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Allowable CO₂ 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 CO₂ emissions. Translation of CO₂ 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 CO₂ 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 CO₂ emissions from 1870 onwards¹ (Fig. 1). This figure is compelling

because it shows a clear linear relationship between cumulative CO₂ emissions and a measure of the global climate response. The obvious consequences are that every ton of CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ emissions targets to changes in regional extremes or other impact-relevant quantities in addition to changes in global mean temperature. While the IPCC Synthesis Report²¹ has shown cumulative CO₂ 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 CO₂ emissions

We thus assess the extent to which the implications of Fig. SPM.10 (Fig. 1) from the IPCC AR5 WG1 SPM¹ can be expanded to relate cumulative global emissions in CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 impacts²², 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 CO₂ 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 CO₂ 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 temperature²⁶ (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 scale²⁷, 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 points²⁹. 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 equilibrium³⁰ and the probability of abrupt changes for given global temperature thresholds³¹).

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, aerosols³⁹, land use and land cover change^{40,41,42}, urban development⁴³, 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 (SREX⁷) 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 CO₂ 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

184 cumulative carbon would be wider, and as a consequence the cumulative carbon
185 budget would be smaller if the desire were to avoid the impact with high
186 probability⁵. More in-depth analyses of the CMIP5 archive would help determine
187 the total uncertainty range when directly relating imposed greenhouse gas forcing
188 to simulated regional extremes.

189

190 **Using regional targets in decision making**

191 We focus here on regional changes because local stakeholders and decision-makers are
192 more likely to be able to relate to them than to global mean temperature changes.
193 However, we stress that this does not imply that countries should only be concerned
194 about climate changes affecting them directly in a geographical sense. Indeed, because of
195 globalization, major climate disruptions in some countries can strongly affect others, for
196 instance due to political unrest, migration, impacts on global food production, supply
197 chains and trade^{23,46,47}. Even when not directly affected by given changes, individual
198 countries are more likely to understand the implications of respective climate targets for
199 other parties if they can more readily quantify their implications for different regions.
200 This could also help pave the way to solutions that integrate both climate mitigation and
201 adaptation within climate negotiations, by incorporating the avoided costs of impacts in
202 negotiations when discussing the costs of mitigation. In this context, it is possible that
203 different (and possibly lower global targets^{48,49,50}) than 2°C may well be desirable.

204

205 Linking cumulative CO₂ emission targets to regional consequences, such as changing
206 climate extremes, would be of particular benefit for political decision making, both in the

207 context of climate negotiations and adaptation. We stress that the quantification of
208 regional targets will not necessarily imply that involved parties will agree on the suitable
209 (and common) cumulative global CO₂ emission target. However, this information can
210 help in the development of solutions and in the communication with the public. Similarly
211 robust regional scaling might be expected for other features of the climate system beside
212 those considered here^{51,52}, and could be explored for impact-based simulations^{53,54,55}.
213 Indeed, such relationships can be determined for any regional and/or impact-relevant
214 climatic feature that scales robustly with changes in global mean temperature (or is at
215 least monotonically related to it), and which is not associated with larger uncertainty
216 ranges or biases in current climate models.

217

218 In view of the inherent model uncertainty and in order to avoid possible risks associated
219 with the indiscriminate use of such information, we recommend that IPCC calibrated
220 language be applied when assessing the *confidence* of any such derived relationships,
221 with only situations of *high confidence* justifying derivation of quantitative estimates⁷. In
222 addition to the requirement of *high confidence* levels, high signal to (model) noise ratio
223 (traditionally referred to in *likelihood* terms in the IPCC language⁷) is a prerequisite for
224 deriving meaningful allowable CO₂ emissions ranges. Furthermore, any assessment of
225 projected changes in climate risks and impacts also needs to consider the contributions of
226 changes in vulnerability and exposure of human and natural systems to those climate
227 hazards²⁵. Bearing in mind these requirements, quantitative tools for decision making that
228 relate regional (or even country-scale) impacts to global CO₂ emissions targets could be
229 one way of advancing climate negotiations by more locally exposing what is at stake.

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416

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418

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435 **Author contributions**

436 S.I.S., M.G.D. and A.J.P. designed the study, following an initial discussion between
437 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 CO₂ emissions. This figure from the IPCC WG1 SPM¹ (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 CO₂ increase of 1% per year is given by the thin black line and grey area. For a specific amount of cumulative CO₂ emissions, the 1% per year CO₂ simulations exhibit less warming than those driven by RCPs, which include additional non-CO₂ 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 CO₂ 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 / CO₂ 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 CO₂ 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

493 average ratio $\Delta Rx5day / \Delta T_{glob}$). ΔT_{glob} and $\Delta Rx5day$ were calculated from each model run
494 as the difference between the average of the first (1861-1880) and last (2080-2099) 20-
495 year time slices. (b) Scaling of percentage changes in Rx5day in Southern Asia (10:30N,
496 60:110E; see outlined box on Fig. 4a) with global mean temperature changes and
497 cumulative global CO₂ emissions. The solid black line denotes the ensemble average in
498 the historical runs until 2010 (combined with RCP8.5 for 2006-2010) and the solid red
499 (blue) line denotes the ensemble average of the future projections following the RCP8.5
500 (RCP4.5) scenario simulations. The red shaded area indicates the total range (minimum
501 to maximum value) between all considered simulations and experiments. Grey dashed
502 lines show the percentage change in Rx5day / CO₂ emissions associated with a 2°C
503 increase in global mean temperature. Only land grid cells were used for calculating the
504 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 indices⁵⁷ were calculated for the historical simulations⁵⁸ and future projections⁵⁹ 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 CO₂ emissions corresponding to different global mean temperature increases (red ticks 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 tick 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.

a TXx local change when $\Delta T_{\text{glob}} = 2^{\circ}\text{C}$

b TNn local change when $\Delta T_{\text{glob}} = 2^{\circ}\text{C}$

c Tmean local change when $\Delta T_{\text{glob}} = 2^{\circ}\text{C}$

[°C]

a**TXx Mediterranean** **b****TXx Contiguous U.S.** **c****TXx Brazil** **d****TNn Arctic**

aRx5day local scaling with ΔT_{glob} **b**

Rx5day Southern Asia