GtC (ref. 12). Observed global mean surface temperature change since 1880–1899 is estimated to be 1.1 °C (ref. 13).

to 5,000 GtC in the four comprehensive CMIP5-ESMs (red line in Fig. 1). Thus, there is no evidence of the pronounced decrease in the ratio under high CO_2 emission levels as simulated by the seven EMICs analysed (blue line in Fig. 1) and shown with simpler models[2]. This lower predicted warming in EMICs than in CMIP5-ESMs is in agreement with an earlier study[6] and is of particular concern because EMICs are the tool of choice for long-term climate response simulations as simulations with CMIP5-ESMs are still computationally too expensive to run for more than a couple of centuries.

One element that was not investigated in detail in this study is why the global warming response to cumulative carbon emissions in the four CMIP5-ESMs differs from the EMICs. It is well known that radiative forcing increases non-linearly as the concentration of CO_2 in the atmosphere increases; at higher CO_2 concentrations the increase in radiative forcing becomes smaller. Therefore further addition of CO_2 to the atmosphere has a progressively smaller warming effect. At the same time, the ability of the ocean and land to take up heat and CO_2 is also diminished under higher CO_2 concentrations, counteracting the dampening in radiative forcing and resulting in a linear relationship between warming and cumulative CO_2 emissions up to 2,000 GtC (ref. 7). In EMICs, it is believed[2] that the diminished radiative forcing dominates over the decreasing ability of the ocean and land to take up heat and CO_2 at high emissions. This results in a decrease in the ratio of warming to emissions at high cumulative carbon emissions in EMICs. The fact that CMIP5-ESMs instead show a constant ratio of warming with carbon emissions even at high cumulative CO_2 emissions is likely to be related to some physical processes that are included in the CMIP5-ESMs — but not in the EMICs — that result in different warming responses. Three possible factors are: first, CMIP5-ESMs tend to initially warm at a slower rate after being forced by CO_2 than EMICs[6]. As a result, the CMIP5-ESMs simulate a stronger weakening of the heat fluxes into the deep ocean under continued CO_2 emissions, and a stronger global warming. Second, the climate sensitivity — the change in temperature for a given change in CO_2 concentration — may also increase as cloud cover[8] and ocean heat uptake patterns[9] change under global warming. Third, the radiative forcing of CO_2 might rise slightly (~5%) more linearly with high CO_2 concentrations[10] in CMIP5-ESMs. Ocean physics, clouds feedbacks and radiative forcing are all features that are simulated only in a simplified manner and at a coarse resolution in EMICs. But how can we verify these processes and validate the models? Observations might help constrain ocean circulation changes, which have been identified as contributing factors for changes in ocean heat uptake efficiency and efficacy[11], whereas the changes in climate sensitivity over time may be less approachable with observational constraints. In any case, additional analysis and sensitivity studies are urgently needed to better understand not only the causes of the differences between CMIP5-ESMs and EMICs, but also among the individual models.

Ultimately, the work by Tokarska and colleagues[1] highlights that the regulatory framework based on cumulative CO_2 emissions is probably robust over a much wider range of plausible CO_2 emissions than previously thought. This implies that the unregulated exploitation of fossil fuel resources could result in significant, more profound climate change. ❐

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ATMOSPHERIC DYNAMICS

Arctic winds of change

The Earth's climate evolves in response to both externally forced changes and internal variability. Now research suggests that both drivers combine to set the pace of Arctic warming caused by large-scale sea-ice loss.

Dirk Notz

Never before, since the beginning of reliable observations, has the maximum extent of Arctic winter sea ice been as low as this year[1]. Such large-scale loss of sea ice is one of the most visible manifestations of climate change, and also a key driver of the rapid warming that the Arctic currently experiences[2]. However, the quantitative contribution of sea-ice loss to Arctic warming has remained unclear. Now writing in *Nature Climate Change*, James Screen and Jennifer Francis[3] suggest that the warming contribution of sea ice is not constant, but modified by atmospheric circulation patterns that are related to the surface temperature distribution in the Pacific.

Despite its geographical remoteness, the Arctic is probably one of the regions most intensely studied by climate researchers. Their interest is, among others, driven by the rapidity of climate change in the high northern latitudes, with a warming rate that is two to three times as fast as for rest of the planet (Fig. 1). This Arctic amplification, which is both a robust outcome of climate model simulations[4] and of observational records, increases the melt rates of sea ice, land ice and permafrost soils alike. The various melting processes, in turn, further amplify the initial warming, as less sea ice reflects less warming sunlight, a lower ice sheet has a higher temperature because