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

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Global temperature targets, such as the widely accepted 2°C limit, may fail to communicate the urgency of reducing CO_2 emissions. Translation of CO_2 emissions into regional- and impact-related climate targets could be more powerful because they resonate better with 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 IPCC 5th Assessment Report included a figure in the Summary for Policymakers (SPM) of the Working Group 1 (WG1) 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 that every ton of CO_2 contributes about the same amount of global-scale warming, no matter when it is emitted, that any target for the stabilization of ΔT_{glob} implies a finite CO_2 budget or quota that can be emitted, and that global net emissions at some point need to be zero[2,3,4,5,6].

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 with the climate system response. Yet, another obstacle remains the actual 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 of – as well as make the case for – quantitatively relating global-scale 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.

Global vs regional climate targets

Our experience shows that the implications of projected global mean temperature changes tend to be underestimated at regional (and country) level, because these are much smaller than the expected changes in regional temperature mean and extremes over most land areas[7,8,9,10]. The limitations of focusing on global mean temperature as a measure of climate change has, for instance, been evidenced by the public debate about the recent "hiatus". This has fixated attention on changes in ΔT_{glob} instead of the discernible worldwide impacts of the continued increases in radiative forcing[1,11,12,13,14].

As illustrated in Fig. 2, a 2°C target for ΔT_{glob} implies increases in both warm and cold temperature extremes 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 (e.g. from decreases in soil moisture, snow, or ice[7,8,17,18,19,20]), 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 ca. 5.5° 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 ca. 1.5 and 2.5 to 3 (Supplementary Figure S1), 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 (Figs. 2a,b). Subjectively, such regional changes in extremes may better convey the consequences of crossing the respective cumulative CO_2 emissions threshold, compared to the associated change in ΔT_{glob} (2°C), which appears 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. While the IPCC Synthesis Report[21] has shown cumulative CO_2 emissions alongside the famous "reasons for concerns", the employed bars of various degrees of red only provide a qualitative assessment. We highlight hereafter 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.

Relating extremes to global CO_2 emissions

We thus assess the extent to which the implications of Fig. SPM.10 (Fig. 1) from the IPCC AR5 WG1 SPM[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 (Mediterranean basin, contiguous U.S., and Brazil for annual maximum daytime temperatures; the Arctic for annual minimum nighttime temperatures; for other regions, see Supplementary Figures S4 and S5). The analyses display the scaling of the considered regional changes 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 Figures S4 and S5). 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, TXx) 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 600 GtC for a 2°C warming of hot extremes in the Mediterranean region compared to ca. 750-800 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 U.S. and Brazil (Figs. 3b,c) by ΔT_{glob} provides qualitatively similar results, but highlights greater uncertainty of projections in these regions. In the contiguous U.S., although the expected value of scaling with ΔT_{glob} is greater than 1, the uncertainty range bounds the 1:1 line. Conversely, the regional response in 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 daily temperatures (TNn) in the Arctic (Fig. 3d) conveys a very stark message. In this case, as seen in Fig. 2, the regional response is ca. 2.5-3 times greater for 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 year 2000 for TNn in the Arctic, while it is projected to be reached by ca. 2030 for TXx in the Mediterranean, Brazil and the contiguous U.S., and only by the mid-2040s for the global mean temperature, under the business-as-usual (RCP8.5) emissions scenario.

While we 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] (e.g. changes in heavy precipitation events, see hereafter). 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 global mean temperature[26] (roughly consistent with the Clausius-Clapeyron relationship in that region), and thus could be used to inform regional decision-makers on suitable allowable targets for global emissions. Moreover, it should be noted that, while the ensemble mean response is robust across models and emissions scenarios, individual model projections can diverge strongly from this mean response (in the investigated region as well as in other locations, see Supplementary Figures S6 and S7). This point is denoted by the red-shaded uncertainty range, which, in most regions, is substantially larger than for temperature extremes. This behaviour is due to the increasing relevance of internal climate variability at 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 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 based on avoiding changes in these extremes.
2. Some changes in the climate system may be abrupt (i.e. non-linearly related to emissions) due to tipping points[29]. Again, uncertainties in the associated projections are very large, especially under high-end emissions. Due to the non-linearity 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-scale temperature and precipitation extremes with ΔT_{glob}, we can expect that the reliability of scaling will diminish at increasingly smaller scales due 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.).
4. It is likely that climate models share common biases for some regional climate phenomena[33,34,35,36]. 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[40,41,42], urban development[43], or human water use[44,45]. These effects are likely to play an important role on local scale, but less for the larger regions considered here (Figs. 3 and 4 and regions from the IPCC Special Report on Extremes (SREX[7]) in Supplementary Information).
6. The ranges in Fig. 3 and Fig. 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 due to political unrest, migration, impacts on global food production, supply chains and trade[23,46,47]. Even when not directly affected by given changes, individual countries are more likely to understand the implications of respective climate targets for other parties if they can more readily quantify their 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 avoided costs of impacts in negotiations when discussing the costs of mitigation. In this context, it is possible that different (and possibly lower global targets[48,49,50]) than 2°C may well be desirable.

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 adaptation. We stress that the quantification of regional targets will not necessarily imply that involved parties will agree on the suitable (and common) cumulative global CO_2 emission target. However, this information can help in the development of solutions and in the 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[53,54,55]. Indeed, such relationships can be determined for any regional and/or impact-relevant climatic feature that scales robustly with changes in global mean temperature (or is at least monotonically related to it), and which is not associated with larger uncertainty ranges or biases in current climate models.

In view of the inherent model uncertainty and in order 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 derivation of quantitative estimates[7]. In addition to the requirement of *high confidence* levels, high signal to (model) noise ratio (traditionally referred to in *likelihood* terms in the IPCC language[7]) 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 more locally exposing what is at stake.

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

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

Acknowledgements

S.I.S. acknowledges the ERC DROUGHT-HEAT project funded by the European Community's Seventh Framework Programme (grant agreement FP7-IDEAS-ERC-617518). A.J.P. and M.G.D. were supported by the Australian Research Council (ARC) Centre of Excellence for Climate System Science grant CE110001028. M.G.D. was also supported by ARC Grant DE150100456. This work contributes to the World Climate Research Programme (WCRP) Grand Challenge on Extremes. We acknowledge the WCRP Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modelling groups for producing and making available their model output. For CMIP the US Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. We are grateful to Nicola Maher for help with processing CMIP5 data. The climate extremes indices calculated for the different CMIP5 runs were obtained from the Environment Canada CLIMDEX website http://cccma.ec.gc.ca/data/climdex/.

Author contributions

S.I.S., M.G.D. and A.J.P. designed the study, following an initial discussion between S.I.S, A.J.P. and R.K. S.I.S. coordinated the conception and writing of the article. M.G.D.

performed the analyses. R.L.W. contributed to the interpretation of regional impacts. All authors commented on the manuscript and analyses.

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Figure legends

Figure 1. Global mean surface temperature increase as a function of cumulative total global CO_2 emissions. This figure from the IPCC WG1 SPM[1] (Fig. SPM.10) was derived from various lines of evidence. Model results over the historical period (1860 to 2010) are indicated in black. The coloured plume illustrates the multi-model spread over the four RCP scenarios. The multi-model mean and range simulated by CMIP5 models, forced by a CO_2 increase of 1% per year is given by the thin black line and grey area. For a specific 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 relative to 1870.

Figure 2. **Extreme (and mean) temperature changes associated with 2°C target**. The figure displays the local changes in (a) hottest daytime temperature (TXx), (b) annual coldest nighttime temperature (TNn), (c) and mean temperature (Tmean) associated with a global warming of 2°C. The analysis is based on RCP8.5 scenario simulations (ensemble average year: 2044). The respective scaling expressed as ratio of global mean temperature increase is provided in Supplementary Figure S1. Note that very similar results are obtained with the RCP4.5 scenario simulations (Fig. 3 and Supplementary Figures S2 and S3). Figs 2a and 2b also display the outlines of the regions analysed in Fig. 3.

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 (TXx) in (a) the Mediterranean region (30:45N, 10W:45E), (b) the contiguous U.S. (25:50N, 125W:67W), and (c) Brazil (30S:0N, 65W:50W), and for the annual minimum nighttime temperature (TNn) in (d) the Arctic (65:90N, 180W:180E). The four analysed regions are indicated in Figs. 2a and 2b. 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. The red shaded area indicates the total range (minimum to maximum value) between all considered simulations and experiments. The dashed black line shows the 1:1-line. Grey dashed lines show the temperatures / CO_2 emissions associated with 2°C increases in global mean and regional extreme temperatures, respectively. Note the different vertical axis for TXx and TNn. Only land grid cells were used for calculating the regional TXx and TNn averages.

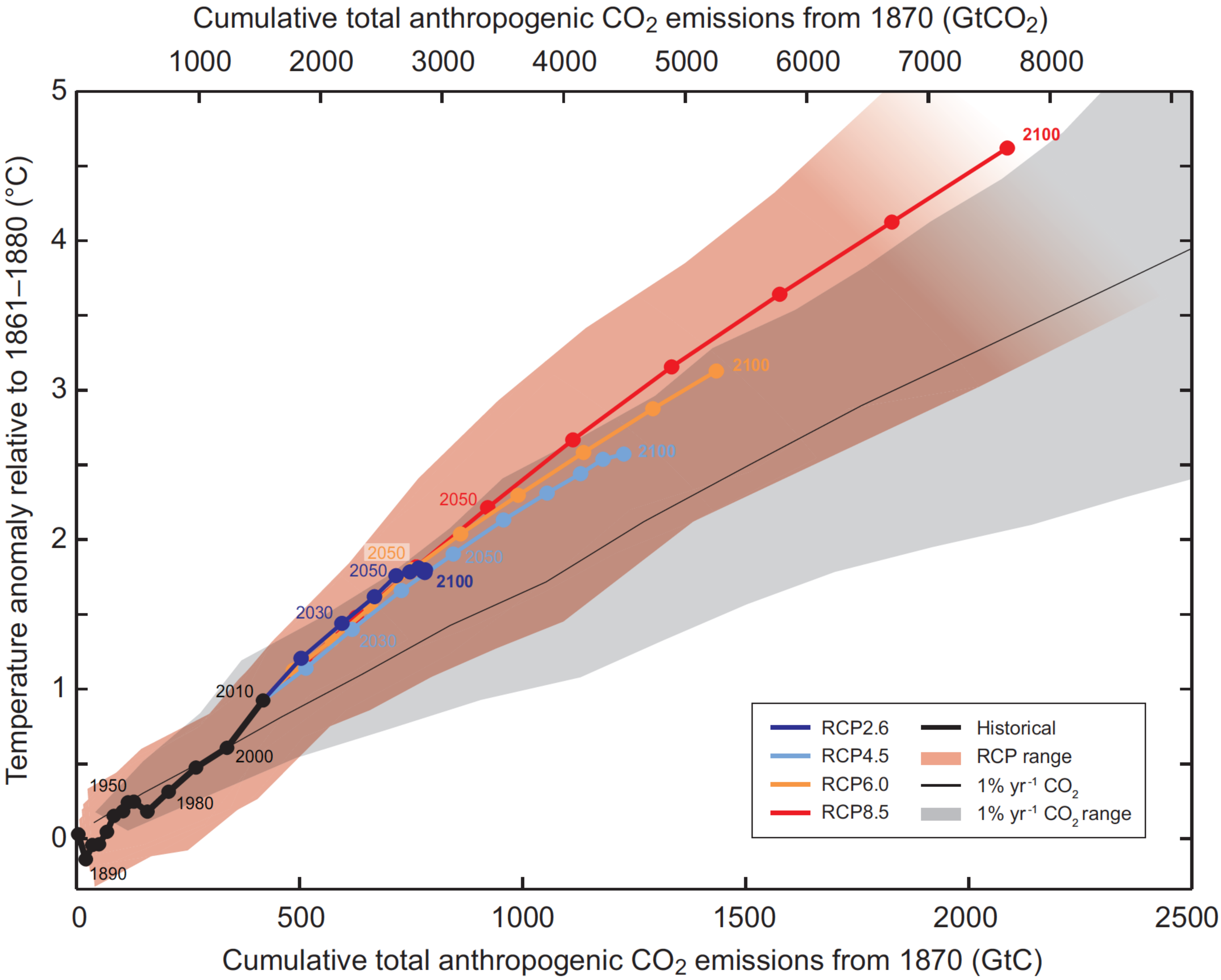
Figure 4. Scaling of 5-day heavy precipitation events with global mean temperature changes, with associated global cumulative CO_2 emissions targets. See Box 1 for details on the underlying analysis. (a) Map of ratio of percentage changes in heavy precipitation events (annual maximum consecutive 5-day precipitation, Rx5day) with changes in global mean temperature for the RCP8.5 scenario simulations (ensemble

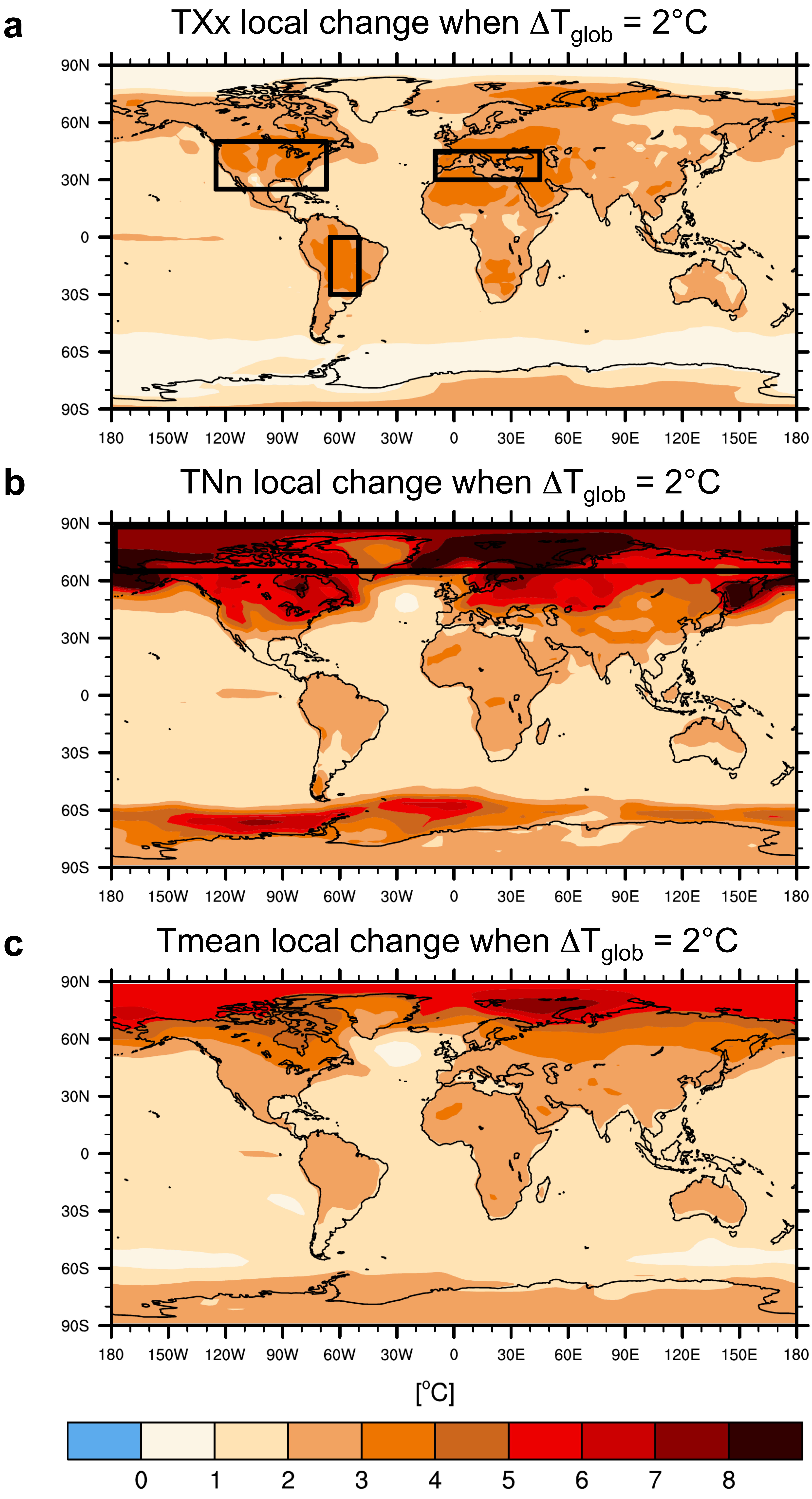
average ratio $\Delta Rx5day/\Delta T_{glob}$). ΔT_{glob} and $\Delta Rx5day$ were calculated from each model run as the difference between the average of the first (1861-1880) and last (2080-2099) 20-year time slices. (b) Scaling of percentage changes in Rx5day in Southern Asia (10:30N, 60:110E; see outlined box on Fig. 4a) 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. The red shaded area indicates the total range (minimum to maximum value) between all considered simulations and experiments. Grey dashed lines show the percentage change in Rx5day / CO_2 emissions associated with a 2°C increase in global mean temperature. Only land grid cells were used for calculating the regional Rx5day average.

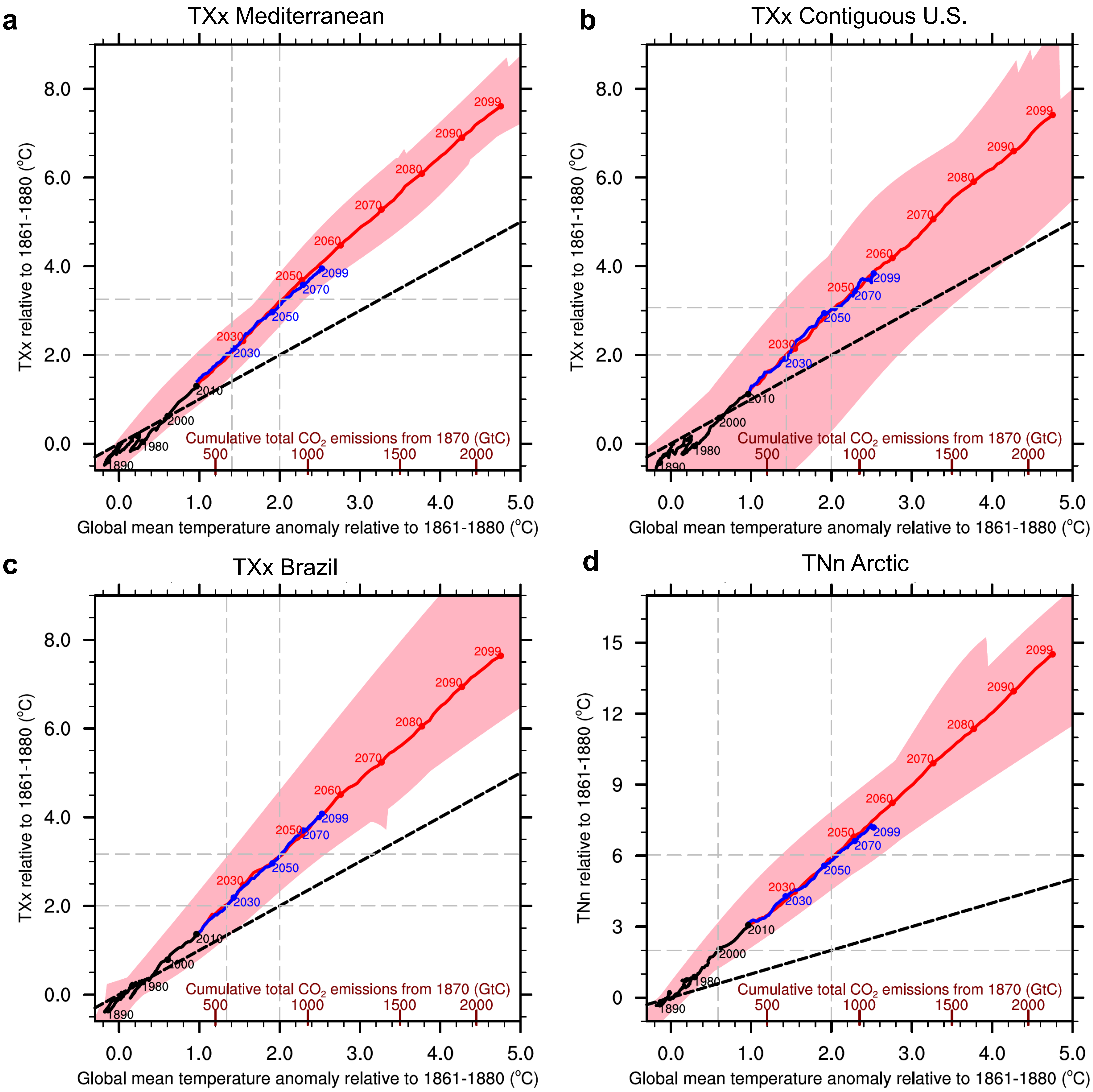
Box 1: Calculating the relationships among regional extremes, global means, and cumulative emissions.

We use output from the climate model simulations contributing to the Coupled Model Intercomparison Project Phase 5 (CMIP5)[56]. Here we present results for climate extreme indices representative of the hottest day (TXx) and coldest night (TNn) of the year, as well as the annual maximum consecutive 5-day precipitation total (Rx5day). Climate extremes 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 21st 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 indices fields were remapped to a common 2.5°x2.5° 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 extremes indices changes (e.g. Figures 3, 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 10-year windows, and moving average values were assigned to the last year of each window period (i.e., 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 10-year averages were also used to produce maps of local changes for a global mean temperature increase of 2°C (e.g. Figure 2). The indicated cumulative CO_2 emissions corresponding to different global mean temperature increases (red tics on horizontal axis in Figures 3 and 4b) were approximated from the RCP8.5 ensemble average in Figure 1 (single values were assigned to each of the chosen tic marks). This means, 500 GtC at approximately 1.2°C, 1000 GtC at 2.35°C, 1500 GtC at 3.5°C, and 2000 GtC at 4.45°C. Respective analyses regarding the scaling of extreme temperatures and precipitation in all 26 regions of the IPCC Special Report on Extremes (SREX)[7] and the global land are provided in the Supplementary Information.


Cumulative total anthropogenic CO_2 emissions from 1870 ($GtCO_2$)
1000
2000
3000
4000
5000
6000
7000
8000
Temperature anomaly relative to 1861–1880 (°C)
5
4
3
2
1
0
2100
2100
2100
2050
2050
2050
2050
2100
2030
2030
2010
2000
1950
1980
1890
RCP2.6
RCP4.5
RCP6.0
RCP8.5
Historical
RCP range
1% yr^{-1} CO_2
1% yr^{-1} CO_2 range
0
500
1000
1500
2000
2500
Cumulative total anthropogenic CO_2 emissions from 1870 (GtC)


a
TXx local change when ΔT_glob = 2°C
b
TNn local change when ΔT_glob = 2°C
c
Tmean local change when ΔT_glob = 2°C
90N
60N
30N
0
30S
60S
90S
180
150W
120W
90W
60W
30W
0
30E
60E
90E
120E
150E
180
[°C]
0
1
2
3
4
5
6
7
8


a
TXx Mediterranean
b
TXx Contiguous U.S.
c
TXx Brazil
d
TNn Arctic
TXx relative to 1861-1880 (°C)
TNn relative to 1861-1880 (°C)
0.0
2.0
4.0
6.0
8.0
0
3
6
9
12
15
Global mean temperature anomaly relative to 1861-1880 (°C)
0.0
1.0
2.0
3.0
4.0
5.0
Cumulative total CO2 emissions from 1870 (GtC)
500
1000
1500
2000
1890
1980
2000
2010
2030
2050
2060
2070
2080
2090
2099


a
Rx5day local scaling with ΔT_{glob}
90N
60N
30N
0
30S
60S
90S
180
150W
120W
90W
60W
30W
0
30E
60E
90E
120E
150E
180
[%/°C]
-6
-3
0
3
6
9
12
15
b
Rx5day Southern Asia
Rx5day relative to 1861-1880 (%)
40
30
20
10
0
2099
2090
2080
2070
2060
2050
2030
2099
2080
2060
2050
2030
2010
2000
1980
1890
Cumulative total CO_2 emissions from 1870 (GtC)
500
1000
1500
2000
0.0
1.0
2.0
3.0
4.0
5.0
Global mean temperature anomaly relative to 1861-1880 (°C)