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Comparing the Observational Record to Socio-Economic  
Scenarios**

**Felix Pretis and Max Roser**

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# Carbon Dioxide Emission-Intensity in Climate Projections: Comparing the Observational Record to Socio-Economic Scenarios

Felix Pretis\* and Max Roser\*<sup>i</sup>

\*Department of Economics and Oxford Martin School,  
University of Oxford

## Contact

Felix Pretis: [felix.pretis@nuffield.ox.ac.uk](mailto:felix.pretis@nuffield.ox.ac.uk)

Max Roser: [max.rosen@oxfordmartin.ox.ac.uk](mailto:max.rosen@oxfordmartin.ox.ac.uk)

## Abstract

*The large span of long-run projected temperature changes in climate projections does not predominately originate from uncertainty across climate models; instead it is the wide range of different global socio-economic scenarios and the implied energy production that results in high uncertainty about climate change. It is therefore important to assess the observational tracking of these scenarios. For the first time observations over two decades are available against which the initial sets of socio-economic scenarios used in IPCC reports can be assessed. Here we compare these socio-economic scenarios created in both 1992 and 2000 against the recent observational record to investigate the coupling of economic growth and fossil-fuel CO<sub>2</sub> emissions. We find that the growth rate in fossil fuel CO<sub>2</sub> emission intensity – fossil fuel CO<sub>2</sub> emissions per GDP – over the 2000s exceeds the projections of all main emission scenarios. Proposing a method to disaggregate differences in global growth rates to country-by-country contributions, we find that the relative discrepancy is driven by high growth rates in Asia and Eastern Europe, in particular in Russia and China. The growth of emission intensity over the 2000s highlights the relevance of unforeseen local shifts in projections on a global scale.*

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<sup>i</sup>Both authors contributed equally to the work. Contact: [felix.pretis@nuffield.ox.ac.uk](mailto:felix.pretis@nuffield.ox.ac.uk), [max.rosen@inet.ox.ac.uk](mailto:max.rosen@inet.ox.ac.uk). This research was supported in part by grants from the Open Society Foundations, the British Academy, the Robertson Foundation, and the Oxford Martin School. We are grateful to Tony Atkinson, Sven Crone, Alexis Grigorieff, Neil Ericsson, Cameron Hepburn, David F. Hendry, Oleg Kitov, Andrew Martinez, and Peter Thorne for helpful comments and suggestions.

## 1 Introduction

The large span of projected temperature changes in climate projections does not predominately originate from uncertainty across climate models; instead it is the wide range of different global socio-economic scenarios and the implied energy production that results in high uncertainty about climate change. While the physical-science basis of models used in IPCC (Intergovernmental Panel on Climate Change, 1990-2013) reports is very much the focus of the debate in climate research (Rowlands et al. 2012), the underlying socio-economic scenarios that determine emissions of greenhouse gases have received comparably less attention. For the first time observations over two decades are available against which the initial sets of socio-economic scenarios underlying the IPCC reports can be assessed to study the tracking of observations. Here we compare these socio-economic scenarios created in both 1992 (IS92 – see Leggett et al. 1992, Pepper et al. 1992) and 2000 (SRES – see Nakicenovic et al. 2000) against the recent observational record to investigate the coupling of economic growth and fossil-fuel CO<sub>2</sub> emissions. We find that observed fossil fuel CO<sub>2</sub> emission intensity – fossil fuel CO<sub>2</sub> emissions per GDP – was rising over the 2000s while all main emission scenarios envisaged a decline. Studying the differences between projections and observations we find that the relative discrepancy is driven by high growth rates in Asia, in particular in Russia and China. The growth of emission intensity over the 2000s highlights the relevance of unforeseen local shifts in projections on a global scale and our results are robust to the downscaling method applied.

We make three main contributions to the existing literature. First, we provide an assessment of socio-economic scenarios in terms of their growth rates over a long time-span matching the intervals of the IPCC scenarios. The assessment is particularly relevant to investigate any suggested de-coupling of economic growth from fossil-fuel CO<sub>2</sub> emissions. Second, we provide a method to decompose aggregate differences in growth rates into individual contributions when down-scaling is necessary due to a coarser resolution of the projected values relative to observational data. This can be used for future scenarios on a global level to assess whether particular countries (or regions) have led to systematic deviations from the projected paths. Our analysis highlights that unforeseen shifts in single countries can contribute substantially to global differences and our decomposition allows this contribution to be quantified directly. Third, based on our conclusions we provide guidance for the development of future scenarios.

Four sets of scenarios have been used in the IPCC reports – the first IPCC report used the SA90 scenarios, the 2<sup>nd</sup> IPCC report used the IS92 projections, the 3<sup>rd</sup> and 4<sup>th</sup> IPCC report used the SRES (Special Report on Emission Scenarios) and the 5<sup>th</sup> IPCC report relied on the Representative Concentration Pathways (RCPs).<sup>ii</sup> We assess all main socio-economic indicators in the IS92 and SRES – real gross domestic product (GDP), population and fossil fuel CO<sub>2</sub> emissions – all major components in the Kaya identity (Kaya 1997). We focus on emission intensity as it is a crucial measure for the environmental impact of energy production and economic growth. This combines two projected socio-economic series, real gross domestic product (GDP) and fossil-fuel CO<sub>2</sub> emissions.<sup>iii</sup> Additional results for all other socio-economic series are reported in the supplementary material.

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<sup>ii</sup> The RCPs are scenarios of concentrations, corresponding socio-economic scenarios will be available as the shared socio-economic pathways (SSPs).

<sup>iii</sup> We investigate population projections and fossil-fuel CO<sub>2</sub> emissions per GDP per capita which combines all three socio-economic scenarios in supplementary material 6.5.

There are six socio-economic paths in the 1992 scenarios (named A-F). The later SRES projections are made up of multiple individual scenarios falling within four broad groups: A1 (rapid growth and convergence, where A1FI denotes fossil fuel intensive while A1T concentrates on non-fossil fuels), A2 (heterogeneous development), B1 (convergence and ecologically friendly), and B2 (heterogeneous and ecologically friendly). As the use of sub-group averages is not appropriate (Manning et al. 2010), we instead focus on the six main 'illustrative' SRES marker scenarios<sup>iv</sup> together with the six IS92 scenarios. We also report the results for the full set of all SRES scenarios. Emission scenarios used in the early IPCC climate models are reported at a decadal interval (1990, 2000, 2010) precluding us from assessing the sensitivity of projections to the choice of time interval. Different SRES scenarios were allowed varying initial values at the start of the scenario projections (see Figure 1 panel *a*, and supplementary Figures S1-S2). This results in small differences for global population (up to 0.38%) but in large differences in world GDP and CO<sub>2</sub> emissions – up to 4.3% between scenarios A2 and B1. This variation in starting values stems from uncertainty around observed GDP and socio-economic variables and complicates any study of the accuracy in levels. Discrepancies in initial values make it necessary to focus on growth rates. Since scenarios cannot be expected to capture short-term year-on-year fluctuations, a comparison on a decadal scale is appropriate. Crucially for the future development of scenarios it is important to ensure consistent initial values across all projections despite intrinsic uncertainties around observations – this has now been embraced by the RCP scenarios in the latest IPCC assessment.

Unlike temperature forecasts derived from climate model ensembles conditioned on scenarios, the socio-economic scenarios are not probabilistic projections, they are meant to describe scenarios of possible paths. Nevertheless it is interesting to see whether any of the possible paths have been realised, and to provide guidance for conditioning when assessing the accuracy of climate forecasts. Uncertainties on observed CO<sub>2</sub> emissions and GDP are not available, therefore we cannot employ a formal test of a scenario against the observed record.<sup>v</sup> Instead we assess the relative performance of scenarios against observations. However, future development of scenarios could apply the methods proposed by Müller and Watson (2014) to create approximate probabilistic projections of socio-economic paths. Müller and Watson introduce an approach to construct prediction sets for long-horizon forecasts of scalar variables – and in their application consider projections of US economic time series over horizons ranging from 10 to 75 years.

The adequacy of IPCC projections has been discussed previously (see Höök et al. 2010, van Vuuren et al. 2010, Richardson et al. 2009), however, the focus has remained predominately on levels, which is less meaningful given the aforementioned variation in initial values. Additionally the focus remained primarily on CO<sub>2</sub> emissions and not the wider socio-economic variables or crucially, emission intensity.<sup>vi</sup> Due to a lack of data, few studies investigated the performance of scenarios inclusive of the year 2010. Indeed, earlier studies, such as Raupach et al. (2007) find fossil-fuel CO<sub>2</sub> emissions to be accelerating over the 1990s and early 2000s. However, with IPCC projections only available at a decadal interval, the growth over the 2000s could not be

<sup>iv</sup> The six 'illustrative scenarios' (Manning et al. 2010) consist of the four core marker scenarios (A1 AIM, A2 ASF, B1 IMAGE, B2 MESSAGE) and the additional scenarios of A1FI (A1G MiniCAM) and A1T MESSAGE). In total there are 40 scenarios in the SRES, out of the 40, only two A2 AIM (0.65), A1 AIM (0.54) show higher than observed growth rates, and these two are not the 'illustrative' scenarios or marker scenarios. The next highest 0.16, then 0.14, all others are negative.

<sup>v</sup> Equally a test of the average annual growth rate against scenario growth rates provides little insight since the assumption that the observed growth rate in a particular year is equal to the scenario growth rate is not made in the scenarios.

<sup>vi</sup> Some studies focus on a subset of projected series, for example Patzek and Croft (2010) assess the IPCC coal-production projections.

assessed. Additional earlier studies using data up to 2009 find the level of CO<sub>2</sub> emissions to fall within the SRES range (van Vuuren et al. 2010), and using within model group averages, to lie on the upper scale of the 2000 scenarios (Richardson et al. 2009). However, wider socio-economic variables, emission intensity, or the longer projections (published in 1992) are not considered. On the physical-science side, a first assessment of an early probabilistic temperature forecast conditioned on a single scenario finds that observed global mean temperatures fall within the predicted interval (Allen et al. 2013). We provide a similar analysis by assessing the accuracy of the underlying socio-economic scenarios. This equally permits an assessment of whether the single scenario chosen in the temperature forecast analysis by Allen et al. (2013) not only matches observed temperatures, but also the socio-economic evolution which determines the anthropogenic component in changes in climate.

## 2 Methods

Due to variations in initial values of the socio-economic scenarios we calculate growth rates and compare these to the observed growth rates of population, fossil-fuel CO<sub>2</sub> emissions, real GDP (based on market exchange rates to be consistent with the units used in the scenarios), and emission intensity. We compute the annual average growth over decades (referred to as decadal growth rate throughout) for both global observed and projected values of the socio-economic series.

A method is needed to disaggregate global differences in growth rates to country-by-country contributions to assess what drives any observed global discrepancy. We therefore propose a method to disaggregate global differences in growth rates to country levels based on decomposing aggregate growth rates and downscaled country values, where the decomposition can be applied to any downscaling method chosen. We explore the sources of the differences between global observations and global scenarios by assessing the discrepancies on a country-by-country level. For this we downscale the scenario values (relying on two different downscaling approaches) to individual countries and decompose the aggregate (global) difference between observed and projected growth rates into country contributions, the downscaling is not used to assess the accuracy of the scenarios but rather to explain the observed global differences.

### 2.1 Downscaling the SRES projections

To disaggregate the global difference in projected and observed growth rates, we require country-by-country contributions to this global difference. We use two downscaled data sets, first we apply a simple linear downscaling procedure, second, we use the downscaled values provided by van Vuuren (2007) et al.

We emphasize that this is done to disaggregate the difference between global projected and observed growth rates, and not to assess the accuracy of the scenarios by comparing them to country-observed values. This is done to determine if the aggregate difference is driven by a subset of countries in particular, or if the contribution to the global error is roughly the same across countries.

In linear downscaling individual countries are assigned their corresponding regional growth rate based on the four regions defined in the IPCC SRES projections. These regions are: REF – countries undergoing economic

reform, OECD90, ASIA, and ALM – Africa and Latin America.<sup>vii</sup> Each region in the SRES projections has a common growth rate across all countries. Due to the variation in observed growth rates, there is variation in differences within each region. For level reconstructions the projected growth rates are applied to the individual country's<sup>viii</sup> observed values in 2000 (Boden et al. 2013, UN 2014, World Bank, 2014). Linear downscaling is chosen here as the first method for transparency as it does not require additional assumptions on regional convergence and preserves the differences in initial values which are crucial for the task at hand. While linear downscaling does not account for heterogeneity of growth rates within regions, the difference in observed initial values implies there will be no convergence in the level of the variables within the regions.

To assess the robustness of our results to the downscaling method, we also use the van Vuuren et al. (2007) downscaled SRES data set<sup>ix</sup> based on assumptions of gradual regional convergence as an alternative to linear downscaling. Regional convergence is subject of debate (see van Vuuren 2007) and over long time scales (e.g. the 100 years often considered in climate projections from 2000-2100) we expect the values of different downscaling methods to diverge due to compounding. However, over the drastically shorter time period considered here (2000-2010 for the SRES scenarios), the type of downscaling approach has little effect on the final values (see section 4).

## 2.2 Decomposition of Aggregate Growth Rates

We are interested in explaining the difference between observed global and projected global growth rates. For this we investigate which countries are most important in explaining the aggregate difference. We use individual country level data from 2000-2010 to calculate observed country-level growth rates. For each scenario we use the downscaled projected country level growth rates. To attribute the discrepancies in global growth rates to individual contributions in growth rates at country-level, we propose the following approach to decompose aggregate growth rates:

First, we show how to decompose aggregate growth rates into individual country contributions. Second, this allows us to decompose the aggregate difference into individual country-level contributions. The derivations are shown in detail in the supplementary material. The decomposition proposed here is independent of the downscaling method applied, and we present the results of applying this decomposition to both linearly downscaled, as well as the van Vuuren et al. downscaled data in section 4.

### 2.2.1 Decomposing Aggregate Growth Rates

Let  $Y_t = \sum_j Y_t^j$  denote aggregate GDP over countries  $j$ , and let  $Z_t = \frac{C_t}{Y_t}$  denote aggregate fossil fuel CO<sub>2</sub> emissions per GDP, where aggregate fossil fuel emissions  $C_t = \sum_j C_t^j$  are summed over countries  $j$ . Each country  $j$ 's fossil fuel CO<sub>2</sub> emissions per GDP is defined as  $Z_t^j = \frac{C_t^j}{Y_t^j}$ . The corresponding aggregate ( $G_t$ ) and individual ( $G_t^j$ ) growth rates are given by  $G_t = \frac{Z_t - Z_{t-1}}{Z_{t-1}}$  and  $G_t^j = \frac{Z_t^j - Z_{t-1}^j}{Z_{t-1}^j}$  respectively.

<sup>vii</sup> While the IPCC regional list does not include the United Kingdom, we include it within the OECD90 region.

<sup>viii</sup> Starting values in 2000 are chosen to be able to include a wide range of Eastern European countries for which no observations in 1990 are available.

<sup>ix</sup> van Vuuren et al. (2007) provide the downscaled values for the IMAGE model groups, of which B1 is part of the set of 'illustrative marker scenarios' recommended by Manning et al. 2010.

The aggregate growth rate can then be re-expressed as:

$$G_t = \frac{Z_t - Z_{t-1}}{Z_{t-1}} = \frac{1}{Z_{t-1}} \left( \sum_j \frac{c_t^j}{Y_t} - \sum_j \frac{c_{t-1}^j}{Y_{t-1}} \right) \quad (1)$$

As shown in the supplementary material this can be simplified to:

$$G_t = \left( \sum_j \frac{c_{t-1}^j}{Y_{t-1}^j} \left[ \frac{Y_t^j}{Y_t} (1 + G_t^j) - \frac{Y_{t-1}^j}{Y_{t-1}^j} \right] \right) \frac{1}{Z_{t-1}} = \left( \sum_j \frac{z_{t-1}^j}{Z_{t-1}} \left[ \frac{Y_t^j}{Y_t} - \frac{Y_{t-1}^j}{Y_{t-1}^j} + G_t^j \frac{Y_{t-1}^j}{Y_t} \right] \right) \quad (5)$$

$$G_t = \left( \sum_j \frac{z_{t-1}^j}{Z_{t-1}} \left[ \Delta \frac{Y_t^j}{Y_t} + G_t^j \frac{Y_{t-1}^j}{Y_t} \right] \right) = \left( \sum_j d_j \right) \quad (6)$$

Where  $d_j = \frac{z_{t-1}^j}{Z_{t-1}} \left[ \Delta \frac{Y_t^j}{Y_t} + G_t^j \frac{Y_{t-1}^j}{Y_t} \right]$  and the term  $\Delta \frac{Y_t^j}{Y_t} = \frac{Y_t^j}{Y_t} - \frac{Y_{t-1}^j}{Y_{t-1}^j}$  captures the change in the proportion of country  $j$ 's GDP relative to total GDP. This yields the aggregate growth rates as the sum of the individual components  $j$  and allows for a decomposition of the aggregate growth rates into individual contributions  $d_j$ .

The individual contributions can be decomposed into an emission intensity “growth rate effect” and a “GDP effect”, which is the relative change in GDP:

$$d_j = \frac{z_{t-1}^j}{Z_{t-1}} \left[ \underbrace{\Delta \frac{Y_t^j}{Y_t}}_{\text{GDP Effect}} + \underbrace{G_t^j \frac{Y_{t-1}^j}{Y_t}}_{\text{Growth Rate Effect}} \right] \quad (7)$$

If the ratio of the particular country's GDP to global GDP is unchanged ( $\Delta \frac{Y_t^j}{Y_t} = 0$ ), then the only contribution to the overall growth rate is derived from the growth rate effect:  $\frac{z_{t-1}^j}{Z_{t-1}} G_t^j \frac{Y_{t-1}^j}{Y_t}$ . Whether the contribution to the overall growth rate is positive or negative therefore depends on the change in the ratio of a country's GDP relative to the global GDP, and a country's growth rate in emissions per GDP,  $G_t^j$  scaled by the share of the country's GDP relative to the global GDP.

### 2.2.1 Decomposing the Difference between Observed and Projected Aggregate Growth Rates

When comparing an observed growth rate ( $G_t$ ) against a scenario predicted growth rate ( $\hat{G}_t$ ), using the same decomposition procedure as above, the difference between observed and predicted growth rates can be attributed to disaggregated country contributions, and further into relative GDP change and emission intensity growth rate effects as shown in (8) and (9). Given the summability, simple regional aggregates can be considered as well as country-level disaggregation. These are plotted in Figure 2 (panel *b*) for individual contributions to the overall difference in growth rates exceeding 0.1%.

$$G_t - \hat{G}_t = \sum_j d_j - \sum_j \hat{d}_j \quad (8)$$

$$G_t - \hat{G}_t = \sum_j \underbrace{\left( \frac{z_{t-1}^j}{Z_{t-1}} \left[ \Delta \frac{Y_t^j}{Y_t} \right] - \frac{\hat{z}_{t-1}^j}{\hat{Z}_{t-1}} \left[ \Delta \frac{\hat{Y}_t^j}{\hat{Y}_t} \right] \right)}_{\text{GDP Effect}} + \underbrace{\left( \frac{z_{t-1}^j}{Z_{t-1}} G_t^j \left[ \frac{Y_{t-1}^j}{Y_t} \right] - \frac{\hat{z}_{t-1}^j}{\hat{Z}_{t-1}} \hat{G}_t^j \left[ \frac{\hat{Y}_{t-1}^j}{\hat{Y}_t} \right] \right)}_{\text{Growth Rate Effect}} \quad (9)$$

### 3 Data

IPCC scenario data are obtained from the IPCC Data Distribution Center (IPCC, 2014). Observed fossil-fuel emissions<sup>x</sup> are available at global and national level (Boden et al. 2013). Global and national population data are obtained from the UN Population Division (UN, 2014). Gross domestic product (GDP) on global and national scale is measured in 1990 market exchange rate converted USD (World Bank, 2014) to be consistent with SRES measures.

### 4 Results

The world has seen growth in CO<sub>2</sub> emission intensity over the 2000s not envisaged by any of the main scenarios (Figure 1, panel b). While all main socio-economic scenarios projected declining emission intensity, the observational record shows that emission intensity was in fact rising. The average decadal growth rate in emission intensity over the 2000s of 0.37% per year considerably exceeded even the closest marker scenario growth rate (A1) which projected a decline of -0.1%. The remaining main SRES and IS92 scenarios project declines ranging from -0.3% to -1.75%. The plot of levels of emissions intensity (Figure 1, panel a) hides this discrepancy between scenarios and observations – the level projections only appear to match the observations closely due to the mismatch in starting values. These results are consistent for fossil-fuel CO<sub>2</sub> emissions per GDP per capita – observed growth rates in per capita terms exceed all projected IS92 and SRES marker scenarios (supplementary Figure S9). Following a consistent decline in emission intensity over the 1990s, over the 2000s the world has not seen a de-coupling of growth from emissions, though observations from the 2010s provide evidence that there may have been a recent turn-around (see Jackson et. al 2015).

Figure 2 expands the set of scenarios considered beyond the main scenarios by plotting the 2000s growth rates across the full set of SRES scenarios created.<sup>xi</sup> Consistent with the results relative to the main scenarios, observed growth rates exceed projected growth rates – only 2 out of the 39 scenarios are higher than observed emission intensity growth for the time period considered, and only 4 out of 39 projections suggest an increase of emission intensity relative to a decline.

To investigate the systematic discrepancy in global emission intensity growth rates between observations and scenarios, we decompose the aggregate difference (using methods in section 2) on a country-level disaggregation for four of the SRES projections (Figure 3, panel a). We chose these scenarios as they are the core marker scenarios, and A1 and B1 mark the scenarios with the smallest and highest global deviation from observations respectively. This is to investigate whether the difference between observations and projections differs across scenarios (results using the van Vuuren et al. 2007 downscaled data are reported in the supplementary material S6). The apparent regional differences are consistent across all four marker scenarios: the observed growth rates of fossil-fuel CO<sub>2</sub> emission intensity in Sub-Saharan African and South Asian countries exceed those of the scenarios as shown in the map in Figure 3. Across all scenarios, growth rates observed in Latin American are predominantly below scenario projections. However, these results have to be interpreted with caution as regional projections were not aimed at capturing complete heterogeneity across countries within a region.

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<sup>x</sup> The measure of CO<sub>2</sub> accounts for fossil-fuel emissions to match the measure used in the IPCC projections.

<sup>xi</sup> There is a total of 41 SRES scenarios, GDP projections are available for 39 of these.



**Figure 1:** Observed and projected global emission intensity (fossil fuel CO<sub>2</sub> emissions per GDP) in levels (a) and growth rates (b). Panel a graphs global observed emission intensity (black) together with decadal IS92 (dashed colour) and main SRES (marker) projections (solid colour). Starting values are shaded grey while projected values are shaded light blue. Note that initial values for SRES vary across scenarios. Panel b shows observed annual growth rates (continuous black) together with observed decadal growth rates (horizontal black) over both decades. Projected growth rates are shown in colour for IS92 (dashed) and SRES marker projections (solid). Observed decadal growth rates exceed all scenario projections over the 2000s.

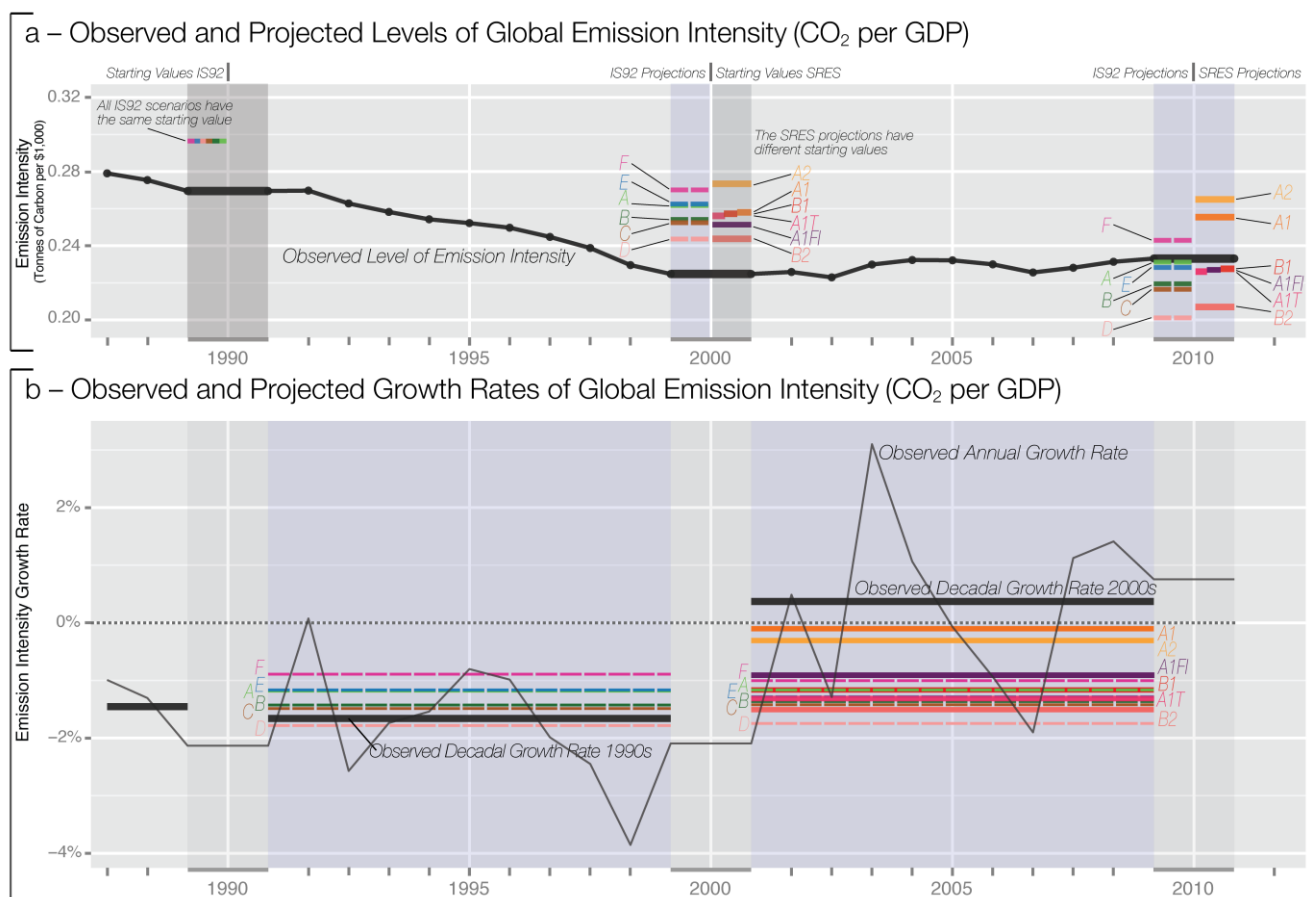
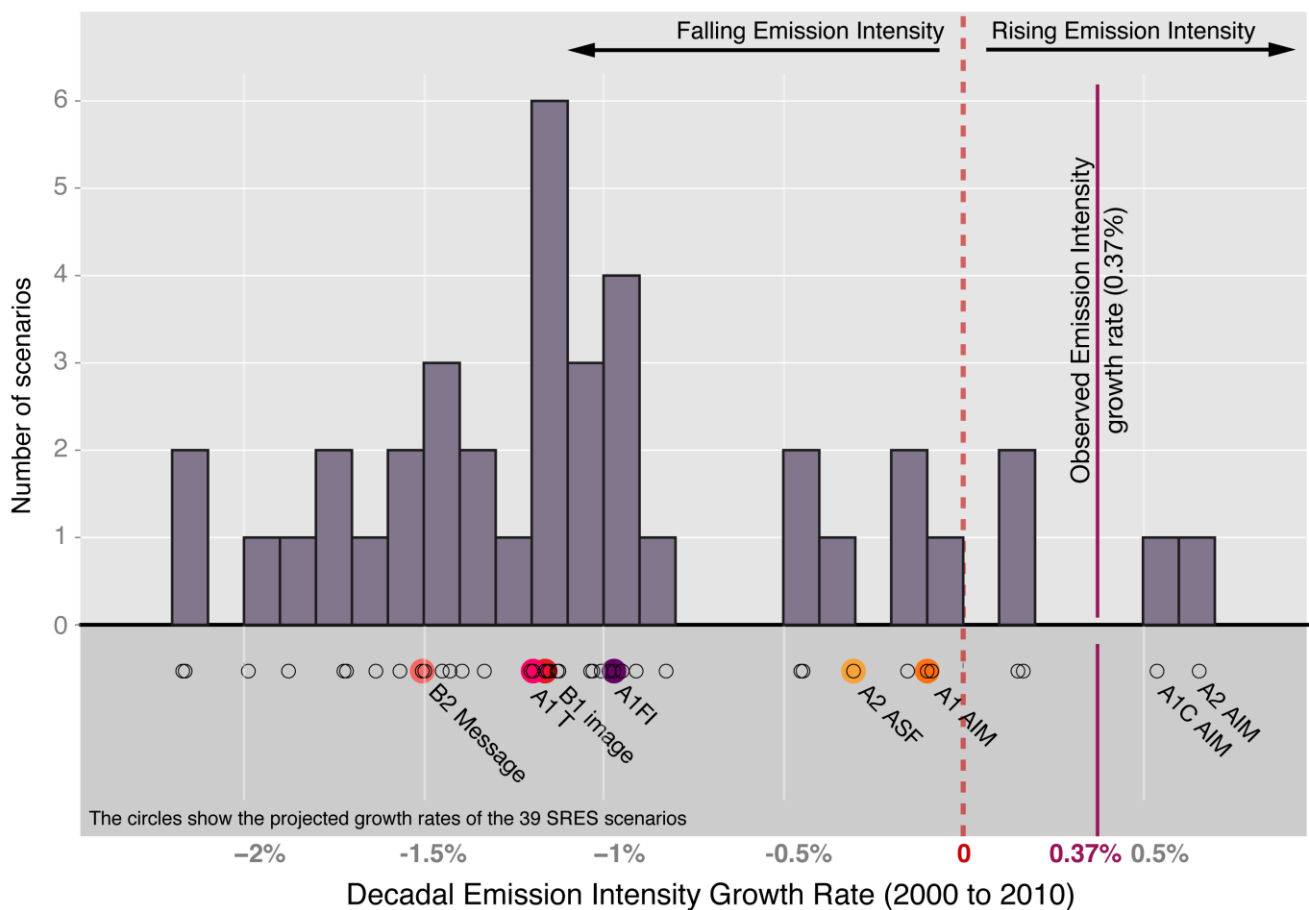


Figure 2: Histogram and density of projected global emission intensity (fossil fuel CO<sub>2</sub> emissions per GDP) decadal growth rates over the 2000s for all SRES scenarios and observed global decadal growth rate (solid purple). Projected growth rates for the 6 main SRES scenarios are shown in colour, circles show projected growth rates across all 39 SRES scenarios. Observed positive decadal growth rates (solid purple) exceed all main scenario projections over the 2000s, which envisaged a decline in emission intensity rather than an increase.

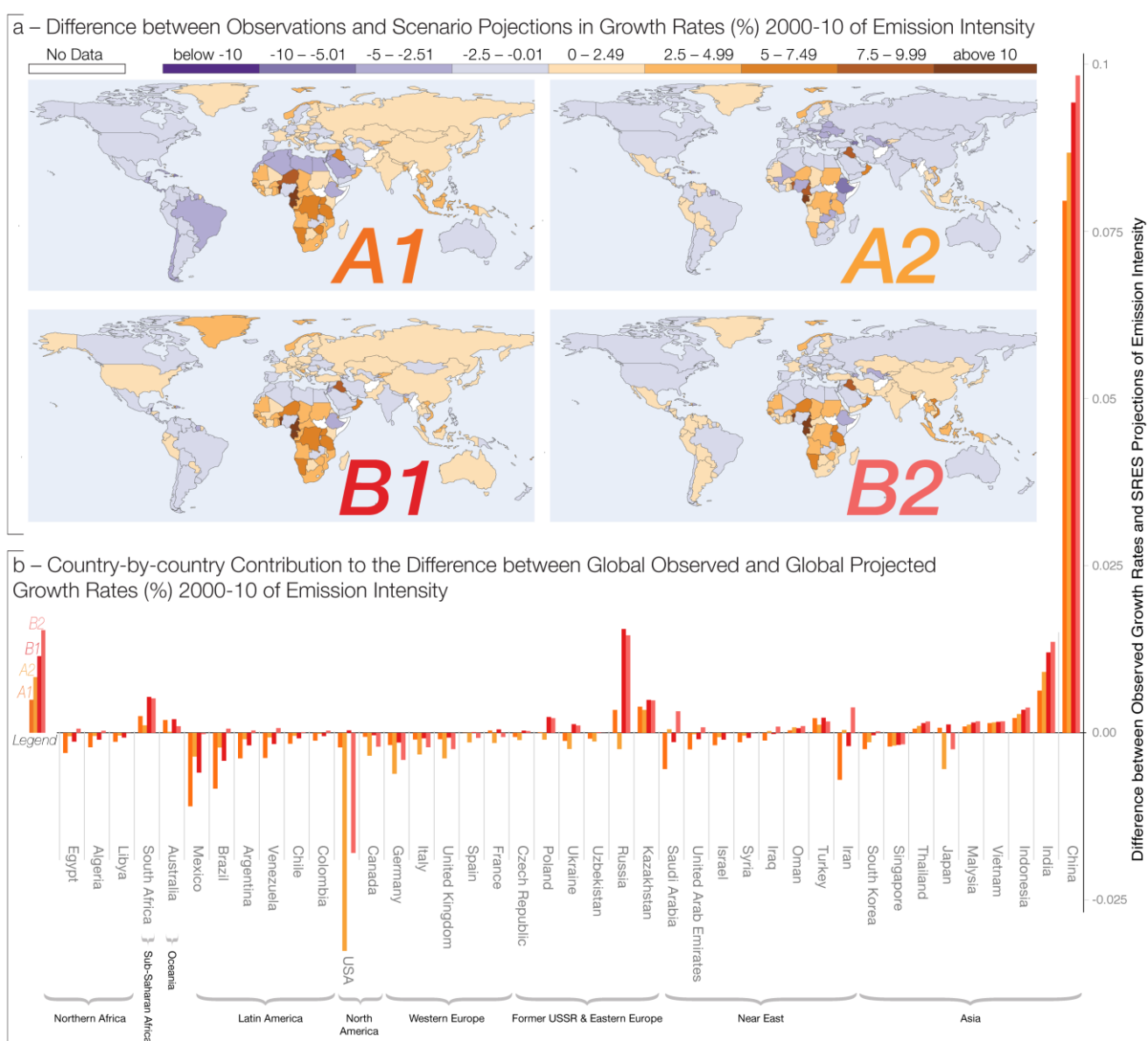


To explain what drives the global difference between observed and projected growth rates, we quantify the country-by-country contribution to this global difference. The importance of the country in terms of the level of GDP and emissions intensity can be obtained through their relative weighting using the decomposition in section 2.2. While Sub-Saharan African countries exhibit the highest deviations from regional-scenario projections (Figure 2, panel a), their overall contribution to the global difference in growth rates is small (Figure 2, panel b). When weighted according to their contribution to global emission intensity, it becomes apparent that unforeseen changes in emission intensity and GDP in China, Russia, and wider Asia account for the dominant share of the difference between global observed and SRES projected growth rates (Figure 2, panel b using linear downscaling, and Figure S10 using downscaled data from van Vuuren et al. 2007). It is important to emphasize that this is *relative to the projections* and that the emission intensity in China and Russia actually declined over the 2000s (see supplementary Figure S8). The discrepancy is primarily driven by unanticipated growth in GDP (the ‘GDP effect’ in equation 7 – see supplementary section S3.3) in Asia.<sup>xii</sup> Our study over this longer time-span provides evidence for the continuation of the trends found by Raupach et al. (2007). The results are not driven by the choice of downscaling method - repeating the analysis with the van Vuuren et al (2007) downscaled SRES results which assumes regional convergence, Figure S10 shows that the main difference is driven by unanticipated high growth in Asia, a pattern consistent with Figure 3 which uses linear downscaling. Rapid growth in Asia was not anticipated in most projections. Comparing the socio-economic scenarios to actual forecasts, even over much shorter horizons of one quarter to one-and a half years, GDP forecasts produced by the Federal Reserve exhibit the highest forecast errors for China over the 2000s (Ericsson et al. 2014). On a decadal scale, observed Chinese GDP growth exceeds the Consensus Economics (2013) forecasts by 7%, a similar magnitude as SRES projections, which are exceeded by 2-11%. IPCC projections - despite not being forecasts per-se and while considering much longer time horizons - do not appear systematically worse than alternative projections for the time period. The unforeseen shift in growth in Asia drives the systematic under-projection of the paths in all main scenarios.

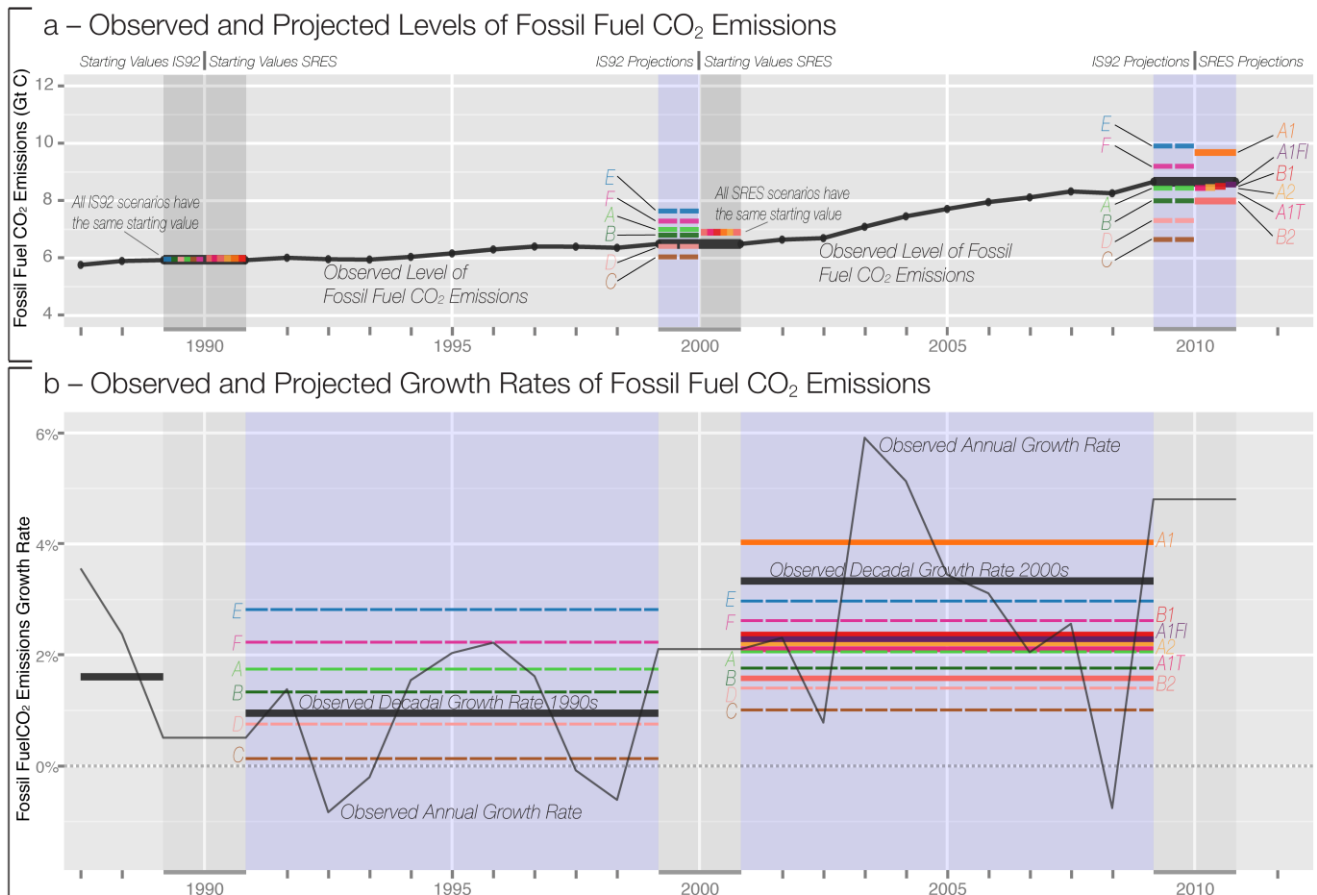
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<sup>xii</sup> It is not primarily changes in CO<sub>2</sub> emissions in China but rather the increase in Chinese GDP relative to world total GDP that account for China’s contribution to the difference in aggregate growth rates. As we show in supplementary section 6.2, real GDP in China relative to aggregate global GDP increased more than anticipated in the scenarios, and drives the aggregate discrepancy in emission intensity growth rates.

**Figure 3: Decomposition of the global difference between global observed and projected emission intensity using Country-by-country downscaled difference between observed and projected decadal growth rates in emission intensity for SRES marker projections over 2000-2010.** The four world maps in panel *a* show the difference between observed and projected growth rates in fossil-fuel CO<sub>2</sub> emissions per GDP. Growth rates in emission intensity underestimated by the projections are shown in brown tones, overestimated growth rates in purple tones. Panel *b* graphs the country-by-country contribution to the difference between global observed and global projected growth rates in emission intensity. Only countries contributing more than 0.001 towards the difference are shown. While growth rates in Sub-Saharan Africa exceeded scenario projections, they contributed little to the overall magnitude of the difference in global observed and projected growth rates. The primary contribution to the differences in global growth rates relative to SRES projections stems from changes in Asia and China in particular, while some (e.g. US) observations remain close to projections, thus lowering the difference between global observed and projected growth rates. Results using van Vuuren et al. (2007) data are shown in Supplementary Figure S10.



**Figure 4:** Observed and projected global fossil-fuel CO<sub>2</sub> emissions in levels (a) and growth rates (b). Panel a graphs global observed annual fossil-fuel CO<sub>2</sub> emissions (black) together with decadal IS92 (dashed colour) and main SRES marker projections (solid colour). Starting values are shaded grey while projected values are shaded light blue. Panel b shows observed annual growth rates (continuous black) together with observed decadal growth rates (horizontal black) over both decades. Projected growth rates are shown in colour for IS92 (dashed) and SRES marker projections (solid). Observed decadal growth rates exceed nine out of ten scenario projections over the 2000s.



More broadly, we aim to determine if there is a single scenario that observations are tracking closely. This is to assess if one of the scenario groups (ranging from fossil-fuel intense convergent growth, to ecologically-friendly divergence) provides a comprehensive explanation for socio-economic developments over the 1990s and 2000s. We assess which scenario is closest to the observed record measured by the smallest proportional deviation from observed levels and lowest absolute difference to growth rates. The details of the best fitting scenarios of each main socio-economic projection are listed in the supplementary material for both levels and growth rates. No single scenario uniquely dominates other scenarios when assessed against the observed variables over both time intervals (see Figures 1, 3, supplementary Figures S1-S6, and supplementary Table S1). Notably, earlier IS92 scenarios are not systematically further away from observations than later SRES projections. Given the inertia of population dynamics, it is not surprising that population projections exhibit the lowest deviations from observations (supplementary Figure S2) (see also Lutz et al. 2001). Overall, no single 'story-line' of the scenarios captures the observed socio-economic development more closely than others during the 1990s and 2000s.

The 1992 A scenario chosen for the assessment of the temperature forecast by Allen et al. (2013) is the closest IS92 scenario in levels of CO<sub>2</sub> emissions, supporting the choice of this scenario as the level of CO<sub>2</sub> emissions is most relevant for a global mean temperature forecast. There is no forecast failure of global mean temperature in Allen et al., as the levels of observed CO<sub>2</sub> emissions are closely matched. However, over the 2000s, nine out of the ten projections underestimated decadal growth in fossil-fuel CO<sub>2</sub> emissions (Figure 4, panel b) similarly to emission intensity. While temperature forecasts are not rejected in the short-run, we may expect increasing divergence of temperatures from early scenario values in the long run based on the under-projection of both growth rates in CO<sub>2</sub> emission, and growth rates of emission intensity. Evidence for this can already be seen through the accelerating accumulation of concentrations of CO<sub>2</sub> in the atmosphere – the growth between 2012 and 2013 was the highest observed since 1984 (WMO, 2014), and is also supported through the future outlook on CO<sub>2</sub> emissions by Friedlingstein et al. (2014).

## 5 Conclusion

An assessment of socio-economic projections can potentially reduce the uncertainty about future climate change by highlighting systematic discrepancies in existing scenarios. Evaluation of the IPCC projections against the observed record over two decades requires careful analysis of the growth rates due to substantial differences in initial values in levels across the different projections. The analysis of the growth rates revealed that global emissions intensity growth exceeded 37 of all 39 SRES scenarios – including all 6 main scenarios – over the decade 2000-2010. Similarly, observed growth rates of fossil-fuel CO<sub>2</sub> emissions exceeded projections in all but one of the main scenarios over the same period. Generating projections about the future is challenging particularly over long time horizons and our analysis highlights the relevance of (local) unforeseen shifts. No projection (and few forecasts from other agencies) closely tracked the unforeseen growth in China and wider Asia in general. These results are robust to the downscaling method chosen. Our scenario evaluation shows the impact of unforeseen shifts in growth, and demonstrates that observations over the 1990s and 2000s do not track any single scenario family more closely than others.

Based on the findings of our paper we provide the following guidance for future development and assessment of scenarios. First, when assessing scenarios with varied initial values, it is important to account for these different initialisations by focusing on growth rates. In turn, it is important to ensure that future scenarios

have consistent starting values (despite intrinsic uncertainties about observations) to enable comparisons in the level as well as growth rates, as the RCPs now do. Second, unforeseen shifts in individual countries (as seen in the unanticipated growth of China) can have large effects on a global scale. To assess the contributions of individual countries, we show how aggregate differences in growth rates can be decomposed into individual contributions when down-scaling is necessary due to a coarser resolution of the projected values relative to observational data. Equally, given the impact of shifts in single countries (as identified using the growth decomposition) additional focus could be shifted onto creating projections on a more local rather than global scale. Third, the approach proposed by Müller and Watson (2014) could be used to move towards probabilistic socio-economic projections in the next set of scenarios.

Overall, this underestimation of emission intensity raises concerns about achieving sustainable energy production. There appears to be little evidence of a de-coupling of growth from emissions during the 2000s, though the outlook appears a little brighter: Jackson et al. (2015) suggest that data for 2014 and 2015 show an 'unexpected' recent de-coupling of growth from emissions. Though as we agree, emissions from China (and Asia in general), together with future unforeseen shifts will strongly influence outcomes.

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## Supplementary Material

### S1 Observed Socio-Economic Indicators and Scenario Projections

Figure S1: Global real GDP in levels in 1990 USD (top) and growth rates (bottom). Observed are shown in black, projections in colour.

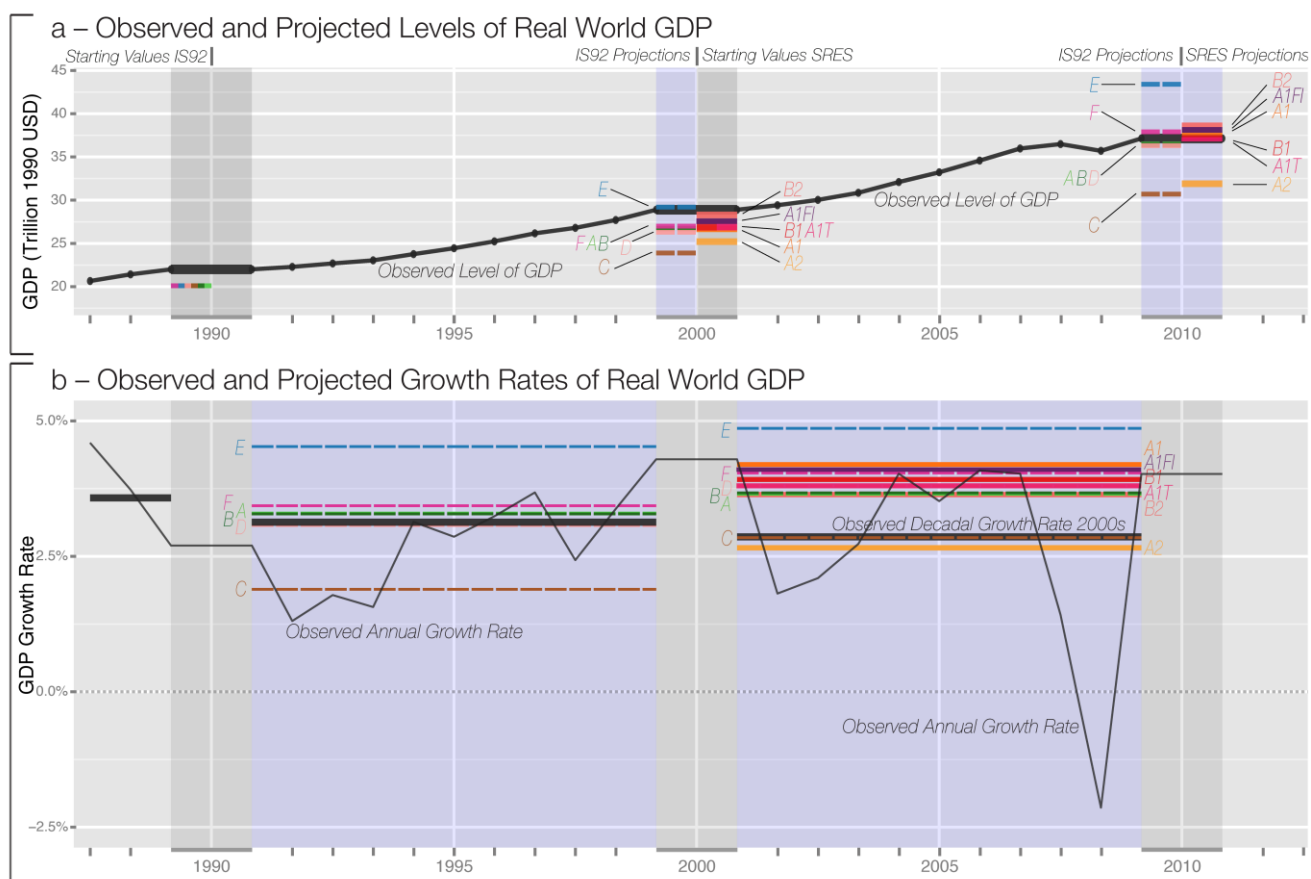
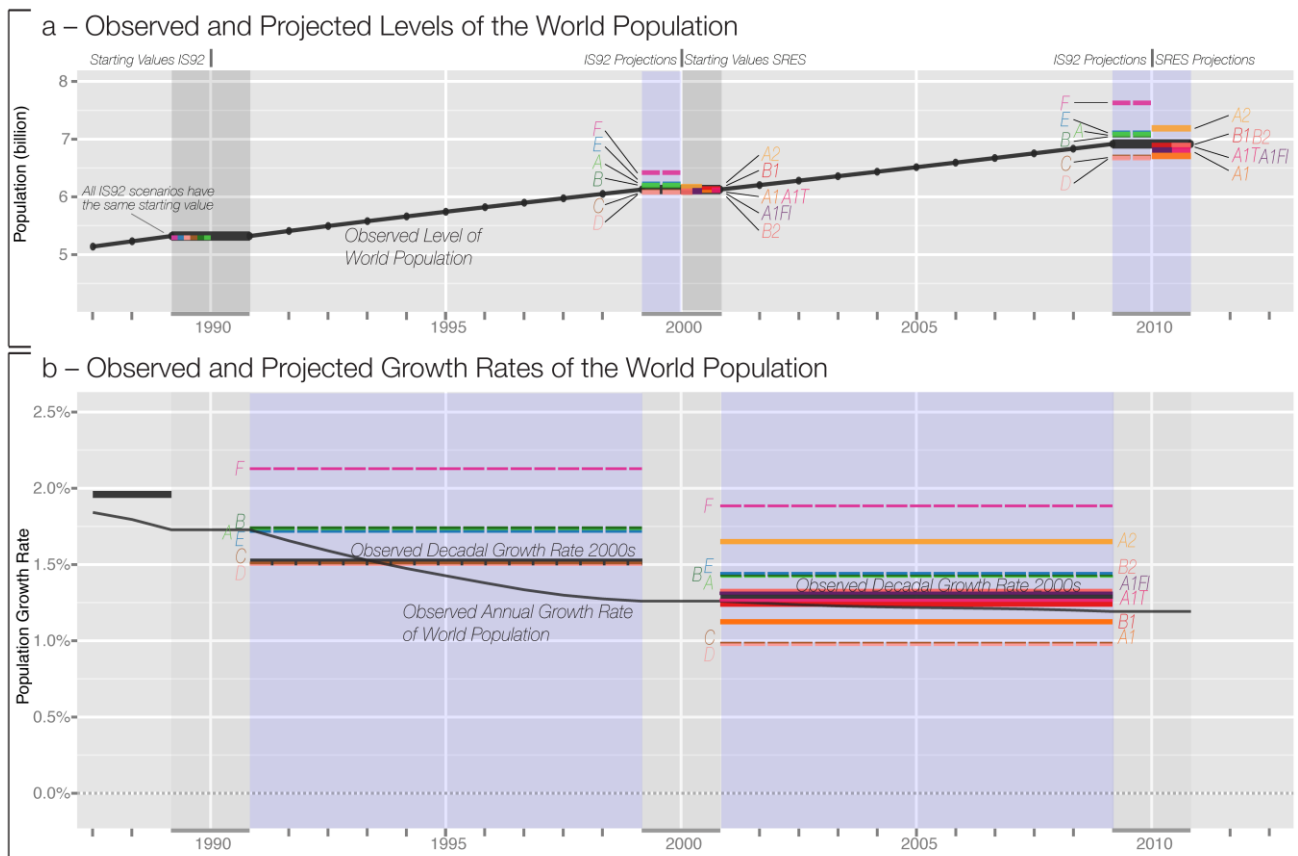


Figure S2: Global population in levels (top) and growth rates (bottom). Observed are shown in black, projections in colour.



## S2 Relative Scenario Performances

Table S1 lists the most accurate scenario based both on levels and growth rates for both 1990s and 2000s. Accuracy here is measured by the smallest absolute percentage deviation in levels, and the smallest absolute deviation in growth rates.

*Table S1: Closest SRES (red) and IS92 (blue) scenarios for 1990-2000 and 2000-2010 based on proportional deviation from observed levels and absolute difference from observed growth rates. Deviations are shown in parentheses.*

Time	GDP		Population		Fossil Fuel CO <sub>2</sub>		CO <sub>2</sub> Intensity	
	Level E (0.011)	Growth D (-0.045)	Level C/D (0.013)	Growth C/D (0.206)	Level D (-0.012)	Growth D (-0.196)	Level D (0.084)	Growth D (-0.122)
1990-2000								
2000-2010	B (-0.017) B1 (0.004)	C (-0.015) A2 (-0.201)	A/B/E (0.025) B1 (-0.003)	A/B/E (0.137) A1FI (-0.016)	A1FI (-0.001) B1 (-0.018)	E (-0.361) A1 (0.697)	E (-0.008) B1 (-0.023)	F (-1.375) A1 (-0.474)

Figure S3: CO<sub>2</sub> Intensity Differences to Observed Levels (top) and Growth Rates (bottom) over 1990-2000 (left) and 2000-2010 (right)

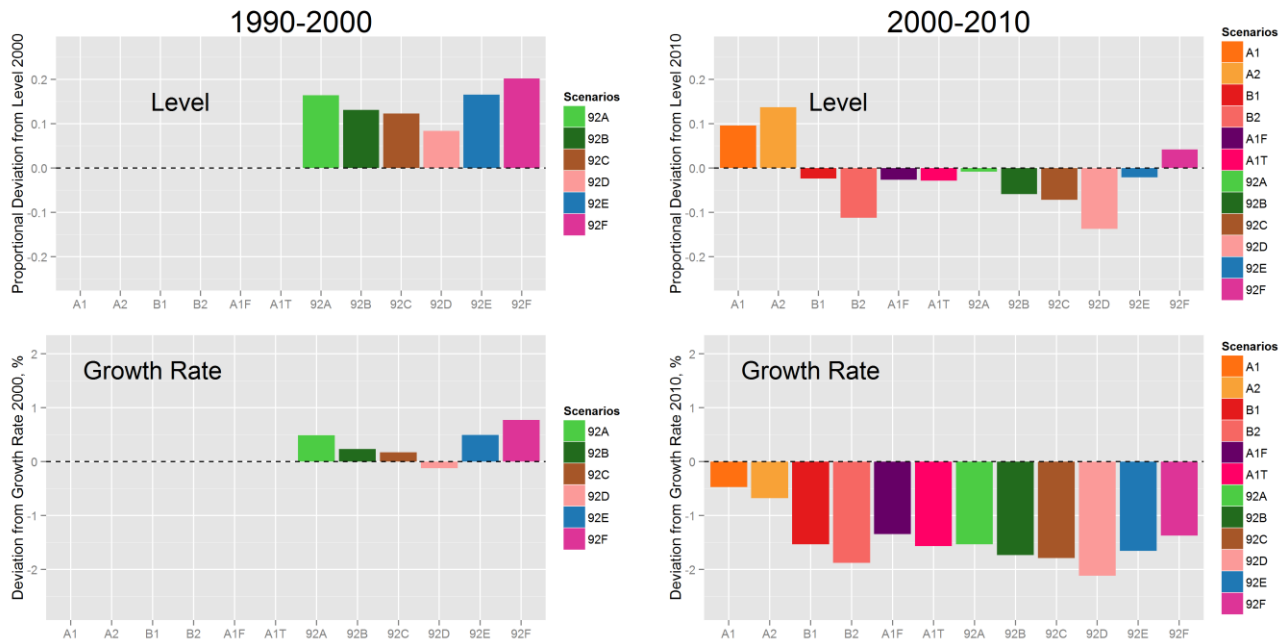


Figure S4: GDP Differences to Observed Levels (top) and Growth Rates (bottom) over 1990-2000 (left) and 2000-2010 (right)

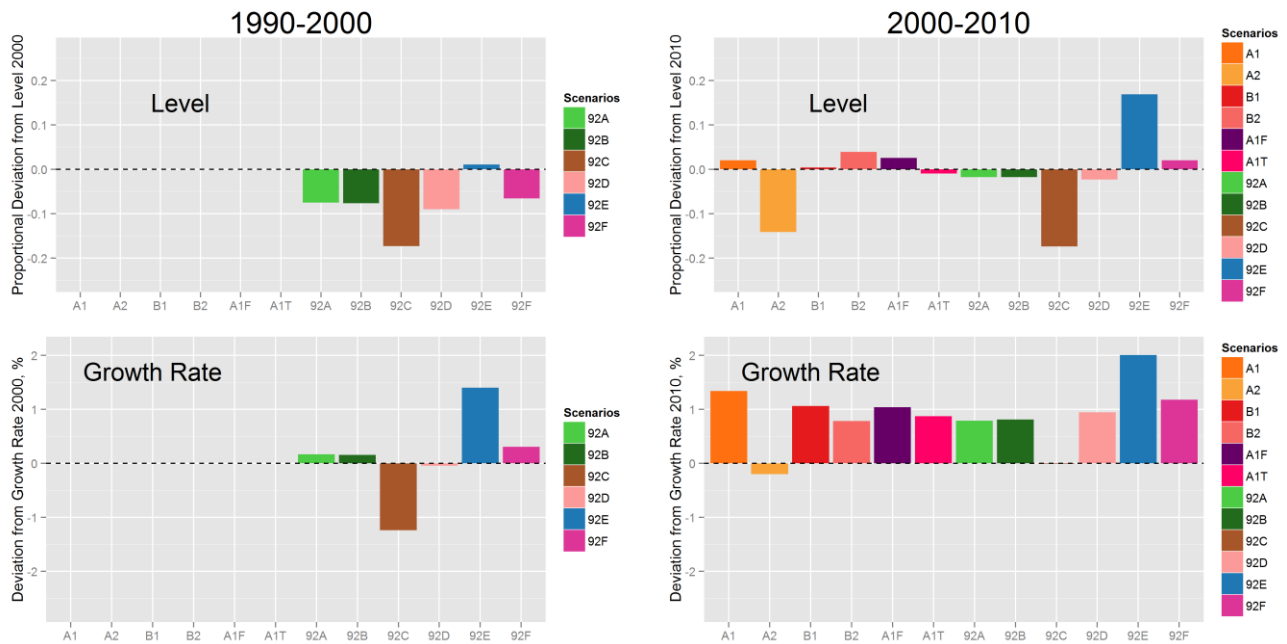


Figure S5: Population Differences to Observed Levels (top) and Growth Rates (bottom) over 1990-2000 (left) and 2000-2010 (right)

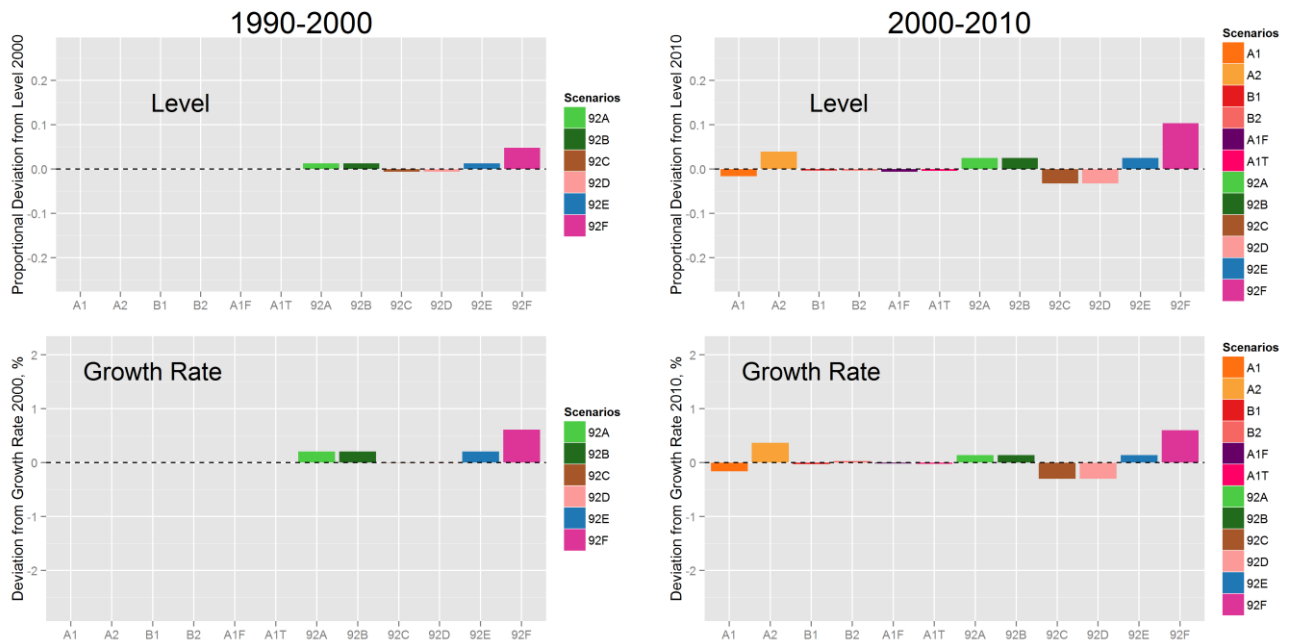
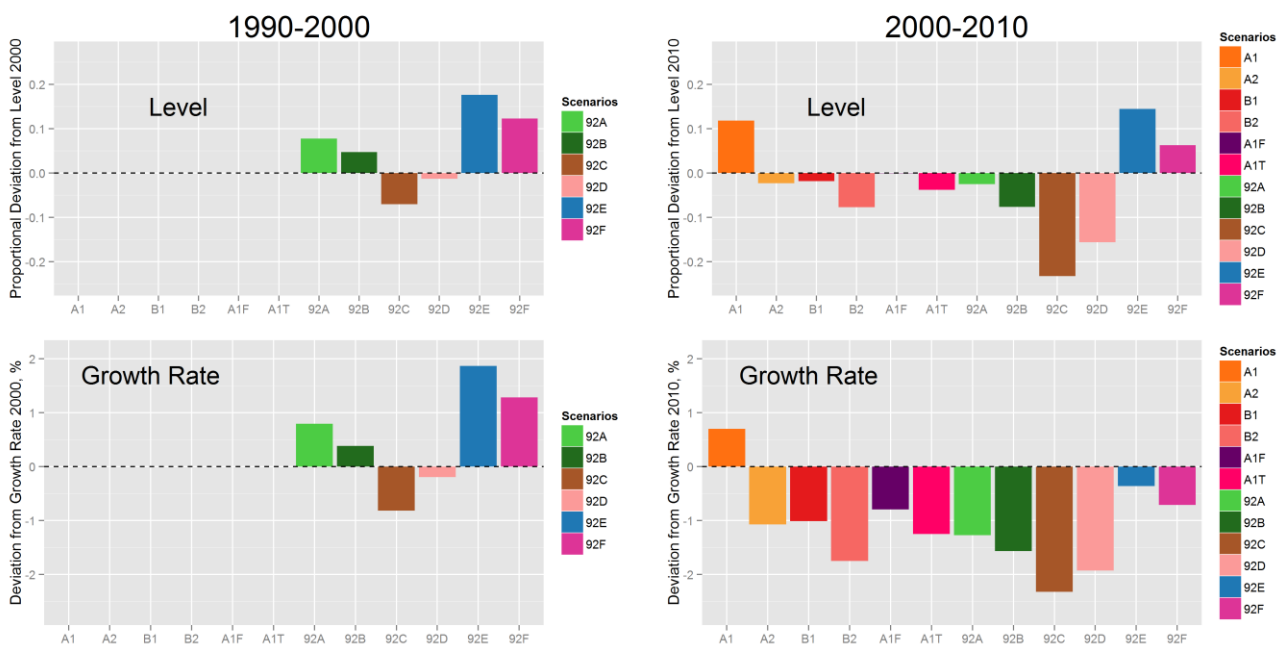


Figure S6: Fossil Fuel CO<sub>2</sub> Differences to Observed Levels (top) and Growth Rates (bottom) over 1990-2000 (left) and 2000-2010 (right)



### S3: Details of the Growth Decomposition

#### S3.1 Decomposing Aggregate Growth Rates

Let  $Y_t = \sum_j Y_t^j$  denote aggregate GDP over countries  $j$ , and let  $Z_t = \frac{C_t}{Y_t}$  denote aggregate fossil fuel CO<sub>2</sub> emissions per GDP, where aggregate fossil fuel emissions  $C_t = \sum_j C_t^j$  are summed over countries  $j$ . Each country  $j$ 's fossil fuel CO<sub>2</sub> emissions per GDP is defined as  $Z_t^j = \frac{C_t^j}{Y_t^j}$ . The corresponding aggregate ( $G_t$ ) and individual ( $G_t^j$ ) growth rates are given by  $G_t = \frac{Z_t - Z_{t-1}}{Z_{t-1}}$  and  $G_t^j = \frac{Z_t^j - Z_{t-1}^j}{Z_{t-1}^j}$  respectively.

The aggregate growth rate can then be re-expressed as:

$$G_t = \frac{Z_t - Z_{t-1}}{Z_{t-1}} = \frac{1}{Z_{t-1}} \left( \sum_j \frac{C_t^j}{Y_t} - \sum_j \frac{C_{t-1}^j}{Y_{t-1}} \right) \quad (1)$$

From above we use that the equation for the individual growth rate can be re-arranged to yield:

$$G_t^j \frac{C_{t-1}^j}{Y_{t-1}^j} = \frac{C_t^j}{Y_t^j} - \frac{C_{t-1}^j}{Y_{t-1}^j} \quad (2)$$

This provides an expression for country  $j$ 's fossil fuel emissions  $C_t^j$ :

$$C_t^j = (1 + G_t^j) C_{t-1}^j \frac{Y_t^j}{Y_{t-1}^j} \quad (3)$$

Therefore we can write the aggregate growth rate as a function of disaggregate growth rates by substituting for  $C_t^j$  in:

$$G_t = \left( \sum_j \frac{1}{Y_t} C_t^j - \frac{1}{Y_{t-1}} C_{t-1}^j \right) \frac{1}{Z_{t-1}} \quad (4)$$

This can be simplified to:

$$G_t = \left( \sum_j \frac{C_{t-1}^j}{Y_{t-1}^j} \left[ \frac{Y_t^j}{Y_t} (1 + G_t^j) - \frac{Y_{t-1}^j}{Y_{t-1}} \right] \right) \frac{1}{Z_{t-1}} = \left( \sum_j \frac{Z_{t-1}^j}{Z_{t-1}} \left[ \frac{Y_t^j}{Y_t} - \frac{Y_{t-1}^j}{Y_{t-1}} + G_t^j \frac{Y_t^j}{Y_t} \right] \right) \quad (5)$$

$$G_t = \left( \sum_j \frac{Z_{t-1}^j}{Z_{t-1}} \left[ \Delta \frac{Y_t^j}{Y_t} + G_t^j \frac{Y_t^j}{Y_t} \right] \right) = \left( \sum_j d_j \right) \quad (6)$$

Where  $d_j = \frac{Z_{t-1}^j}{Z_{t-1}} \left[ \Delta \frac{Y_t^j}{Y_t} + G_t^j \frac{Y_t^j}{Y_t} \right]$  and the term  $\Delta \frac{Y_t^j}{Y_t} = \frac{Y_t^j}{Y_t} - \frac{Y_{t-1}^j}{Y_{t-1}}$  captures the change in the proportion of country  $j$ 's GDP relative to total GDP. This yields the aggregate growth rates as the sum of the individual components  $j$  and allows for a decomposition of the aggregate growth rates into individual contributions  $d_j$ .

The individual contributions can be decomposed further into an “emission intensity growth rate effect” and a “relative change in GDP effect”:

$$d_j = \frac{Z_{t-1}^j}{Z_{t-1}} \left[ \underbrace{\Delta \frac{Y_t^j}{Y_t}}_{GDP\ Effect} + \underbrace{G_t^j \frac{Y_t^j}{Y_t}}_{Growth\ Rate\ Effect} \right] \quad (7)$$

If the ratio of the particular country's GDP to global GDP is unchanged ( $\Delta \frac{Y_t^j}{Y_t} = 0$ ), then the only contribution to the overall growth rate is derived from the growth rate effect:  $\frac{Z_{t-1}^j}{Z_{t-1}} G_t^j \frac{Y_t^j}{Y_t}$ . Whether the contribution to the overall growth rate is positive or negative therefore depends on the change in the ratio of a country's GDP relative to the global GDP, and a country's growth rate in emissions per GDP,  $G_t^j$  scaled by the weight of the country's GDP relative to the global GDP.

### S3.2 Decomposing the Difference between Observed and Projected Aggregate Growth Rates

When comparing an observed growth rate ( $G_t$ ) against a scenario predicted growth rate ( $\hat{G}_t$ ), using the same decomposition procedure as above, the difference between observed and predicted growth rates can be attributed to disaggregated country contributions, and further into relative GDP change and emission intensity growth rate effects. Given the summability, simple regional aggregates can be considered as well as country-level disaggregation. These are plotted in Figure 2 (panel b) for individual contributions to the overall difference in growth rates exceeding 0.1%.

$$G_t - \hat{G}_t = \sum_j d_j - \sum_j \hat{d}_j \quad (8)$$

$$G_t - \hat{G}_t = \sum_j \frac{Z_{t-1}^j}{Z_{t-1}} \left[ \Delta \frac{Y_t^j}{Y_t} + G_t^j \frac{Y_t^j}{Y_t} \right] - \sum_j \frac{\hat{Z}_{t-1}^j}{\hat{Z}_{t-1}} \left[ \Delta \frac{\hat{Y}_t^j}{\hat{Y}_t} + \hat{G}_t^j \frac{\hat{Y}_t^j}{\hat{Y}_t} \right] \quad (9)$$

$$G_t - \hat{G}_t = \sum_j \underbrace{\left( \frac{Z_{t-1}^j}{Z_{t-1}} \left[ \Delta \frac{Y_t^j}{Y_t} \right] - \frac{\hat{Z}_{t-1}^j}{\hat{Z}_{t-1}} \left[ \Delta \frac{\hat{Y}_t^j}{\hat{Y}_t} \right] \right)}_{GDP\ Effect} + \underbrace{\left( \frac{Z_{t-1}^j}{Z_{t-1}} G_t^j \left[ \frac{Y_t^j}{Y_t} \right] - \frac{\hat{Z}_{t-1}^j}{\hat{Z}_{t-1}} \hat{G}_t^j \left[ \frac{\hat{Y}_t^j}{\hat{Y}_t} \right] \right)}_{Growth\ Rate\ Effect} \quad (10)$$

### S3.3 Total Growth Rate Decomposition into GDP and pure Emission Intensity Growth Rate Effect

Country-by-country contributions to the difference in observed world growth rates and projected growth rates can be further decomposed into a GDP effect and a growth rate effect using the results from section 5.2:

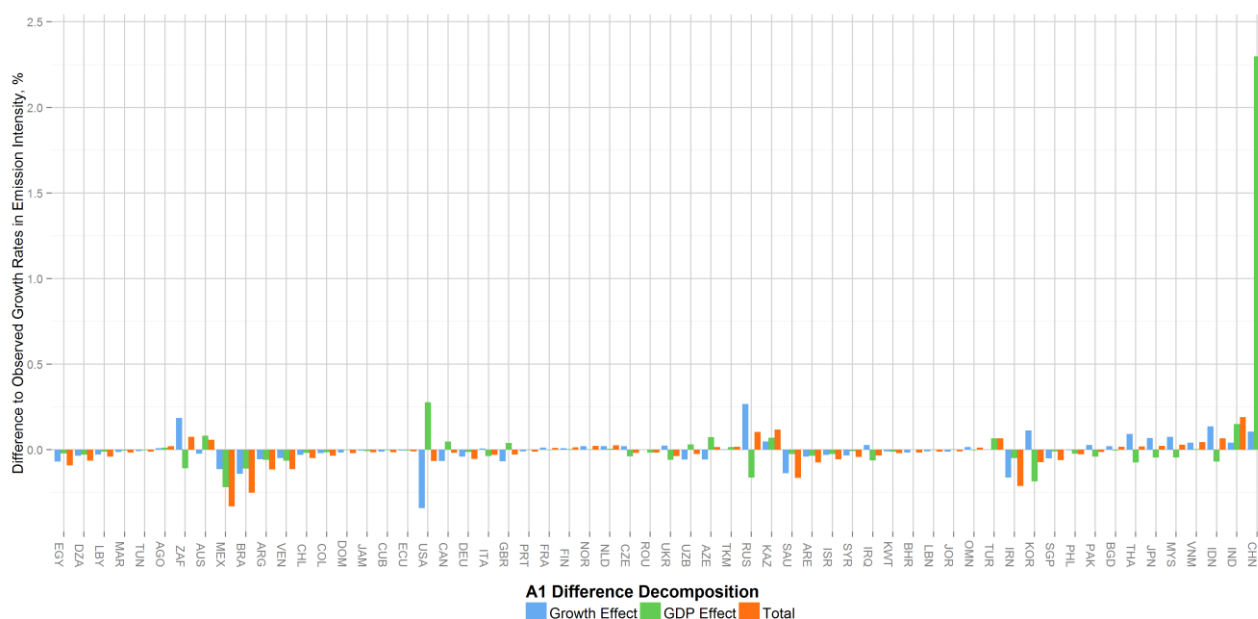
$$G_t - \hat{G}_t = \sum_j \underbrace{\left( \frac{Z_{t-1}^j}{Z_{t-1}} \left[ \Delta \frac{Y_t^j}{Y_t} \right] - \frac{\hat{Z}_{t-1}^j}{\hat{Z}_{t-1}} \left[ \Delta \frac{\hat{Y}_t^j}{\hat{Y}_t} \right] \right)}_{GDP\ Effect} + \underbrace{\left( \frac{Z_{t-1}^j}{Z_{t-1}} G_t^j \left[ \frac{Y_t^j}{Y_t} \right] - \frac{\hat{Z}_{t-1}^j}{\hat{Z}_{t-1}} \hat{G}_t^j \left[ \frac{\hat{Y}_t^j}{\hat{Y}_t} \right] \right)}_{Growth\ Rate\ Effect}$$

Figure S7 graphs the difference in growth rate decomposition for the SRES projection A1 for countries with an overall effect exceeding 0.01 (1%). China contributes the largest absolute amount, this is primarily driven by changes in the ratio of China's GDP relative to aggregate GDP. The largest CO<sub>2</sub> intensity growth rate effects



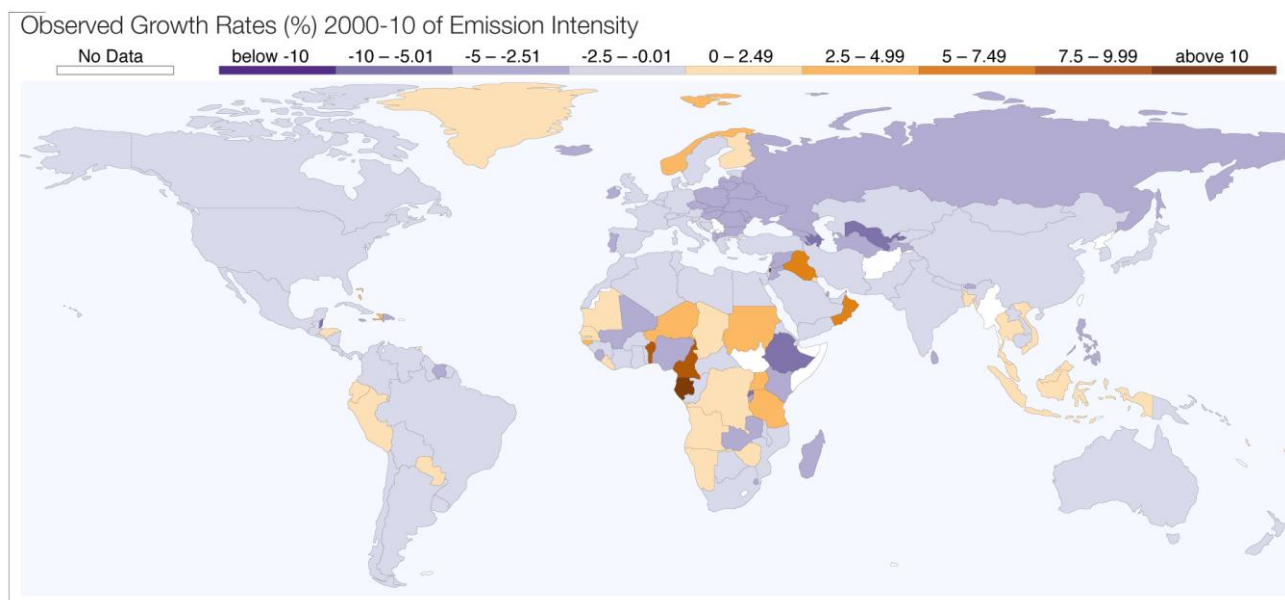
stem from Russia and South Africa, however, the total effect of these is comparatively minor due to their small weight in global emission intensity.

Figure S7: Country-by-country contribution to the Global Difference between Observations and Scenario Projections (A1) in Growth Rates 2000-10 of Emission Intensity Decomposed into CO<sub>2</sub> intensity Growth (blue), GDP (green) and Total Effects (orange).



#### S4 Observed Country-by-Country Growth Rates of Emission Intensity

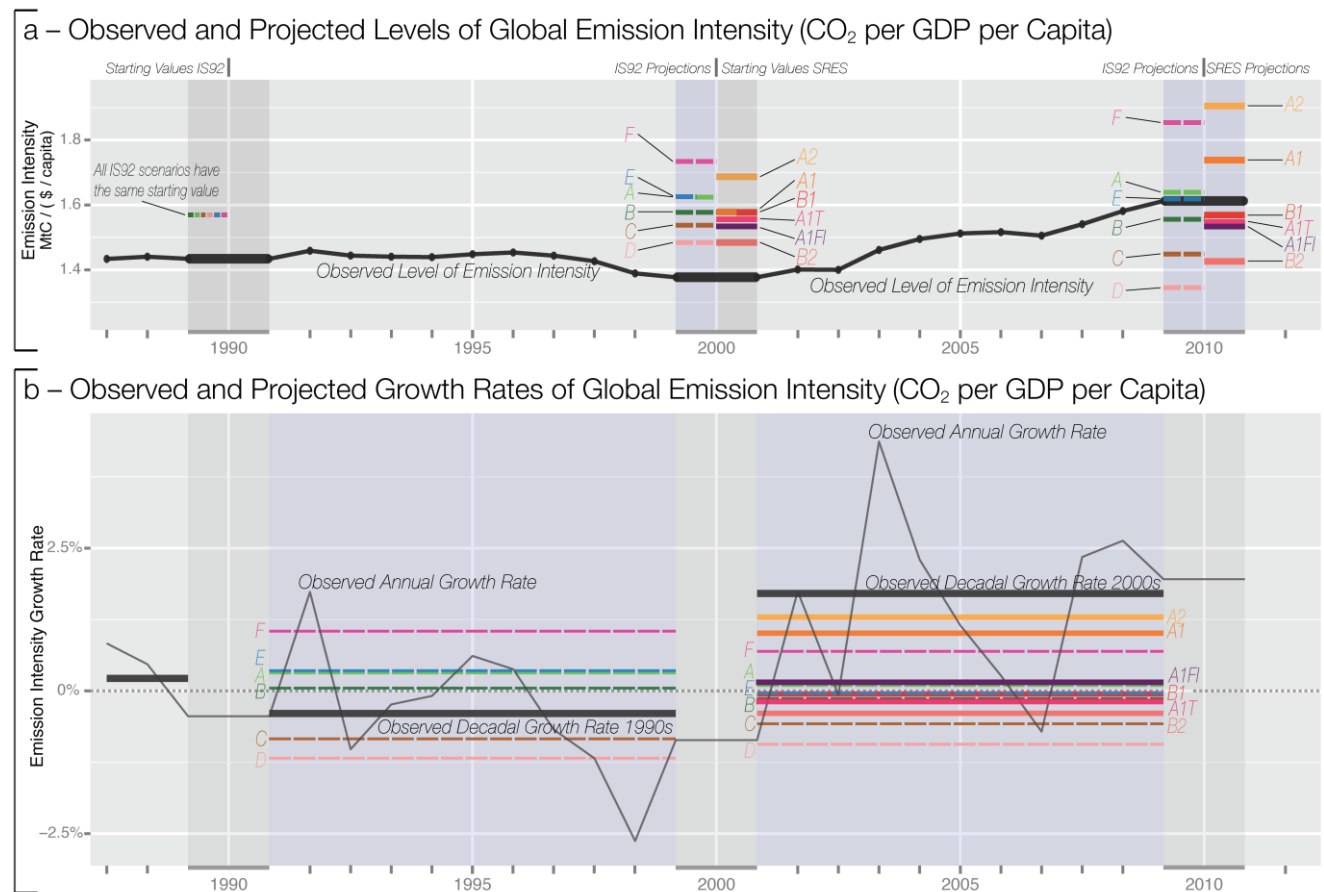
Figure S8: Observed average decadal growth rates of Emission Intensity ( $\text{CO}_2$  per GDP) by country over 2000-2010.



## S5 Fossil-fuel CO<sub>2</sub> Emissions per GDP per Capita

Here we present results of emission intensity measured as fossil-fuel CO<sub>2</sub> emissions per GDP per capita. Consistent with the results in the main text, decadal emission intensity per capita growth over the 2000s exceeded all IS92 and SRES marker scenarios (Figure S9).

**Figure S9:** Observed and projected global emission intensity measured in fossil-fuel CO<sub>2</sub> emissions per GDP per capita in levels (a) and growth rates (b). Panel a graphs global observed annual fossil-fuel CO<sub>2</sub> emissions per GDP (black) together with decadal IS92 (dashed colour) and SRES marker projections (solid colour). Starting values are shaded grey while projected values are shaded light blue. Note that initial values for SRES vary across scenarios. Panel b shows observed annual growth rates (continuous black) together with observed decadal growth rates (horizontal black) over both decades. Projected growth rates are shown in colour for IS92 (dashed) and SRES marker projections (solid). Observed decadal growth rates exceed all scenario projections over the 2000s.



## S6 Alternative down-scaling method using data from van Vuuren et al. (2007)

Figure S10: Decomposition of the global difference between global observed and projected emission intensity using the van Vuuren et al. (2007) country-by-country downscaled difference between observed and projected decadal growth rates in emission intensity for SRES marker projections over 2000-2010. The panel graphs the country-by-country contribution to the difference between global observed and global projected growth rates in emission intensity. Only countries contributing more than 0.001 towards the difference are shown. The primary contribution to the differences in global growth rates using relative to SRES projections stems from changes in Asia and China in particular, while some (e.g. US) observations remain close to projections, thus lowering the difference between global observed and projected growth rates.

Country-by-country Contribution to the Difference between Global Observed and Global Projected Growth Rates (downscaled by van Vuuren et al.) (%) 2000-10 of Emission Intensity

