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Emissions and Emergence: a new index comparing relative contributions to climate change with relative climatic consequences

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Abstract

We develop a new index which maps relative climate change contributions to relative emergent impacts of climate change. The index compares cumulative emissions data with patterns of signal-to-noise ratios (S/N) in regional temperature (Frame et al., 2017). The latter act as a proxy for a range of local climate impacts, so emergent patterns of this ratio provide an informative way of summarising the regional disparities of climate change impacts. Here we combine these with measures of regional/national contributions to climate change to develop an "emissions-emergence index" (EEI) linking regions'/countries' contributions to climate change with the emergent regional impacts of climate change. The EEI is a simple but robust indicator which captures relative contributions to and regional impacts from climate change. We demonstrate the applicability of the EEI both for discussions of historical contributions and impacts, and for considering future relative contributions and impacts, and examine its utility in the context of existing related metrics. Finally, we show how future emissions pathways can either imply a growth or reduction of regional climate change inequalities depending on the type and compositions of socioeconomic development strategies.

Introduction

Many indices characterising aspects of climate change have been developed; most have attempted to address mitigation responsibilities by developing some line-of-sight regarding *contributions* to climate change, usually by consideration of past emissions (Agarwal and Narain, 1991 , Heede, 2014) or through some allocation structure applied to future emissions (den Elzen et al., 2005, Botzen et al., 2008). In general, indices summarising the differential *impacts* of climate change have received a less attention, though in the last few years there has been increased attention to regional differences in the physical manifestation of future climate change. This is now becoming recognised as an emerging issue of climate equity and justice (Diffenbaugh and Scherer, 2011, Althor et al., 2016, Davis and Diffenbaugh, 2016, Green, 2016, Diffenbaugh and Burke, 2019) .

In this paper we develop a new index which aims to capture regional variations both in contributions to climate change, and in the expected impacts. In doing so, the index captures more of the causal chain that characterises climate change (see Figure 1). Our approach compares emissions – a good proxy for contributions – against impacts of climate change as captured by emergent signal-to-noise (S/N) ratios in annual mean near-surface air temperature. The latter are a reasonable proxy for many important impacts. Figure 1 illustrates conceptually the emissions-emergence index as it spans the cause-effect chain from socioeconomic drivers to climate damages. It identifies which regions (or countries) are polluting disproportionately compared their projected experience of climate changes.

The index can be constructed in backward-looking or forward-looking modes. In the backward-looking mode, issues of current impacts can be assessed against contributions to date. In forward-looking mode, comparisons can be made between expected (regional) emissions under future emissions scenarios and expected emergent impacts. In the following examples we use the five Shared Socioeconomic pathways (SSPs) (Riahi et al., 2017) and alongside emergence patterns obtained from scenarios driven by the Representative Concentration Pathways (RCPs) (Meinshausen et al., 2011) to illustrate the index's forward-looking properties, and then we use historical contributions (to date) and patterns of emergence to show differential contributions and impacts at a national level. Finally, we discuss the utility of EEI in the context of existing related metrics of climate change. We use the SSPs as driver of emissions, as these offer broad-based, regional storylines about regional socioeconomic development and associated emissions. We use the RCPs to drive the emergence patterns, since these drive global patterns of emerging climate change. The SSPs and RCPs were developed via a "parallel process" (Moss et al., 2010), such that an over-arching "scenario matrix architecture" sits over both processes. Readers should note that not all SSPs are compatible with all RCPs: in particular high fossil fuel SSPs are not compatible with low concentration pathways, and low fossil fuel trajectories are not compatible with high concentration pathways. Readers should consult (Riahi et al., 2017) for details.

Inputs to the index

Contributions

Projected population and greenhouse gas emissions have been taken from all available Integrated Assessment Models (IAMs) for the five Shared Socioeconomic pathways (SSPs). Projected estimates of CO_2, CH_4 and N_2O emissions and population are available for each of the five regions of interest for each decade from 2020 to 2090, alongside observed totals for the years between 1990 and 2010.

To better estimate the climate effects of a portfolio of different greenhouse gases, in preference to the more customary global warming potentials, GWP_{100}, we use GWP* (Allen et al., 2016), since the latter provide a much better mapping between an emissions portfolio and surface temperature impacts (Allen et al., 2018). (The "star" in GWP* is a reflection that GWP* is not a "new" metric; it is in fact GWP_{100} used in a way that gives a better mapping between emissions and temperature change.) GWP*-weighted annual emissions rates are calculated using a GWP_{100} weighted sum (IPCC-AR5 values) of the annual CO_2 emissions rate, the annual N_2O emissions rate, and the rate of change in the annual CH_4 emissions rate multiplied by a time horizon factor of 100 years. We calculate the rate of change in the annual CH_4 emissions rate using the difference in annual emissions rate relative to those twenty years previously to reflect the timescales of CH_4's impact on global temperature.

CO_2e^* emissions were then calculated for each of the nine decades between 2010 and 2090. The first 20 years of data (1990-2010) is used to calculate GWP*-based estimates of CO_{2*}-equivalence. These projections of population and CO_2e^* emissions are then summed over the nine decades for each region (respectively denoted as P_i and C_i) and for all five regions together (respectively denoted as P_G and C_G).

There are numerous ways of comparing relative contributions to climate change (Skeie et al., 2017), depending on which sectors and emission components are considered, which indicator of climate change is used, which time periods are chosen for emission and evaluation or responses and so on. Though many reasonable combinations are possible, some of these choices make more physical or policy sense than others. For instance, accurately evaluating the role of long-lived and short-lived pollutants is important for a scientifically-accurate estimate of contribution to long-term warming (Allen et al., 2018). Also important are choices around baselines and reference periods, where different choices seem reasonable (Millar et al., 2017, Schurer et al., 2018, Millar et al., 2018); and while long baselines are conceptually attractive, uncertainty increases as we move backward in time, and it is not obvious how to treat the pre-independence emissions of previously colonized societies. People may disagree over some of these choices, but it is clear that some sets of choices more coherently map to the temperature target-based climate negotiation framework than others (Skeie et al., 2017). Additional innovations regarding the way contributions are assessed are left for future work, but may be important for some potential uses of the index (see *the value of climate indices* below).

Emergent impacts

Following previously published methods (Hawkins and Sutton, 2012, Frame et al., 2017), we calculate S/N for near-surface air temperatures, using the CMIP5 simulations for the 25 models that ran each of RCP2.6, 4.5 and 8.5 scenarios, and presented relative to a baseline climate of 1986-2005 (see also Supplementary Information). The `signal' is diagnosed by calculating the global mean surface air temperature (SAT) and fitting a fourth-order polynomial (GMST) across the period 1950-2100. SATs at each gridpoint are regressed against this smoothed GMST to derive a smoothed gridpoint signal that is proportional to the global mean. The 1986-2005 mean is then removed from the smoothed gridpoint data to produce the change in temperature (S). The N term is the standard deviation of annual mean temperatures in the pre-industrial control simulations at each grid point. The S/N is calculated for each model independently.

To calculate normalised S/N ratios for each of the five regions explicitly represented in the SSPs, and presented in figure 2, we first aggregate, for each model, S/N values averaged over the period 2086-95 for those grid cells which lie within the national boundaries of each of the five regions. We then calculate the mean S/N value for each aggregated region, and divide it by the mean S/N for all five regions aggregated together.

Previous studies investigating the increasing frequency and severity of extreme heat have shown similar spatial patterns of results to those represented by the S/N calculations used here. Examples have been demonstrated across annual (Diffenbaugh and Scherer, 2011, Mahlstein et al., 2011, Lehner and Stocker, 2015, Hawkins and Sutton, 2012), seasonal (Davis and Diffenbaugh, 2016, Mahlstein et al., 2011, Anderson, 2012, Anderson, 2011, Mueller et al., 2016), monthly (Mueller et al., 2016, Sippel et al., 2015, Coumou and Robinson, 2013) and daily (Fischer and Knutti, 2015, Fischer et al., 2014, Fischer et al., 2013, Pfahl et al., 2017, Luke J. Harrington et al., 2016, Andrew et al., 2015, Angélil et al., 2017, Angélil et al., 2016) timescales, as well as for a variety of heatwave metrics (Simone et al., 2016, Nicholas et al., 2017), with all studies sharing a common framing of climate change emergence in the context of pre-existing local variability.

This ranking of emergence correlates with several of the inputs to climate change vulnerability, as well as composite indicators captured by the ND-GAIN index (Notre Dame Global Adaptation Initiative) (Chen et al., 2015) (figure S29), so it seems reasonable to conclude that the emergence pattern reflects important climate change vulnerabilities. National averages can mask domestic heterogeneity, which may be significant(Green, 2016) – however, a positive correlation is found between the magnitude of sub-national income inequality (as measured with a Gini coefficient) and the severity of temperature emergence (figure S27b). In addition, a robust anti-correlation also exists between the magnitude of temperature emergence and metrics of both progress towards achieving the United Nations Sustainable Development Goals, and per capita national incomes (figure S28b and figure S26b respectively). The focus on patterns of temperature-driven emergence is supported by previous results which highlight the links between increasing heat extremes and reduced crop yields (Lobell and Burke, 2008, Battisti and Naylor, 2009, Asseng et al., 2014, Liu et al., 2016, Lobell et al., 2011), as well as impacts on ectotherms (Deutsch et al., 2008), even if slow-emerging impacts, like changes to ecosystem zones (Mahlstein et al., 2011) and more-frequent precipitation extremes (Andrew et al., 2015), will not necessarily be well captured with a focus on temperature S/N ratios. Thus the emergence pattern does not capture all important dimensions of impacts, but it does capture many important ones, and as characterisation of the emergence of other variables develops (e.g. (Rojas et al., 2019, Zhang et al., 2018)) we can look to include these in future revisions. Significantly, spatial patterns similar to the emergence patterns we identify are also evident when comparing the temperature emergence literature with other climate vulnerability indices (Althor et al., 2016).

Defining the emergence-emissions index

Attempts to index relative contributions usually stop at (functions of) shares of emissions or contributions to overall global mean warming or ocean heat content and sea level rise (den Elzen and Lucas, 2005), though they do sometimes consider regionalised impacts (Aamaas et al., 2017, Allen et al., 2016) and the heterogeneity of the responses. Indices of impacts, such as vulnerability indices, sometimes incorporate climate-relevant but not climate-specific information such as information about adaptive capacity, exposure to climate risks, or hazards, but they do not incorporate information regarding shares of emissions.

To quantify whether a region or country's fractional contribution to global GWP* weighted emissions correlates with their expected relative climate emergence, we define the emergence-emissions index for a country or grouping of countries, *i*, as follows:

$$EEI_i = \left[\frac{C_i P_G}{C_G P_i}\right] \div \frac{(S/N)_i}{(S/N)_G} \qquad (1)$$

where C_G, P_G and $(S/N)_G$ denote the cumulative GWP*-weighted GHG emissions (CO_2-e*), population and signal-to-noise ratio associated with the median citizen of the global population.

An EEI above (below) unity indicates the relative contribution of a country or group of countries to the causes of global mean warming is greater (less) than their relative future experience of climate emergence. The EEI goes beyond previous proposals to quantify historical carbon debts and credits (Gignac and Matthews, 2015, Fuglestvedt and Kallbekken, 2016, Otto et al., 2017, Skeie et al., 2017) (square bracket in Eq 1) to also incorporates expected spatial heterogeneity in the future climate change in a single index of climate change inequality. It therefore attempts to capture a quantity of substantial moral relevance: the extent to which those responsible for climate change experience the effects of climate change; and the extent to which those that experience the effects of climate change have contributed to the problem.

Future contributions and future impacts

Figure 2a shows the S/N ratios, normalised relative to the global average, for five regions and three RCP scenarios, with regional aggregations following those used in the SSPs. The different forcing scenarios lead to very overall different levels of climate change, both in terms of temperature change above pre-industrial, and in terms of the S/N ratios expected by the end of the century

(Frame et al., 2017). However, when the S/N ratios are normalised relative to the global average S/N for each of those scenarios, a very consistent order of relative emergence becomes apparent across all three scenarios: the Middle East and Africa experiences the largest relative climate change, followed by Latin America and Asia, with the Organisation of Economic Cooperation and Development (OECD) and reforming economies experiencing slower relative climate change under all scenarios. Despite substantial model uncertainty in the S/N ratios, this general sequence in which regions experience emergence of the climate signal above pre-existing variability faster than others remains strongly robust, and is largely insensitive to the choice of model (Table S1). This lack of scenario uncertainty (Hawkins and Sutton, 2009) therefore suggests that normalized S/N ratios represent a socioeconomically robust variable with which to construct an overall measure of the distribution of important climate impacts.

In terms of assessing the relative roles of different forcing agents on temperatures, for illustration we use the SSP dataset, which implies using production emissions and using 2010 as the start date for counting emissions (choosing of a different start date would make a difference of a few percent to contributions to warming) (Skeie et al., 2017). The long-standing convention of using production emissions rather than consumption emissions (Davis and Caldeira, 2010) is noted, and this clearly matters for discussions about responsibility. With appropriate data inputs, the EEI could easily be tweaked to incorporate a consumption-based approach instead or, indeed, some hybrid partitioning between consumption and production. In line with recent research (Allen et al., 2016), we weight emissions by GWP* because this is a better predictor of temperature development than is GWP (the basis of CO_2-e emissions).

Figure 2b shows normalised cumulative CO_2e^* emissions per capita between 2010 and 2090, for each of five regions resolved in the SSPs under a range of different IAMs. The width of the bars represents inter-IAM spread. Because different regions could follow different development pathways in the future (i.e. development more similar to different SSPs in different regions), we cannot make the same simple pairwise comparison regarding the constancy of the relative contribution to warming in the future that we make for normalized emergence.

In essence, the S/N or emergence elements of climate change are determined by global concentrations of GHG, and are largely insensitive to the national origin of emissions. On the other hand, contributions to climate change are determined by the national origin of emissions (at least insofar as nations provide the usual way of determining contributions). We can use estimates of past GHG emissions to determine contributions, but to estimate future scenarios we must consider the possible patterns of future GHG emissions. This is why it is sufficient to consider only global concentrations for emergence, but why we must resolve emissions at regional or national scale.

We can, however, examine the extent to which differing scenarios of future emissions indicate a reduction or exacerbation of existing differences in terms of emissions per capita. Some SSPs pull regions towards unity (i.e. relative emissions parity); others push them away from it. Most IAMs find that global SSP1, SSP2, or SSP5 trajectories imply a diminution of existing inequalities between the OECD and the rest of the world. The reasons are different in each case: in SSP1 the OECD countries take the lead in emissions reductions and decarbonise their economies much faster than economies elsewhere; by contrast, in the high carbon SSP3 and SSP5 worlds, OECD emissions revert towards the global per capita average because other regions catch up to the OECD's (high) levels. In the intermediate SSPs, emissions per capita inequalities remain high. Interestingly, under the mitigation-oriented SSP1 the Middle East and Africa actually exacerbates existing inequalities in terms of per capita emissions; if everyone mitigates then there is contraction, but no convergence, of relative responsibilities for climate change.

There are of course important caveats, such as the limited number of IAMs with diverse abilities to represent energy-economy in different groups of countries. At more refined levels of aggregation – those at which national policies are set – the picture becomes more variegated. SSPs are indicative, rather than prescriptive, normative, or predictive. As the developeds of SSPs have noted (O'Neill et al., 2014), "SSPs are only examples of the kinds of socioeconomic futures that can produce particular challenges to adaptation and mitigation". In the normalisation we employ, we interpret the SSPs as place-holders for future emissions trajectories to illustrate the point that future fossil fuel emission use will have implications for the pattern of relative contributions to climate change.

Combining the information from Figures 2a and 2b to define the EEI enables a novel method of expressing, relative to the global median, relative contributions to change, alongside the relative emergence of impacts (compared to a baseline local climate).

National level EEI performance

Figure 3 displays an estimate of historical EEIs for all countries with populations above one million people, comparing normalised cumulative GWP* weighted emissions per capita for 1970-2012 against normalised signal-to-noise ratios (using the average of all models across all RCP scenarios from figure 1a). Because the Emergence pattern is relatively insensitive to the amplitude of the forcing, the horizontal ordering of countries is relatively insensitive to whether the world follows a high or low emissions trajectory – because they are robust spatial patterns, and because we are normalising the emergence pattern to pick out national variations, it matters little whether we use emergence patterns to date or diagnose them from future forcing trajectories. EEI values range from as high as 8 – for slow-emerging and prosperous Northern European countries – to well below 1/100 for populous low income countries, such as Burundi. There is also more diversity in the position of individual nations (Table S4), with Singapore and Malaysia being both disproportionate contributors to emissions and disproportionately impacted in terms of how fast their climates are changing. Collectively however, nearly all of the highest and lowest income nations exhibit EEI estimates above 2 or below 1/2 respectively, with few exceptions.

The utility of EEI in the context of other climate indices

This index has value in several ways.

This index jointly considers both relative contributions and relative impacts, thus capturing and integrating two widely discussed ethical principles, prominent in the literature on climate ethics (Caney, 2005, Shue, 2014). First, through its connection to contributions the index connects to arguments which invoke the principle that the polluter should pay and which emphasize the importance of historical responsibility. Furthermore, we argue that by presenting emissions in a framework which incorporates an emission metric which provides greater environmental integrity in assessing the temperature implications of diverse greenhouse gas trajectories, the vertical axis of the EEI is superior to approaches that use more traditional interpretations of CO_2-equivalence. Second, the EEI incorporates a measure of who is most vulnerable to climate change, and most exposed to its harms. By combining the two the EEI provides a fine-grained integrated measure of the extent to which some are imposing the costs of their policies and actions on others. It therefore gives us an account of who is *exporting* harm to others and who is bearing burdens that result from the emissions of others.

A second potential use of the EEI is in guiding debates about specific policy issues. Because it accounts for differential contributions as well as differential impacts, it could, for example, inform policy debates about who should resource adaptation costs. Similar logic would allow it to help guide future mitigation policies; and it can also inform views about loss and damage (Otto et al., 2017).

These potential uses feature strongly in academic and policy conversations regarding climate change; and both potential uses should, as a matter of principle, capture elements from the top and bottom of the causal chain outlined in Figure 2, especially given the centrality of ideas surrounding common but differentiated responsibilities and respective capabilities in the climate change regime complex.

A third possible use of an adapted version of our index would be to alter the vertical axis to focus on abatement costs rather than contributions to climate change. This is relevant to ability to pay considerations, and could be potentially of value in investigating interest-based approaches to international environmental policy (Sprinz and Vaahtoranta, 1994). Further work is underway to explore these potential links. The central point is that the joint index can be re-designed to include other important ethical considerations.

More generally, conversations about the ethical dimensions of climate change ought to capture as much of the climate change causal chain as possible, since differences in the amplitude and speed of the emergence of local climate change are relevant ethical considerations; and predictable considerations, given the robustness of the relative emergence in figure 1a.

At this point we should add that neither the EEI nor any other index is a sufficient input for debates about climate ethics, climate policy or loss and damage since important normative questions remain open. Two of the most important such questions pertain to: (1) integration with non-climate factors and (2) issues regarding relative contribution and relative impact for conversations regarding the scope of both international mitigation obligations and loss and damage.

A common tendency of numerically precise emissions indices is that they treat emissions in isolation from other moral considerations regarding global or intergenerational justice. Even scientifically, this seems peremptory. A recent paper (Skeie et al., 2017) showed that there are several alternative but similarly reasonable ways of ascertaining the historical contributions of countries to climate change, even under the strongly restrictive assumption that historical per capita contribution to climate change is the sole factor considered. By focusing only on inputs to climate change, proponents of quantitative approaches to climate responsibilities tend, implicitly or explicitly, to focus narrowly on contribution to climate change; rather than to consider more fully the role of those emissions in a just world (Caney, 2012). But justice is not discharged exclusively or even primarily through emissions of greenhouse gases, and there are strong arguments against such “isolationist” approaches (Shue, 2014, Caney, 2012).

There are also generic issues regarding the isolated use of climate indices pertaining to loss and damage. Given the large matrix of factors that contribute to vulnerability to climate change loss and damage – including socio-economic considerations such as pre-existing levels of vulnerability and poverty, and also whether there are resilient and accountable governance structures – it is far from obvious that per capita emissions ought to be the only factor in play.

Emissions-related, or abatement cost-based, indices should then be put in context. Their contribution is to give summary information regarding the climate component of a broader approach to distributional justice. However, even if they do not capture all the morally relevant information they do capture important factors whose importance is recognized by a wide variety of different ethical perspectives, and is affirmed in both the climate ethics literature (Gardiner et al., 2010), and in the UNFCCC (Article 3.1 and Article 4.1).

Indices such as the EEI can, then, serve as useful and important summary inputs into a broader evaluation of climate policies, rather than sufficient and determinant prescriptions. Furthermore, to the extent that quantitative information is relevant to climate ethics and climate policy, it is important to focus on as long a segment of the causal chain as is possible. The EEI thus serves a valuable role. Furthermore, as argued above, the emergence index especially is a strikingly robust measure of local change, relative to that experienced by other people in other regions. Patterns of emergence in temperature response correlate well with many of the most significant direct impacts of climate change and, likely, many indirect impacts as well.

Summary

With the introduction of the EEI, we have shown how unequal regional patterns of emergent climate impacts combine with regional disparities in the contributions towards global GHG emissions and global warming. These results illustrate how the pursuit of some SSPs by regional groups would imply a growth of climate change inequalities, while other combinations (particularly SSP1) would reduce it.

Most appeals to fairness in climate change make reference both to relative impacts and relative contributions (Shue, 2014, Caney, 2005, Gardiner et al., 2010). Emerging regional climate impacts (or potential damages) are distributed differently to contributions to climate change. The EEI quantifies this both up to present, and for different future pathways. We suggest that the ability to consider simultaneously both relative impacts and relative contributions can, potentially, offer a promising way to develop a more comprehensive quantitative basis on which to anchor discussions. This can be useful as an important element in evaluation of what can be fair and reasonable efforts to limit future warming under the Paris Agreement, as well as in the context of loss and damage.

Figures

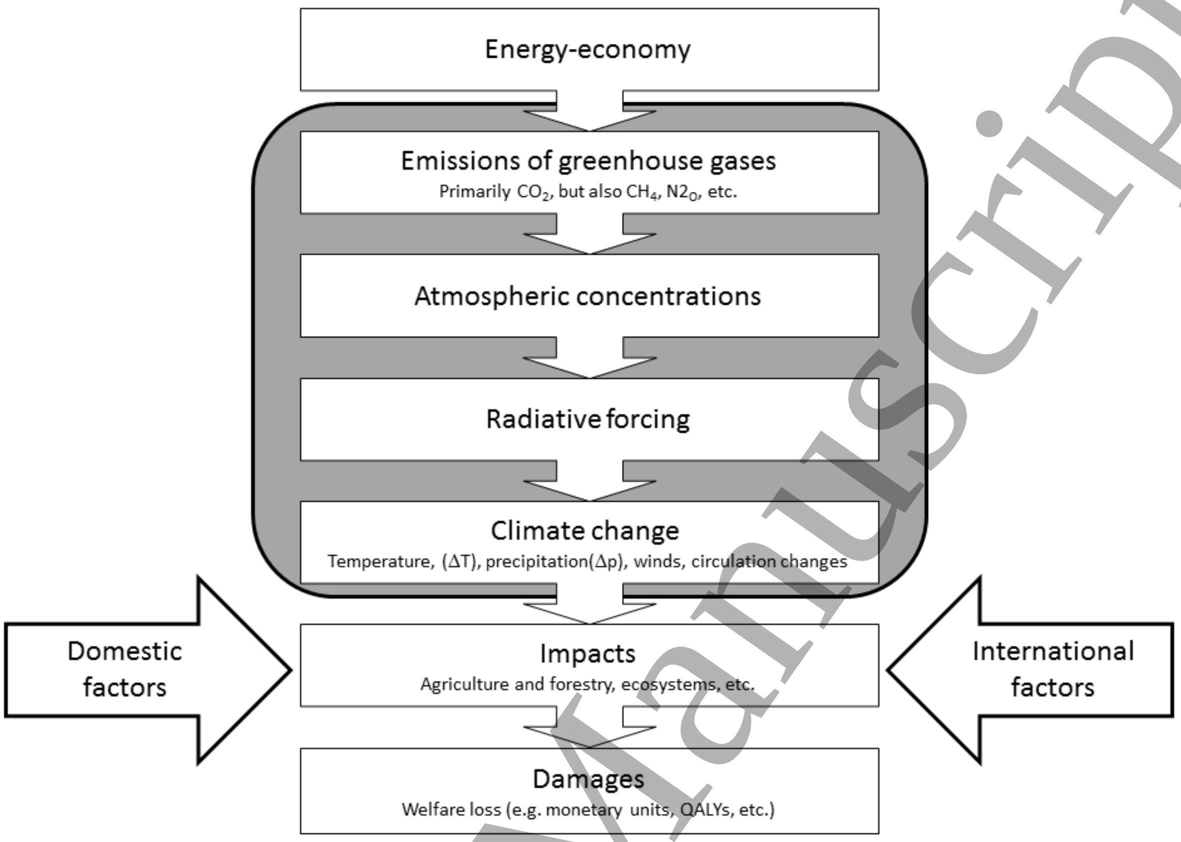

Figure 1: Cause-effect chain from socioeconomic causes of emissions through to climate change and damages. Altered from (Fuglestvedt et al., 2003). The grey box encompasses that segment of the causal chain that is considered in the joint emissions-emergence index. International and domestic factors that are not directly caused by climate change are shown in the arrows.

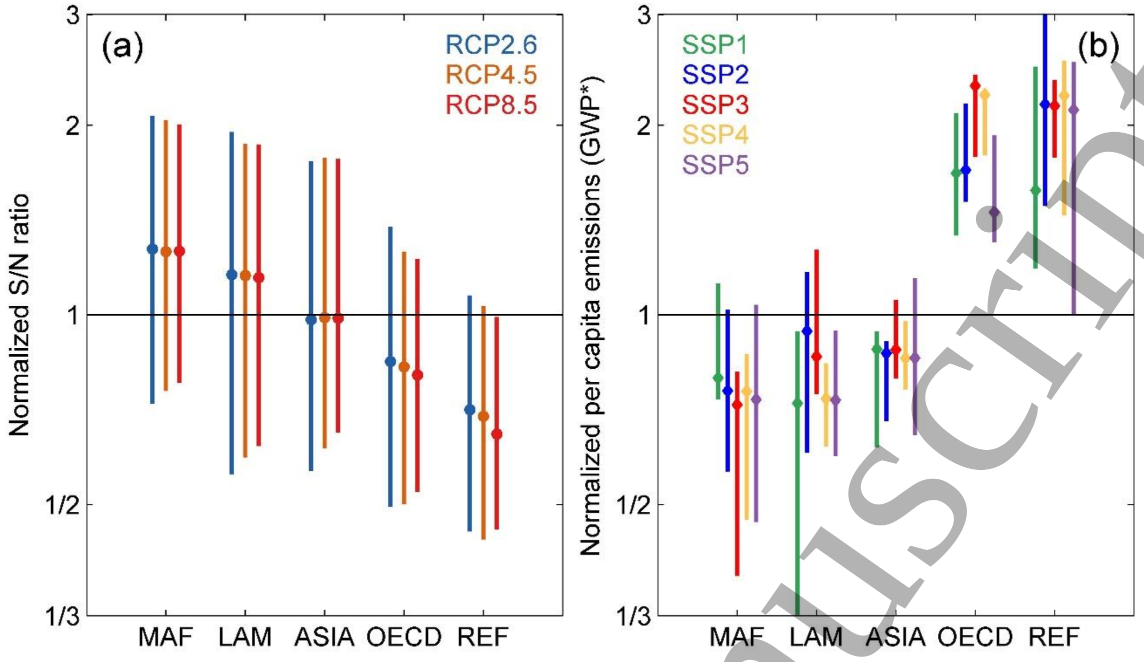

Figure 2: Panel (a) normalised impacts of climate change as represented by S/N ratios, for different regions and taken for the period 2086-2095 under different scenarios. Bars represent 5th-95th percentiles of a 25-model CMIP5 ensemble; circles show the median model response. Panel (b) represents normalised cumulative CO_2e^* emissions per capita between 2010 and 2090, for each of five regions resolved in the SSPs under a range of different IAMs. Here, the diamonds show the mean of the IAMs; bars show the full range of model responses. MAF=Middle East and Africa, LAM=Latin America, ASIA=Asian countries not contained in other groups, OECD, REF=Reforming economies, a slightly outdated term for countries from the former Soviet Union and Warsaw Pact.

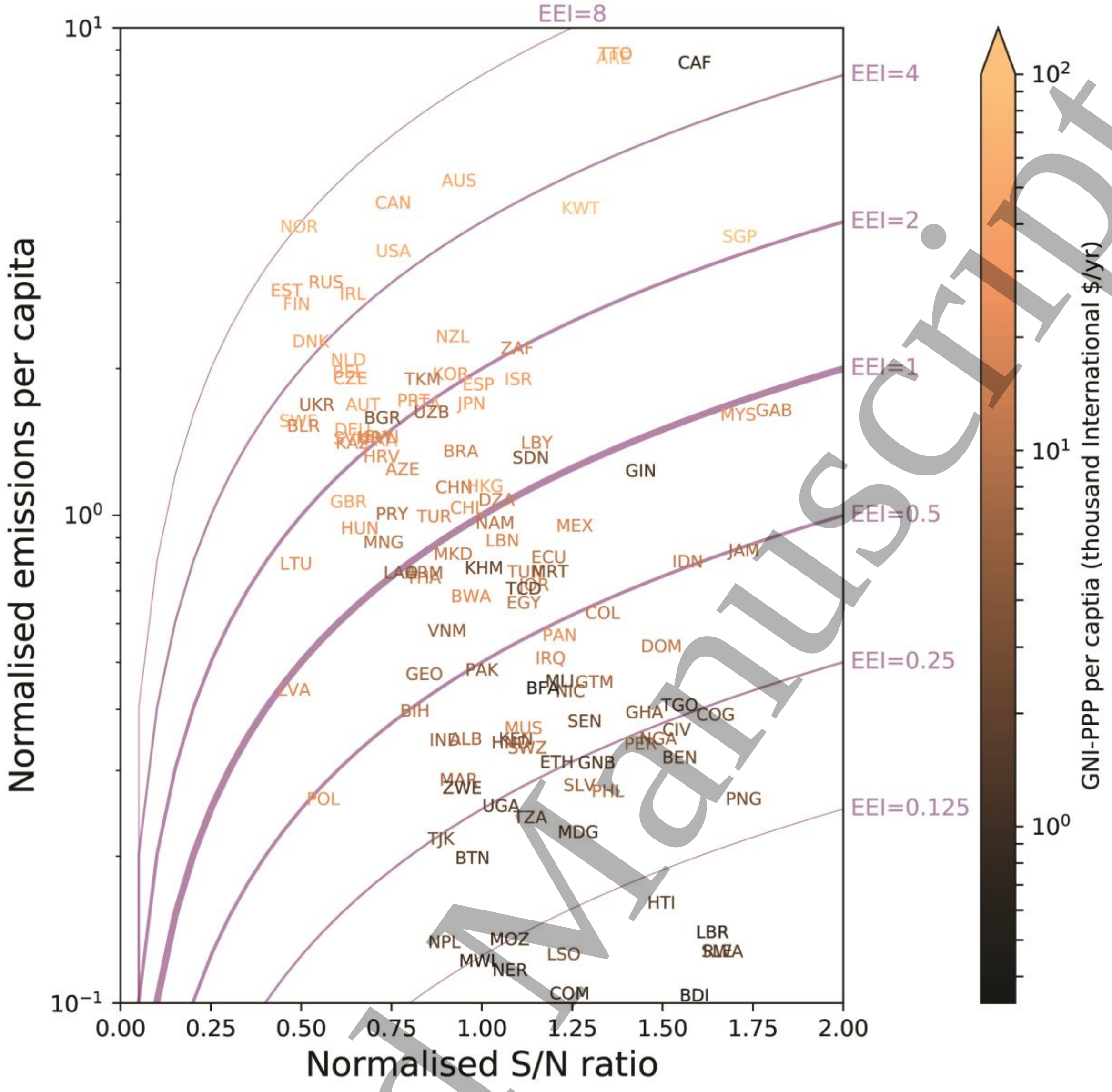

Figure 3. Normalised, population-weighted S/N ratios (bottom axis) and normalised per capita GWP* emissions for 130 countries with populations>1M. Lines of constant EEI are plotted as solid curves. Country acronyms and abbreviations are coloured by purchasing power parity gross national product (GNP-PPP) sourced from The World Bank. Countries experiencing stronger emergence are located towards the right of the plot. Countries contributing more, per capita, to climate change are located towards the top of the plot.

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