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Allowable CO_2 emissions based on regional and impact-related climate targets

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Global temperature targets, such as the widely accepted limit of an increase above pre-industrial temperatures of two degrees Celsius, may fail to communicate the urgency of reducing carbon dioxide (CO_2) emissions. The translation of CO_2 emissions into regional- and impact-related climate targets could be more powerful because such targets are more directly aligned with individual national interests. We illustrate this approach using regional changes in extreme temperatures and precipitation. These scale robustly with global temperature across scenarios, and thus with cumulative CO_2 emissions. This is particularly relevant for changes in regional extreme temperatures on land, which are much greater than changes in the associated global mean.

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report included a figure in the Summary for Policymakers of Working Group 1 that linked global mean temperature changes (ΔT_{glob}) to total CO_2 emissions from 1870 onwards[1] (Fig. 1). This figure is compelling because it shows a clear linear relationship between cumulative CO_2 emissions and a measure of the global climate response. The obvious consequences are (1) that every tonne of CO_2 contributes about the same amount of global warming no matter when it is emitted, (2) that any target for the stabilization of ΔT_{glob} implies a finite CO_2 budget or quota that can be emitted, and (3) that global net emissions at some point need to be zero[2–6].

This simple relationship between CO_2 emissions and changes in ΔT_{glob} (Fig. 1) has helped overcome one communication barrier for the public in relating greenhouse gas emissions to the climate system response. However, there remains another obstacle to the full appreciation of associated climate impacts, namely, the translation of changes in global mean temperature to regional-scale consequences for society and the environment. In this Perspective, we demonstrate the feasibility and utility of quantitatively relating global cumulative CO_2 emissions to regional climate targets. We illustrate this approach by scaling changes in hot and cold extreme temperatures and heavy precipitation events with changes in the global mean temperature.

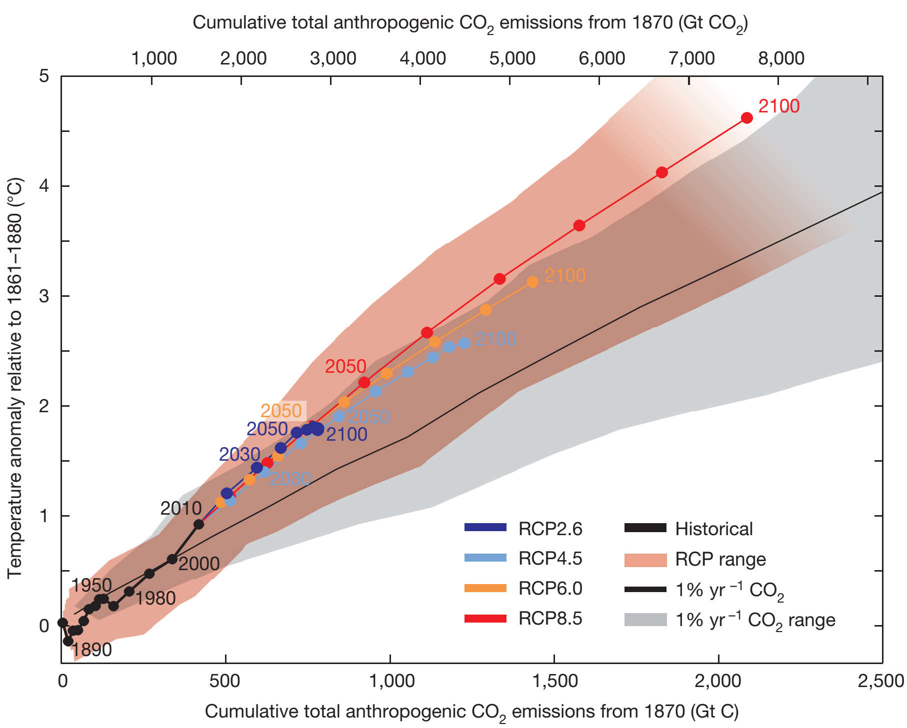

Figure 1 | Simulated global mean surface temperature increase as a function of cumulative total global CO_2 emissions. This is figure SPM.10 from ref. 1. It was derived from various lines of evidence. Model results over the historical period (1860–2010) are indicated in black. The coloured plume illustrates the multi-model spread over the four Representative Concentration Pathway (RCP) scenarios. The multi-model mean and range simulated by Coupled Model Intercomparison Project Phase 5 (CMIP5) models, forced by a CO_2 increase of 1% per year, is given by the thin black line and grey shading. For a given amount of cumulative CO_2 emissions, the 1% per year CO_2 simulations exhibit less warming than those driven by RCPs, which include additional non-CO_2 forcings. Temperature anomalies are given relative to the 1861–1880 base period; emissions are given relative to 1870.

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BOX 1

Linking regional extremes, global means, and cumulative emissions

We use output from the climate model simulations contributing to CMIP5[56]. Here we present results for climate extreme indices representative of the hottest day (T_{Xx}) and coldest night (T_{Nn}) of the year, as well as the annual maximum consecutive 5-day precipitation total (R_{x5day}). Climate extreme indices[57] were calculated for the historical simulations[58] and future projections[59] from the CMIP5 ensemble. We use one run (r1i1p1) from models that provide historical simulations during 1861–2005, as well as RCP8.5 and RCP4.5 scenario simulations for the twenty-first century (see Supplementary Table 1). For the analysis of transient changes we concatenated historical (1861–2005) and RCP (2006–2099) simulations. We restricted our analyses to 1861–2099, which was common to all model runs. Global mean temperatures were calculated as the area-weighted global averages of annual mean temperatures. Extreme index fields were remapped to a common 2.5° × 2.5° analysis grid to allow calculation of local ensemble averages and ensure that the same regions from each model contribute to the regional analyses.

Scatter plots showing the scaling relationship between changes in global mean temperature (ΔT_{glob}) and regional extreme index changes (see Figs 3 and 4b) are based on decadal averages of the respective variables. These averages of local anomalies relative to the 1861–1880 average were calculated for moving ten-year windows, and moving average values were assigned to the last year of each window period (that is, the value for year 2010 represents the average during 2001–2010; note that in the case of Fig. 1 the decadal global temperature averages are assigned to the year directly following that decade). These moving ten-year averages were also used to produce maps of local changes for a global mean temperature increase of 2 °C (see Fig. 2). The indicated cumulative CO_2 emissions corresponding to different global mean temperature increases (red ticks on horizontal axes in Figs 3 and 4b) were approximated from the RCP8.5 ensemble average in Fig. 1 (single values were assigned to each of the chosen tick marks). This means that 500 billion tonnes of carbon (500 Gt C) are emitted for a global increase of approximately 1.2 °C, 1,000 Gt C for 2.35 °C, 1,500 Gt C for 3.5 °C, and 2,000 Gt C for 4.45 °C. Respective analyses regarding the scaling of extreme temperatures and precipitation in all 26 regions of the IPCC Special Report on Extremes[7] and global land are provided in the Supplementary Information.

Global versus regional climate targets

Experience shows that the implications of projected global mean temperature changes tend to be underestimated at regional (and country) level, because the global changes are much smaller than the expected changes in regional temperature mean and extremes over most land areas[7–10]. The limitations of global mean temperature as a measure of climate change have, for instance, been made evident by the public debate about the recent 'hiatus' decade in global warming, which has focused attention on changes in ΔT_{glob} instead of on the discernible worldwide impacts of the continued increases in radiative forcing[1,11–14].

As illustrated in Fig. 2, a 2 °C target for ΔT_{glob} implies increases in both warm and cold temperature extremes that are greater than 2 °C over most land regions. This is due to the land–sea contrast[15,16] in response to radiative forcing, as well as to feedbacks (for example, from decreases in soil moisture, snow or ice[7,8,17–20]), which further amplify changes in extreme temperatures in some key regions. As an example, the 2 °C global mean temperature target implies 3 °C warming in hot temperature extremes in the Mediterranean region (Fig. 2a) and about 5.5 °C warming in cold temperature extremes over land in the Arctic region (Fig. 2b). Hence, these changes in regional extremes are greater than those in global mean temperature by a factor of about 1.5 and 2.5–3 (Supplementary Fig. 1), respectively. As highlighted above, this stronger warming of extremes on land compared to that of global mean temperature is related both to the larger warming of mean temperature on land (Fig. 2c), as well as to an additional specific warming of extremes in several regions (Fig. 2a, b). Subjectively, such regional changes in extremes may convey the consequences of crossing the respective cumulative CO_2 emissions threshold better than the associated change in ΔT_{glob} (2 °C), which seems relatively mild in comparison.

We make the case here for more easily interpretable analyses that relate global cumulative CO_2 emissions targets to changes in regional extremes or other impact-relevant quantities in addition to changes in global mean temperature. Although the IPCC Synthesis Report[21] shows cumulative CO_2 emissions alongside their "reasons for concerns", the bars (of various shades of red) provide only a qualitative assessment. We highlight here how quantitative analyses relating cumulative emissions to climate change at the national or regional scale could provide more targeted and actionable information for the decision process.

Regional extremes versus global CO_2 emissions

We thus assess the extent to which the implications of figure SPM.10 of ref. 1 (Fig. 1) can be expanded to relate cumulative global emissions in CO_2 with regional changes in temperature extremes (annual maximum and minimum temperatures; see Box 1). The result is displayed in Fig. 3 for four example regions with relatively strong scaling (the Mediterranean basin; the contiguous USA; central Brazil for annual maximum daytime temperatures; and the Arctic for annual minimum night-time temperatures). For other regions, see Supplementary Figs 4 and 5. The analyses display the scaling of the regional changes considered with the changes in global mean temperature for a range of climate projections, and provide the associated expected allowable cumulative global CO_2 emissions (but without considering the uncertainty in translating ΔT_{glob} to cumulative emissions).

The results show that changes in regional extreme temperatures display a rather linear scaling with ΔT_{glob}, which is also mostly independent of the emission scenario considered (Fig. 3). Hence, regional changes in temperature extremes can be usefully related to given cumulative CO_2 targets, without any consideration of the emission pathway. However, scaling for regional extremes on land is generally steeper than for ΔT_{glob} (see also analyses for other land regions in Supplementary Figs 4 and 5). Hence, as expected from Fig. 2, the relationship between the increase in regional temperature extremes and the increase in global mean temperature typically implies a larger change of the former at more local scales.

For instance, a 2 °C warming in hot extremes (annual warmest daytime temperature, T_{Xx}) takes place in the Mediterranean for a change of 1.4 °C in ΔT_{glob} (Fig. 3a). The corresponding allowable cumulative CO_2 emissions are therefore about 600 Gt C for a 2 °C warming of hot extremes in the Mediterranean region compared to about 850 Gt C for a 2 °C warming in global mean. Given current political tensions around the Mediterranean basin, implications of locally more rapid climate change could extend to regional impacts[22], adding to wider political instability (see for example the purported impacts of drought in Syria[23,24]).

Scaling extreme hot temperatures in the contiguous USA and central Brazil (Fig. 3b, c) by ΔT_{glob} provides qualitatively similar results, but highlights greater uncertainty of projections in these regions. In the contiguous USA, although the expected value of scaling with ΔT_{glob} is greater than 1, the uncertainty range bounds the 1:1 (identity) line. Conversely, the regional response in central Brazil is significantly different from the 1:1 line despite the larger uncertainty range compared to the Mediterranean region. The response of the regional changes in annual coldest night-time temperatures (T_{Nn}) in the Arctic (Fig. 3d) conveys a very stark message. In this case, as seen in Fig. 2, the regional response is about 2.5–3 times greater for

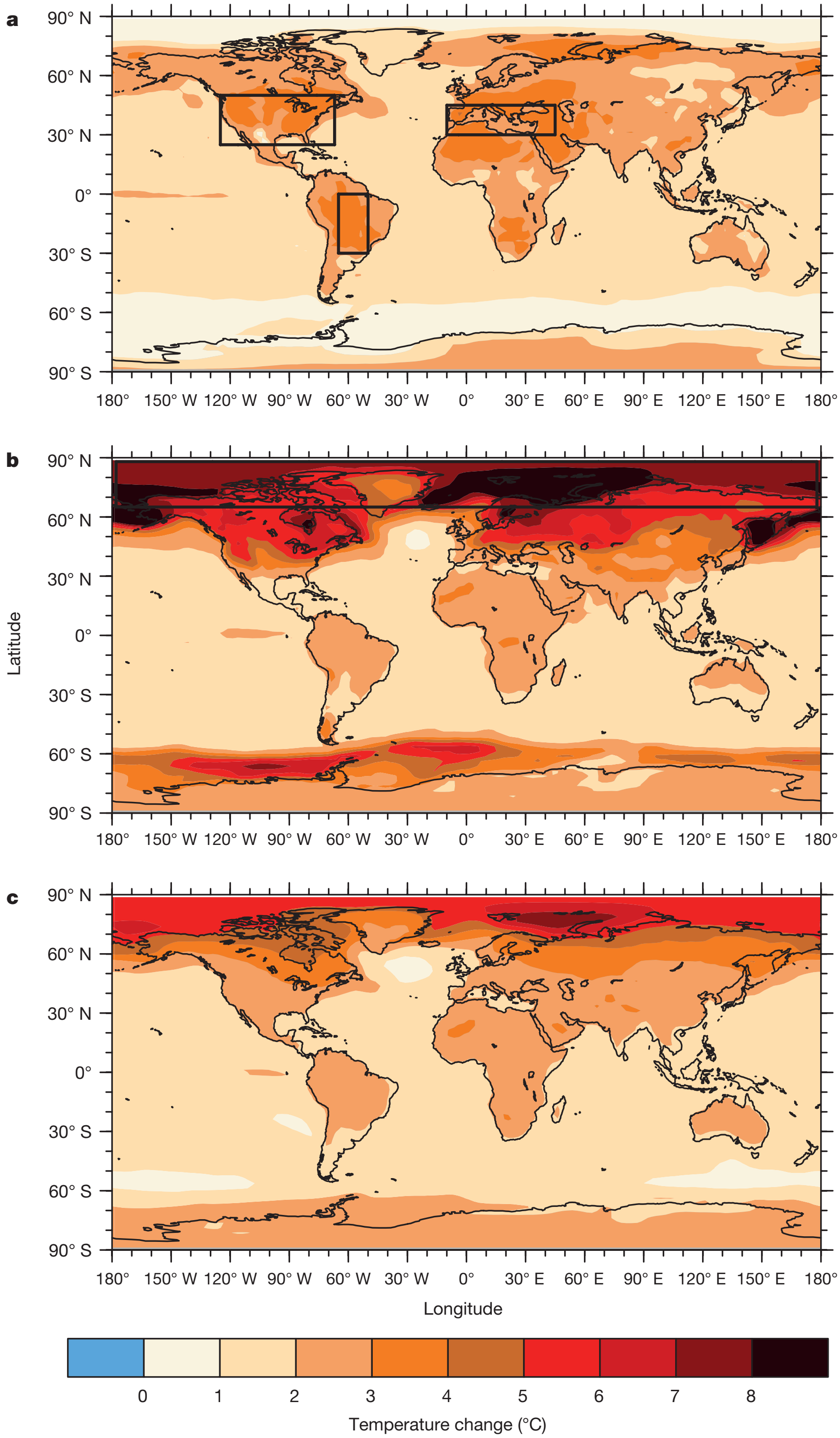

Figure 2 | Extreme (and mean) temperature changes associated with a 2 °C target. Local changes associated with a global warming of 2 °C are shown for hottest daytime temperature (T_{Xx}) (**a**), annual coldest night-time temperature (T_{Nn}) (**b**), and mean temperature (T_{mean}) (**c**). The analysis is based on RCP8.5 scenario simulations (ensemble average year 2044; based on 25 model simulations, see Supplementary Table 1). The respective scaling expressed as ratio of global mean temperature increase is provided in Supplementary Fig. 1. Note that very similar results are obtained with the RCP4.5 scenario simulations (Fig. 3 and Supplementary Figs 2 and 3, based on 22 model simulations). Panels **a** and **b** also display the outlines of the regions analysed in Fig. 3.

the coldest extremes than for the global mean temperature change, with an increase of about 5.5 °C for the 2 °C global warming target. In addition, it is evident that a regional 2 °C threshold was passed in the simulations around the year 2000 for T_{Nn} in the Arctic, while it is projected to be reached by about 2030 for T_{Xx} in the Mediterranean, central Brazil and the contiguous USA, and only by the mid-2040s for the global mean temperature, under the business-as-usual (unchecked) emissions scenario (RCP8.5, which leads to a radiative forcing of 8.5 W m^{-2} by 2100 relative to pre-industrial values). For a 1.5 °C global warming target, we also note that substantial regional changes in temperature extremes would still occur, with (for example) a

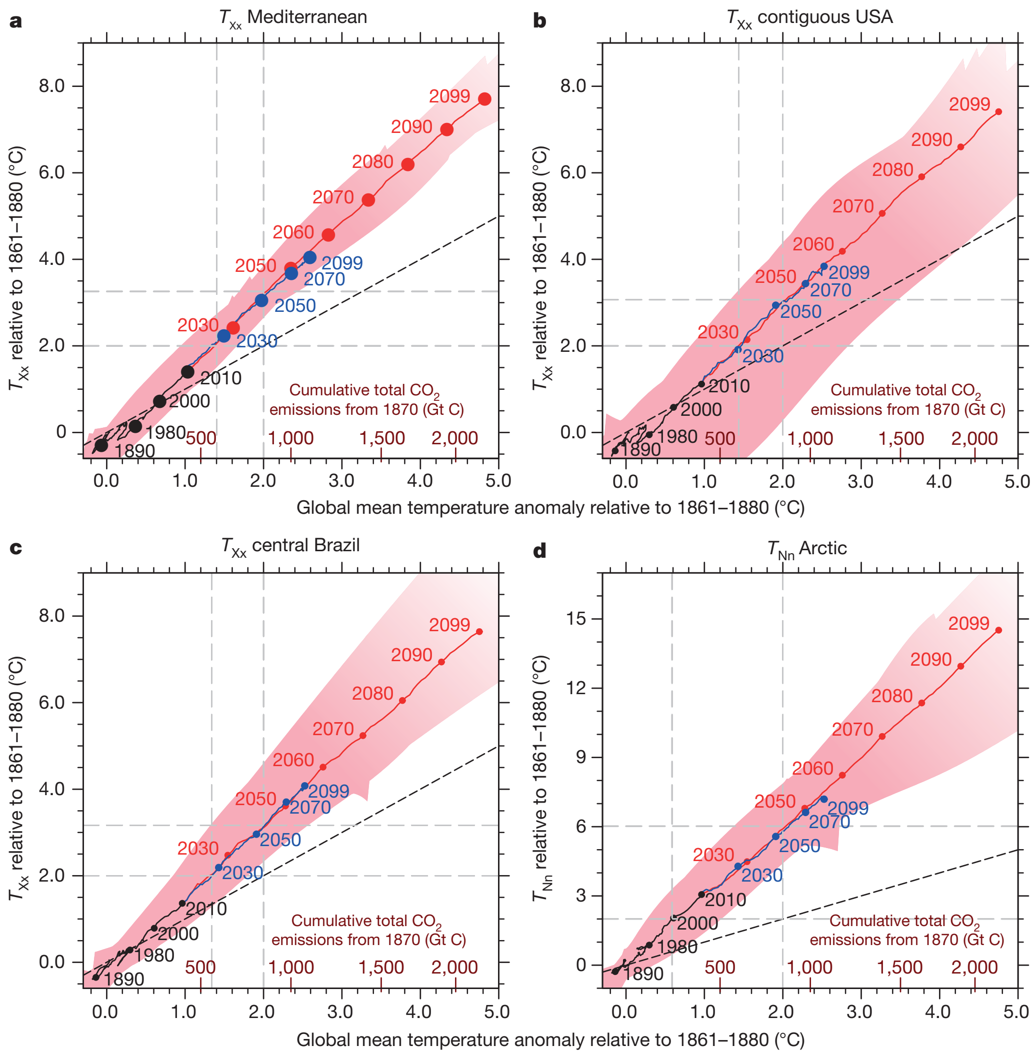

Figure 3 | Scaling between regional changes in annual temperature extremes and changes in global mean temperature, with associated global cumulative CO_2 emissions targets. See Box 1 for details on the underlying analysis. Results are shown for annual maximum daytime temperature (T_{Xx}) in the Mediterranean region (30° to 45° N, 10° W to 45° E) (**a**), the contiguous USA (25° to 50° N, 125° W to 67° W) (**b**), and central Brazil (30° S to 0° N, 65° W to 50° W) (**c**), and for the annual minimum night-time temperature (T_{Nn}) in the Arctic (65° to 90° N, 180° W to 180° E) (**d**). The four analysed regions are indicated in Fig. 2a and b. The solid black line denotes the ensemble average in the historical runs until 2010 (combined with RCP8.5 for 2006–2010) and the solid red (blue) line denotes the ensemble average of the future projections following the RCP8.5 (RCP4.5) scenario simulations, based on 25 (22) model simulations (see Supplementary Table 1). The red shaded area indicates the total range (minimum to maximum value) for all considered simulations and experiments. The dashed black line shows the identity (1:1) line. Grey dashed lines show the temperatures or CO_2 emissions associated with 2 °C increases in global mean and regional extreme temperatures, respectively. Note the different vertical axes for T_{Xx} and T_{Nn}. Only land grid cells were used for calculating the regional T_{Xx} and T_{Nn} averages.

4.4 °C warming in T_{Nn} in the Arctic and a 2.2 °C increase in T_{Xx} in the Mediterranean region (Fig. 3).

Although we have illustrated the concept of regional and impact-related climate targets with regional changes in temperature extremes, similar reasoning can be applied to a range of other responses to global climate forcing[7,25] (for example, changes in heavy precipitation events, see below). These are also highly relevant in comprehending the regional implications of global CO_2 emissions. As a further illustration, we display in Fig. 4 the scaling of heavy precipitation events with global mean temperature, and the respective relationship between cumulative CO_2 emissions and resulting changes in heavy precipitation in Southern Asia. As for regional temperature extremes, multi-model average changes in heavy precipitation display an almost linear scaling with the changes in global mean temperature[26] (roughly consistent with the Clausius–Clapeyron relationship in that region), and thus could be used to provide regional decision-makers with suitable allowable targets for global emissions.

Moreover, it should be noted that, while the ensemble mean response is robust across models and emissions scenarios for heavy precipitation events, individual model projections can diverge strongly from this mean response (in the region investigated as well as in other locations; see Supplementary Figs 6 and 7). This is obvious from the red-shaded uncertainty range in Fig. 4b and Supplementary Figs 6 and 7, which is substantially larger in most regions than for temperature extremes. This behaviour is due to the increasing relevance of internal climate variability at the regional-to-local scale[27], higher model uncertainty, and the spatially more heterogeneous nature of precipitation extremes compared to temperature extremes.

Despite the associated uncertainty, analyses such as the ones in Figs 3 and 4b provide more information to regional stakeholders than a global mean temperature target, since they quantitatively and directly highlight the expected regional response (in extremes and other variables than temperature), with attendant lower and upper bounds. Such estimates are thus more useful when assessing associated impacts, and engaging with policymakers.

Limitations of approach

Some caveats are attached to the above findings, most importantly:

(1) Scaling relationships are only meaningful as long as associated uncertainties in projections are kept within reasonable bounds. This

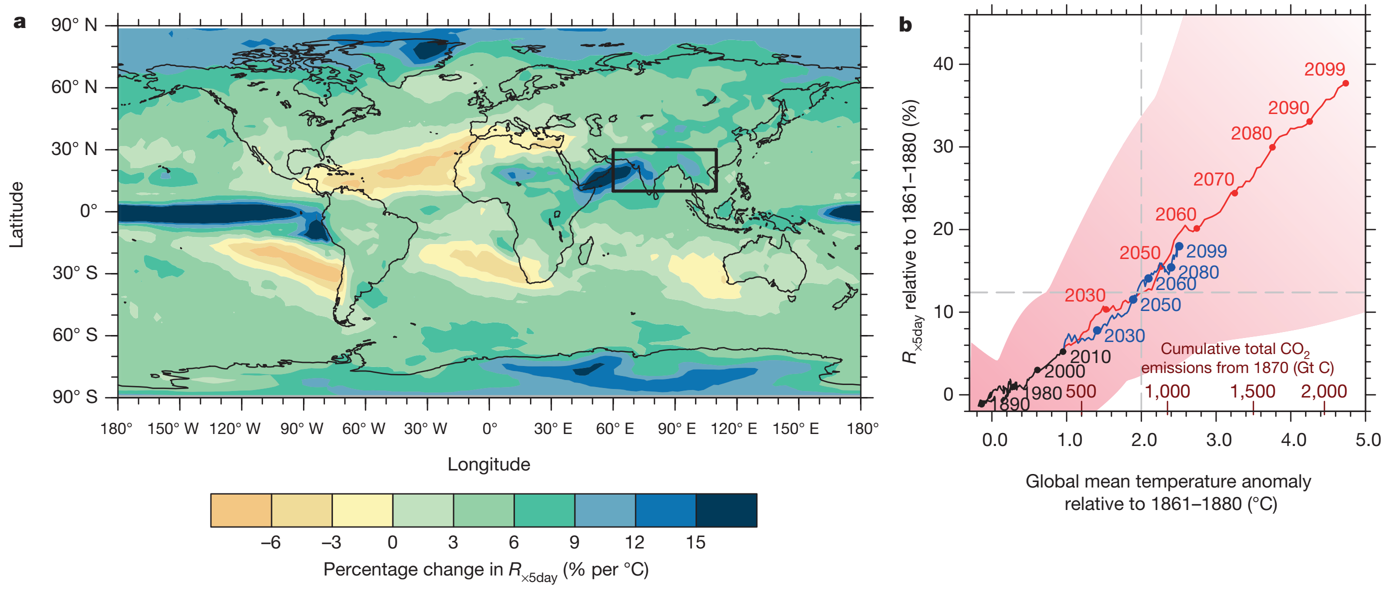

Figure 4 | Scaling of 5-day heavy precipitation events with global mean temperature changes, with associated global cumulative CO_2 emissions targets. See Box 1 for details on the underlying analysis. **a**, Map of the ratio of percentage changes in heavy precipitation events (annual maximum consecutive 5-day precipitation, R_{x5day}) with changes in global mean temperature ΔT_{glob} for the RCP8.5 scenario simulations (ensemble average ratio $\Delta R_{x5day}/\Delta T_{glob}$). ΔT_{glob} and ΔR_{x5day} were calculated from each model run as the difference between the average of the first (1861–1880) and last (2080–2099) 20-year time slices. **b**, Scaling of percentage changes in R_{x5day} in Southern Asia (10° to 30° N, 60° to 110° E; see outlined box in **a**) with global mean temperature changes and cumulative global CO_2 emissions. The solid black line denotes the ensemble average in the historical runs until 2010 (combined with RCP8.5 for 2006–2010), and the solid red (blue) line denotes the ensemble average of the future projections following the RCP8.5 (RCP4.5) scenario simulations, based on 25 (22) model simulations (see Supplementary Table 1). The red shaded area indicates the total range (minimum to maximum value) for all considered simulations and experiments. Grey dashed lines show the percentage change in R_{x5day} or CO_2 emissions associated with a 2 °C increase in global mean temperature. Only land grid cells were used for calculating the regional R_{x5day} average.

is the case for some climate features, such as temperature extremes or heavy precipitation events[1,7], but for others, such as droughts, tropical cyclones or storms, uncertainties are generally larger than the climate change signals[1,7,28]. In such situations, no emissions target (or implied global temperature target) may currently be set on the basis of avoiding changes in these extremes.

(2) Some changes in the climate system may be abrupt (that is, nonlinearly related to emissions) owing to tipping points[29]. Again, uncertainties in the associated projections are very large, especially under high-end emissions. Owing to the nonlinearity of the respective features, relationships could be difficult to derive (although some features have been assessed, such as the dependency of mean sea level rise on global mean temperature increase at equilibrium[30] and the probability of abrupt changes for given global temperature thresholds[31]).

(3) Although we find a relatively robust scaling of regional temperature and precipitation extremes with ΔT_{glob}, we can expect that the reliability of scaling will diminish at increasingly smaller scales owing to internal climate variability[27,32] and a larger contribution of local processes to the response (including by local land surface and human forcing, see point (5) below).

(4) It is likely that climate models share common biases for some regional climate phenomena[33–36]. In this case, scaling features could be derived, but would be erroneous, an issue that would need to be examined with careful model evaluation[37,38] contingent on the availability of appropriate observations.

(5) The relationship between changes in regional climate and ΔT_{glob} would be expected to alter in the presence of time-varying local forcing by, for example, aerosols[39], land-use and land-cover change[40–42], urban development[43], or human water use[44,45]. These effects are likely to be important on the local scale, but less so for the larger regions considered here (see Figs 3 and 4 and the regions from the IPCC Special Report on Extremes[7] in the Supplementary Information).

(6) The ranges in Figs 3 and 4b reflect the uncertainty in the scaling of the regional quantities with ΔT_{glob}, but do not include uncertainties associated with the scaling of ΔT_{glob} with the cumulative CO_2 emissions (Fig. 1). This additional uncertainty source is also relevant for the decision process when assessing regional climate targets (as is the case for climate targets based on the global mean temperature). For a given impact threshold, the uncertainty in the cumulative carbon would be wider, and as a consequence the cumulative carbon budget would be smaller if the desire were to avoid the impact with high probability[5]. More in-depth analyses of the CMIP5 archive would help determine the total uncertainty range when directly relating imposed greenhouse gas forcing to simulated regional extremes.

Using regional targets in decision making

We focus here on regional changes because local stakeholders and decision-makers are more likely to be able to relate to them than to global mean temperature changes. However, we stress that this does not imply that countries should only be concerned about climate changes affecting them directly in a geographical sense. Indeed, because of globalization, major climate disruptions in some countries can strongly affect others, for instance owing to political unrest, migration, impacts on global food production, supply chains and trade[23,46,47]. Even when not directly affected by such changes, individual countries are more likely to understand the implications of climate targets for other parties if they can more readily quantify the specific implications for different regions. This could also help pave the way to solutions that integrate both climate mitigation and adaptation within climate negotiations, by incorporating the costs of impacts into negotiations. Global temperature targets that differ from and are possibly lower than 2 °C (such as 1.5 °C)[48–50] may thus well be desirable on the basis of inferred regional climate targets.

Linking cumulative CO_2 emission targets to regional consequences, such as changing climate extremes, would be of particular benefit for political decision-making, both in the context of climate negotiations and of adaptation. We stress that the quantification of regional targets will not necessarily imply that all involved parties will agree on a suitable (and common) cumulative global CO_2 emission target. However, regional information can help in the development of solutions and in communication with the public. Similarly robust regional scaling might be expected for other features of the climate system beside those considered here[51,52], and could be explored for impact-based simulations[53–55]. Indeed, such relationships can be determined for any regional or impact-relevant climate feature that scales robustly with changes in global mean temperature (or is at least monotonically related to it), and that is not associated with larger uncertainty ranges or biases in current climate models.

In view of the inherent model uncertainty and to avoid possible risks associated with the indiscriminate use of such information, we recommend that IPCC-calibrated language be applied when assessing the confidence of any such derived relationships, with only situations of 'high confidence' justifying the derivation of quantitative estimates[7]. In addition to the requirement of levels of high confidence, a high signal-to-noise model ratio (traditionally referred to in 'likelihood' terms in the language[7] of the IPCC) is a prerequisite for deriving meaningful allowable CO_2 emissions ranges. Furthermore, any assessment of projected changes in climate risks and impacts also needs to consider the contributions of changes in vulnerability and exposure of human and natural systems to those climate hazards[25]. Bearing in mind these requirements, quantitative tools for decision-making that relate regional (or even country-scale) impacts to global CO_2 emissions targets could be one way of advancing climate negotiations by exposing what is at stake in a more local manner.

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This article provides time series of climate extreme indices in CMIP5 projections, which have been used as the basis for the present analyses.

Supplementary Information is available in the online version of the paper.

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