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IPCC baseline scenarios have over-projected CO_2 emissions and economic growth

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Abstract

Scenarios used by the Intergovernmental Panel on Climate Change (IPCC) are central to climate science and policy. Recent studies find that observed trends and International Energy Agency (IEA) projections of global CO_2 emissions have diverged from emission scenario outlooks widely employed in climate research. Here, we quantify the bases for this divergence, focusing on Kaya Identity factors: population, per-capita gross domestic product (GDP), energy intensity (energy consumption/GDP), and carbon intensity (CO_2 emissions/energy consumption). We compare 2005–2017 observations and IEA projections to 2040 of these variables, to 'baseline' scenario projections from the IPCC's Fifth Assessment Report (AR5), and from the shared socioeconomic pathways (SSPs) used in the upcoming Sixth Assessment Report (AR6). We find that the historical divergence of observed CO_2 emissions from baseline scenario projections can be explained largely by slower-than-projected per-capita GDP growth—predating the COVID-19 crisis. We also find carbon intensity divergence from baselines in IEA's projections to 2040. IEA projects less coal energy expansion than the baseline scenarios, with divergence expected to continue to 2100. Future economic growth is uncertain, but we show that past divergence from observations makes it unlikely that per-capita GDP growth will catch up to baselines before mid-century. Some experts hypothesize high enough economic growth rates to allow per-capita GDP growth to catch up to or exceed baseline scenarios by 2100. However, we argue that this magnitude of catch-up may be unlikely, in light of: headwinds such as aging and debt, the likelihood of unanticipated economic crises, the fact that past economic forecasts have tended to over-project, the aftermath of the current pandemic, and economic impacts of climate change unaccounted-for in the baseline scenarios. Our analyses inform the rapidly evolving discussions on climate and development futures, and on uses of scenarios in climate science and policy.

1. Introduction

Scenarios are central to climate change science: connecting physical and social research on projected impacts, and underpinning discussions of adaptation and mitigation. Scenarios are used in both exploratory analyses—sometimes intentionally extreme—and policy-relevant projections, where realism is more important (Pielke and Ritchie 2020). These analyses serve different functions, and should be evaluated differently. Here we focus on policy-relevant uses of scenarios to inform near- and long-term projections. Such scenarios are useful to the extent that they accurately capture real-world trends; inaccurate scenarios can mislead.

The IPCC has long used 'marker scenarios' to represent a family of scenarios sharing a particular storyline or pathway (Nakicenovic *et al* 2000). Recent marker scenarios are associated with representative concentration pathways (RCPs)—each with different radiative forcing in 2100. The RCPs did not originally intend to specify socioeconomic pathways (Moss *et al* 2010), but the RCPs were selected from socioeconomic pathways from integrated assessment modeling groups for marker scenarios producing radiative forcing levels of 2.6, 4.5, 6.0 and 8.5 W m^{-2} (RCPs 2.6, 4.5, 6.0, and 8.5). Scenarios developed for the forthcoming IPCC AR6 associate five 'shared socioeconomic pathways' (SSPs) with a second generation of RCPs. These RCPs include new forcing levels of 1.9, 3.4 and 7.0 W m^{-2} (O'Neill *et al* 2014, Riahi *et al* 2017, International Institute for Applied Systems Analysis (IIASA) 2018, Rogelj *et al* 2018).

IPCC Working Groups I and II typically utilize four or more marker scenarios to project future climate and impacts. However, in practice, research often emphasizes low- and high-forcing scenarios, in ways that can give the impression (Hausfather and Peters 2020) that: the high-forcing scenario is business as usual (BAU) or its equivalent, the low-forcing scenario is what can be achieved through mitigation, and the difference in projected impacts reflects benefit of mitigation (or the cost of not mitigating). For instance, the 2019 IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) (IPCC 2019) focused on RCPs 2.6 and 8.5, and the 2018 U.S. National Climate Assessment (USNCA) (U.S. Global Change Research Program 2018) similarly emphasized RCPs 4.5 and 8.5. These reports avoided the phrase 'business as usual', but used RCP8.5 as a reference scenario (Pielke and Ritchie 2020).

IPCC Working Group III solicits scenario submissions and approved 1184 scenarios for AR5, classifying each as either: baseline scenarios (a.k.a. 'BAU', 'no-policy', or 'reference'; Working Group III of the Intergovernmental Panel on Climate Change (IPCC WGIII) 2014, IPCC 2014, Rogelj *et al* 2016) modeling futures without climate or energy policies (some exclude existing policies); or 'mitigation' (a.k.a. 'policy') scenarios incorporating explicit climate or energy policies. Baseline scenarios, and their aggregate distribution, are often used as counterfactuals for assessing mitigation challenges and benefits (e.g. Rogelj *et al* 2016). The median of AR5 WGIII baseline CO_2 emissions was closest to RCP8.5, among the RCPs (figure 1(a)).

Hausfather and Peters (2020) note that global fossil-fuel CO_2 emissions fall below the pathway underlying RCP8.5 and argue this divergence will widen, noting the International Energy Agency's (IEA) projections to 2040 under its 'Current Policies' scenario (assuming continuity in enacted energy and climate policies) (IEA 2019a). Hausfather and Peters (2020) conclude that RCP8.5 should not be used as a reference scenario, and that RCP4.5 or RCP6 (generally consistent with ∼3 °C of warming by 2100) offer more realistic baselines (see also Raftery *et al* 2017)[5].

To inform improved climate scenarios and understandings of medium-term (2020–2040) to long-term (2020–2100) futures, we quantify factors underlying the divergence between (a) AR5 and SSP baseline scenarios (IPCC WGIII 2014, IIASA 2018) and (b) both observations (IEA 2019b) and energy-outlook projections (BP 2019, U.S. Energy Information Administration (EIA) 2019, ExxonMobil 2019, IEA 2019a)—focusing on the 2019 IEA World Energy Outlook (IEA 2019a). We focus on the four drivers of energy-related CO_2 emissions of the Kaya identity (Kaya and Yokoburi 1997):

$$\begin{aligned} CO_2 \text{ emissions} &= \text{population} \times \text{GDP per capita} \\ &\quad \times \text{energy intensity} \times \text{carbon intensity}, \end{aligned} \tag{1}$$

where 'energy intensity' is primary energy/gross domestic product (GDP), and 'carbon intensity' is CO_2 emissions/primary energy. Our comparisons are both global and regional (using IPCC region definitions; IPCC WGIII 2014).

2. Methods

2.1. Comparing fossil-fuel CO_2 emissions

We compare fossil-fuel CO_2 emission projections from AR5 and SSP baselines[6], RCP marker scenarios, and BAU-like energy outlook scenarios (see supplementary materials (sm), table S1 (available online at https://stacks.iop.org/ERL/16/014016/mmedia)) (shown in figures 1 and S1) (Burgess *et al* 2020). This comparison requires harmonization, as AR5 Working Group III and SSP databases (IPCC WGIII 2014, IIASA 2018) include baseline scenarios of combined fossil-fuel and industry (FF&I) CO_2 emissions, while energy outlooks report only fossil-fuel CO_2 emissions. We apply Ritchie and Dowlatabadi's (2017) harmonization procedure (see sm).

[5] A recent study by Schwalm *et al* (2020) projects that cumulative CO_2 emissions under the IEA's Current Policies scenario (CPS) will track RCP8.5 more closely than other RCPs to 2050, but they arrive at this conclusion by assuming that future land-use emissions (which the IEA does not project) will be substantially higher than any of the SSPs anticipate, thus compensating for RCP8.5's underprojection of CO_2 emissions from fossil fuels (Riahi *et al* 2017).

[6] We focus on these scenarios as they are the basis for Coupled Model Intercomparison Project (CMIP5) and the more recent CMIP6 which provided the scientific evidence base for AR5 and AR6 (Eyring *et al* 2016), but we note that other integrated assessment model scenarios besides these databases have been developed, such as those used in the *IPCC Special Report: Global Warming of 1.5 °C* (IPCC 2018), which were narrower in scope—focusing on '1.5 °C and related scenarios' (IIASA 2019). Analyzing a broader range of IAM scenarios is beyond the scope of the present study.

2.2. Comparing Kaya-identity-factor growth rates

We compare observed Kaya factor growth rates to AR5 WGIII and SSP baseline scenarios (IPCC WGIII 2014, Riahi *et al* 2017, IIASA 2018). For consistency, we utilize observations of all Kaya factors from IEA's CO_2 Emissions from Fuel Combustion 2019 Highlights (IEA 2019b), which has annual country-level data from 1971 to 2017. The SSP database (IIASA 2018) reports GDP in purchasing power parity (PPP) units, while the AR5 WGIII database (IPCC WGIII 2014) reports GDP using market exchange rates (MER), both in constant USD. The IEA (2019b) reports both measures; thus, we use MER GDP when comparing to the AR5 WGIII database, and PPP GDP when comparing to the SSP database.

We compare (a) the annual continuous growth rate in each Kaya factor in each IPCC region (see sm for harmonization procedure) from 2005 (the year most AR5 and SSP scenarios begin projecting) to 2017 (latest year in IEA 2019b) in the observations, to (b) the 2005–2020 annual continuous growth rate in the AR5 WGIII and SSP databases. We calculate the annual continuous growth rate (g) in a factor, X, between year 2005 and year t (2017 or 2020) as (%/y):

$$g = 100\left[\frac{\ln(X_t) - \ln(X_{2005})}{t - 2005}\right]. \tag{2}$$

For each baseline scenario in the AR5 WGIII and SSP databases, we calculate the 'growth error' (denoted E) for each Kaya factor as the difference between the projected (2005–2020) and observed (2005–2017) annual growth rates, g (shown in figure 2):

$$E = g_{\text{projected}} - g_{\text{observed}}. \tag{3}$$

We perform sensitivity analyses (shown in figure S2) regarding economic growth, removing the years 2008–2009 to show short-term effects of the Great Recession, and adding the International Monetary Fund's (IMF) April 2020 World Economic Outlook (WEO) estimates and projections of 2018–2020 per-capita GDP growth, which include projections of COVID-19 impact (IMF 2020a, 2020b).

We follow a similar procedure to calculate divergences between (a) IEA's Current Policies and Stated Policies scenarios, and (b) each baseline scenario for 2020–2040 (figures 1(b) and S3, table S2). The IEA reports GDP projections to 2040 in PPP units; thus, figure 1(b) shows the comparison with SSP baselines[7]. We focus at the global level, because the IEA (2019a) uses different regional classifications than the IPCC.

We compare (a) per-capita GDP growth rates (constant-dollar PPP) projected by SSP baselines to (b) the IMF's October 2019 WEO (2019, 2020b) projections to 2024 and April 2020 WEO (2020a, 2020b) projections to 2021 (shown in figure 3). Because the SSPs project per-capita GDP on 5–10 year intervals, we assume a constant continuous growth rate within each interval. We calculate these growth rates by linearly interpolating log-transformed per-capita GDP within each region-model-scenario combination.

2.3. Catch-up rates for per-capita GDP growth

Given uncertainties and debates surrounding future economic growth, we calculate 'catch-up' rates for per-capita GDP growth from 2020 to 2040 and from 2020 to 2100, defined as the rates of growth needed for overall 2005–2040 or 2005–2100 growth to match each baseline scenario, given past discrepancies. We specifically calculate three different 'catch-up' scenarios, shown in figure 4.

First, we assume 2005–2017 average growth rates continue through 2020. In this scenario, 'catch-up' rates (denoted G_{40} for 2020–2040 and G_{100} for 2020–2100) are calculated as:

$$G_{40} = g_{2020-2040\text{proj}} + 0.75E. \tag{4a}$$

$$G_{100} = g_{2020-2100\text{proj}} + \left(\frac{3}{16}\right)E. \tag{4b}$$

Here, $g_{2020-2040\text{proj}}$ and $g_{2020-2100\text{proj}}$ denote projected 2020–2040 and 2020–2100 per-capita GDP growth rates (calculated analogously to equation (2)) in each AR5 and SSP baseline scenario[8].

Second, we extend the 2005–2017 per-capita GDP growth time series to include the April 2020 IMF WEO (International Monetary Fund (IMF) 2020a, 2020b) estimates and projections from 2018 to 2021. These include their projected COVID-19 impact on 2020 and 2021 growth assuming a V-shaped recovery (figure 3), which some economists consider overly optimistic (e.g. Congressional Budget Office (CBO) 2020). This increases the calculated growth error (E) in equation (4) above, and thus also the calculated catch-up rates (which are now calculated from 2021–2040 to 2021–2100). Third, we simulate a doubling of the COVID-19 effect on the growth of each region by doubling the difference between the average 2020–2021 growth rate and the 2018–2019 growth rate observed. To generate per-capita GDP by IPCC region from the (country-level) IMF data, we sum GDP and population across the countries in each

[7] We show the comparison with AR5 baselines in figure S3, but caution that using PPP units produces higher global growth rates (because poor countries receive higher weights), and thus the comparison is imperfect for per-capita GDP and energy intensity growth.

[8] We multiply E by 0.75 (3/16) because the catch-up period, 2020–2040 (2020–2100), is 20 (80) years, compared to the 15-year period (2005–2020) over which the growth error (E) occurred.

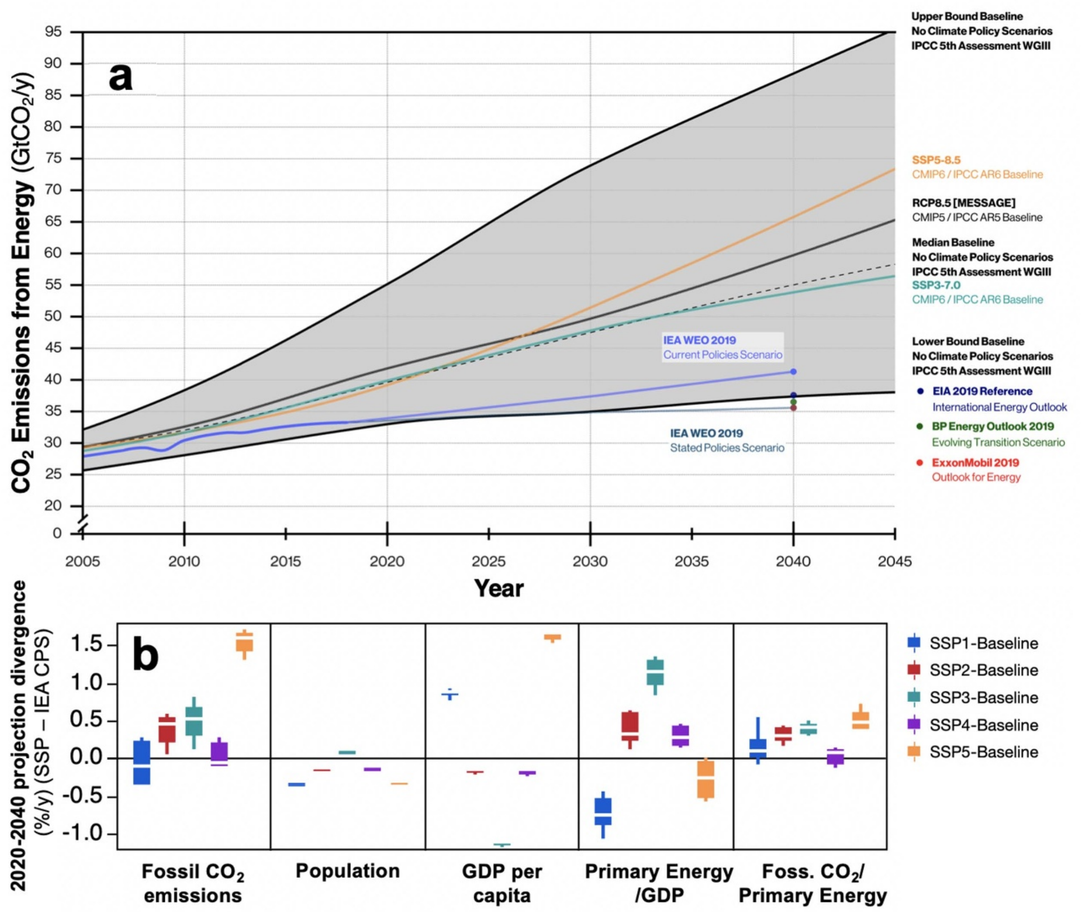

Figure 1. Panel (a) shows a comparison of energy-related CO_2 emissions projected by energy outlooks (British Petroleum (BP) 2019, EIA 2019, ExxonMobil 2019, International Energy Agency (IEA) 2019a) and by IPCC AR5 (IPCC WGIII 2014) and high-emission SSP (Riahi *et al* 2017, IIASA 2018) (SSP5-8.5, SSP3-7.0) baseline scenarios. Panel (b) shows differences in projected average growth rates (%/y, continuous) of Kaya identity factors, between the IEA WEO (2019a) (averaged from 2018 to 2040) and the SSP baseline scenarios (averaged from 2020 to 2040). Boxes represent 25th–75th percentiles (white dashes indicate medians). Lines above and below the boxes represent the full (min–max) range.

region, and then divide the resulting total GDP by total population[9].

We compare these 'catch-up' rates to the range of 2010–2050 and 2010–2100 per-capita GDP growth rates projected by a group of macroeconomists surveyed by Christensen *et al* (2018) (see sm for harmonization procedure).

3. Results

From 2005 to 2017, energy CO_2 emissions grew slower than in 83% of AR5 and 73% of SSP baseline scenarios (figures 1(a) and 2). Consequently, emissions tracked near the low end of the baseline scenario ranges (figures 1(a) and S1). Even before COVID-19, reference energy outlooks (BP 2019, EIA 2019, ExxonMobil 2019, IEA 2019a) projected that this divergence will continue to 2040, such that energy emissions would lie below the entire ranges of AR5 (figure 1(a)) and SSP (figure S1) baseline scenarios.

3.1. Drivers of 2005–2017 baseline scenario divergence from observations

CO_2 emissions-growth divergence between baseline scenarios and observations from 2005 to 2017 is primarily due to baseline scenarios over-projecting per-capita GDP growth (figure 2), with most AR5 baselines too high in all regions except Asia (figure 2(a)), and all SSP baselines too high in all regions (figures 2(b) and 3). Error magnitudes are similar in AR5 and SSP baselines.

Excluding 2008–2009 nearly eliminates growth errors in OECD countries, and significantly reduces errors for the former Soviet Union countries (REF), but has little effect on the errors in other regions (figure S2), where the projection errors largely come from other years (figures 3(b)–(d)).

Baseline scenario projections were limited in range but quite accurate for 2005–2017 population

[9] We use the October 2019 WEO (International Monetary Fund (IMF) 2019) population projections, since these are not readily calculable from the April 2020 WEO (IMF 2020) per-capita GDP projections.

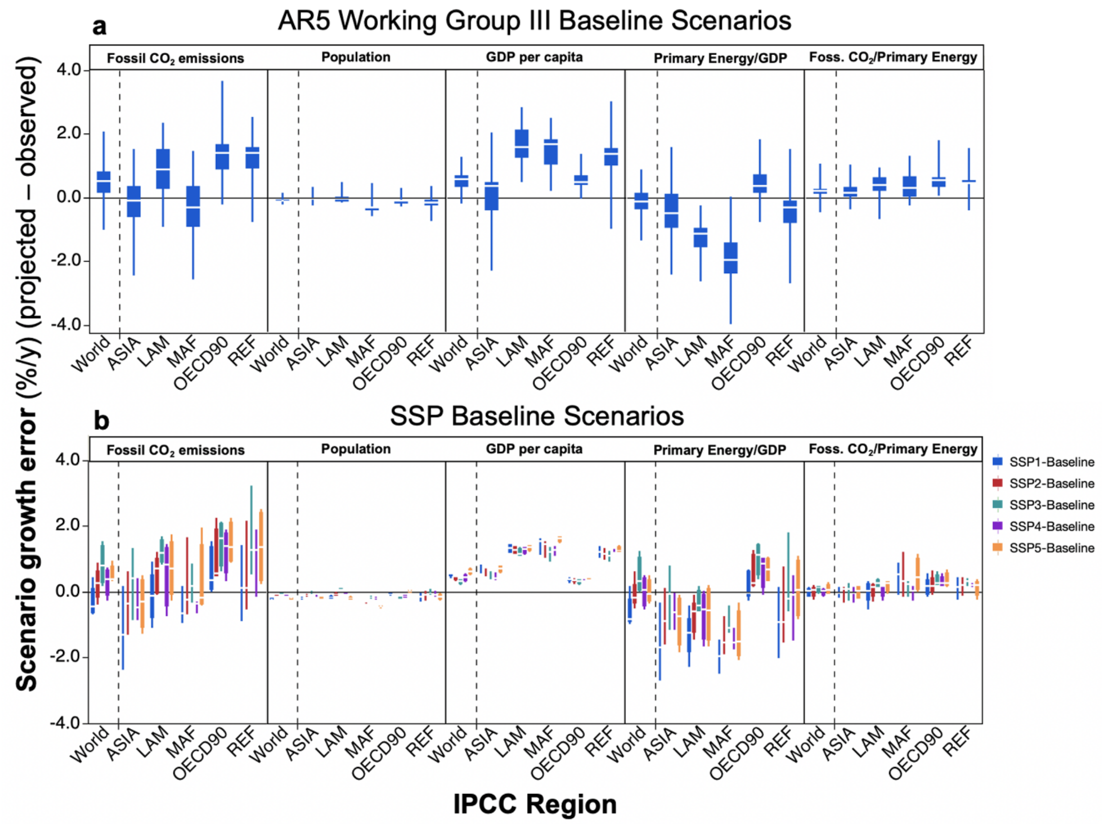

Figure 2. Comparisons in average annual growth rates between AR5 (IPCC WGIII 2014) (a) and SSP (Riahi *et al* 2017, IIASA 2018) (b) baseline scenarios (2005–2020) relative to observations (2005–2017) (IEA 2019b). Boxes represent 25th–75th percentiles (white dashes indicate medians). Lines above and below the boxes represent the full (min–max) range.

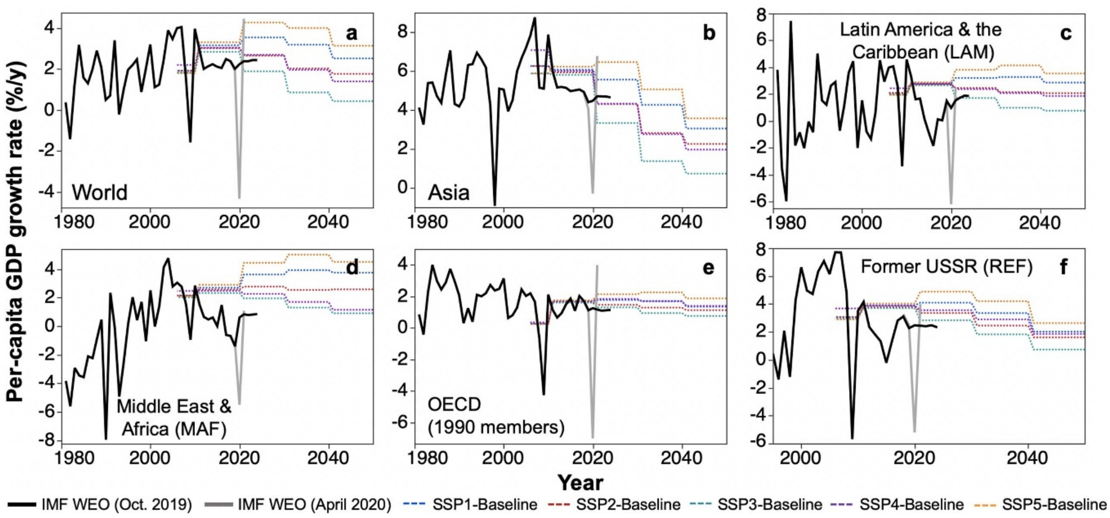

Figure 3. Per-capita GDP growth in SSP baselines (IIASA 2018) compared to data and projections (to 2021 or 2024) from IMF (2019, 2020a, 2020b).

growth (figure 2)[10]. AR5 baseline scenarios slightly over-projected carbon intensity growth (or under-projected its decline) in every region (figure 2(a)), and similarly for SSP baselines in all regions except Asia (figure 2(b)).

Globally, AR5 and SSP baseline energy intensity projections were consistent with observed 2005–2017 trends (figure 2). However, most baseline scenarios over-projected energy intensity in the OECD, and under-projected it in the Middle East and Africa (MAF) and Latin America and the Caribbean (LAM) (figure 2). These regional differences may reflect recent offshoring of energy-intensive

[10] We note that this makes GDP projection errors approximately equal to per-capita GDP projection errors.

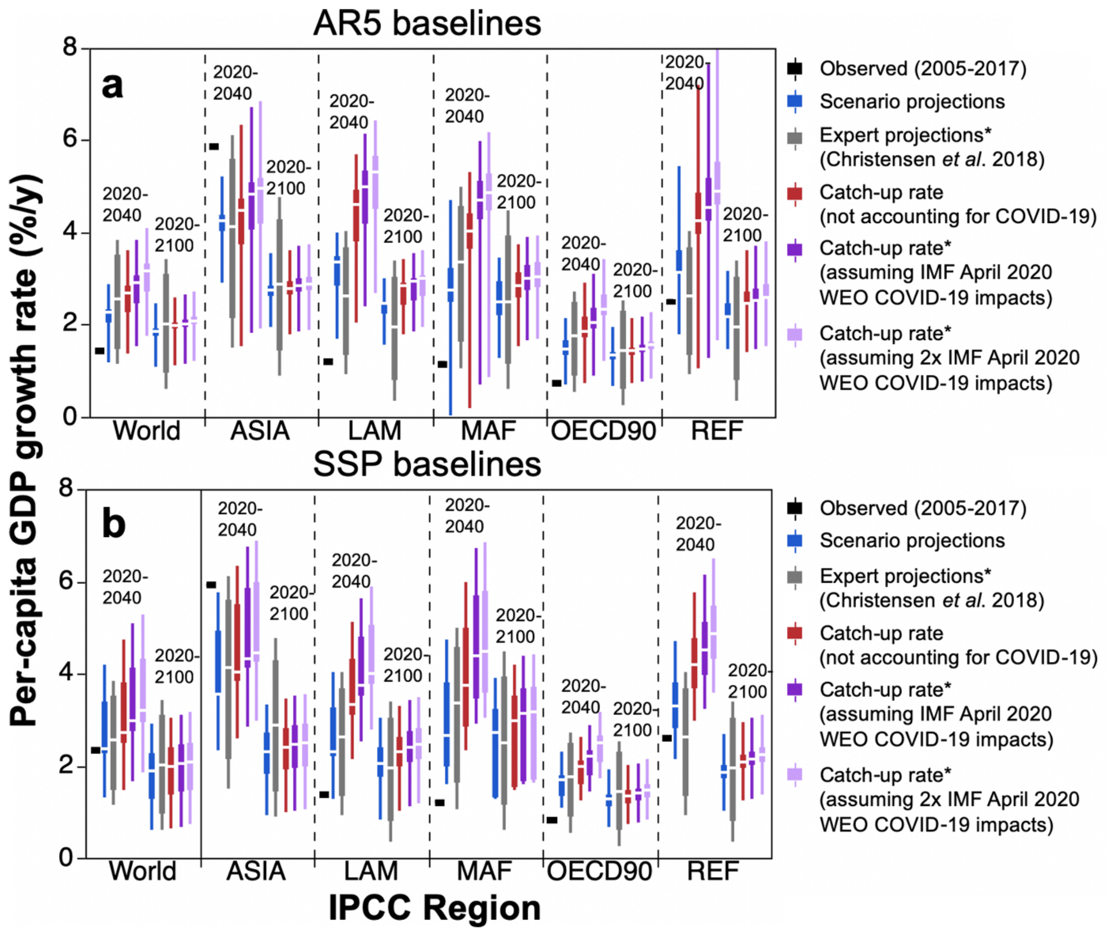

Figure 4. Comparisons of per-capita GDP growth rates: observed (IEA 2019b) from 2005 to 2017 (black), projected by baseline scenarios ((a): AR5 with MER units, (b): SSPs with PPP units) (blue) from 2020 to 2040 or 2020 to 2100 (IPCC WGIII 2014, IIASA 2018), projected by experts (macroeconomists) surveyed by Christensen *et al* (2018) (grey) (*IPCC regions do not perfectly match country groupings from Christensen *et al* (2018); see sm; years are 2010–2050 and 2010–2100; and units are PPP in both panels), required (from 2020 to 2040 or 2020 to 2100) for per-capita GDP to catch up to AR5 (a) and SSP (b) baseline scenarios (red), and required to catch up to baseline scenarios assuming either the IMF's (2020a) April 2020 WEO growth estimates and projections for 2018–2021 (purple) or assuming double the COVID-19 impact on growth (pink) (see Methods). In all cases, boxes represent 25th–75th percentiles (white dashes indicate medians). Lines above and below the boxes represent the full (min–max) range for catch-up rates and AR5/SSP projections, and 10th–90th percentile ranges for expert projections (Christensen *et al* (2018) do not report min and max).

industrial activities from richer countries to poorer countries (Hardt *et al* 2018). Under-projections of energy intensity in Asia, MAF, and LAM may also be related to similar-magnitude over-projections of per-capita GDP growth (because GDP is the denominator of energy intensity) (figure 2).

3.2. Drivers of 2020–2040 baseline scenario divergence from IEA projections

The 2020–2040 divergence of SSP and AR5 baseline CO_2 emissions from IEA Current Policies and Stated Polices projections is partly due to carbon intensity—which grows more slowly (or declines more quickly) in the IEA scenarios (figures 1(b) and S3). Divergences in other factors differ across scenarios. Projecting per-capita GDP and population is not a main focus of the IEA—they base these projections on UN (population) and IMF (per-capita GDP) projections (IEA 2019a).

IEA projects similar 2020–2040 population growth rates as SSP and AR5 baselines (figures 1(b) and S3). IEA 2020–2040 per-capita GDP growth projections are similar to AR5 baselines (see figure S3 and its caption). SSP per-capita GDP growth projections vary in divergence from IEA projections (figure 1(b)). Specifically, SSP1 ('Sustainability') and SSP5 ('Fossil-fueled Development') project much faster growth than IEA, while SSP3 ('Regional Rivalry') projects much slower growth (Dellink *et al* 2017, Riahi *et al* 2017). Growth in SSP1 and SSP5 is accelerated by assuming faster productivity growth, and faster income convergence between poorer and richer countries, due to rapid technological improvement and a greater global focus on lowering inequality in SSP1, and rapidly increasing fossil-fuel use in SSP5. Growth is depressed in SSP3 from assuming slower income convergence between poor and rich, and less international trade (see table 1 in Dellink *et al* 2017). Per-capita GDP growth in SSP2 ('Middle

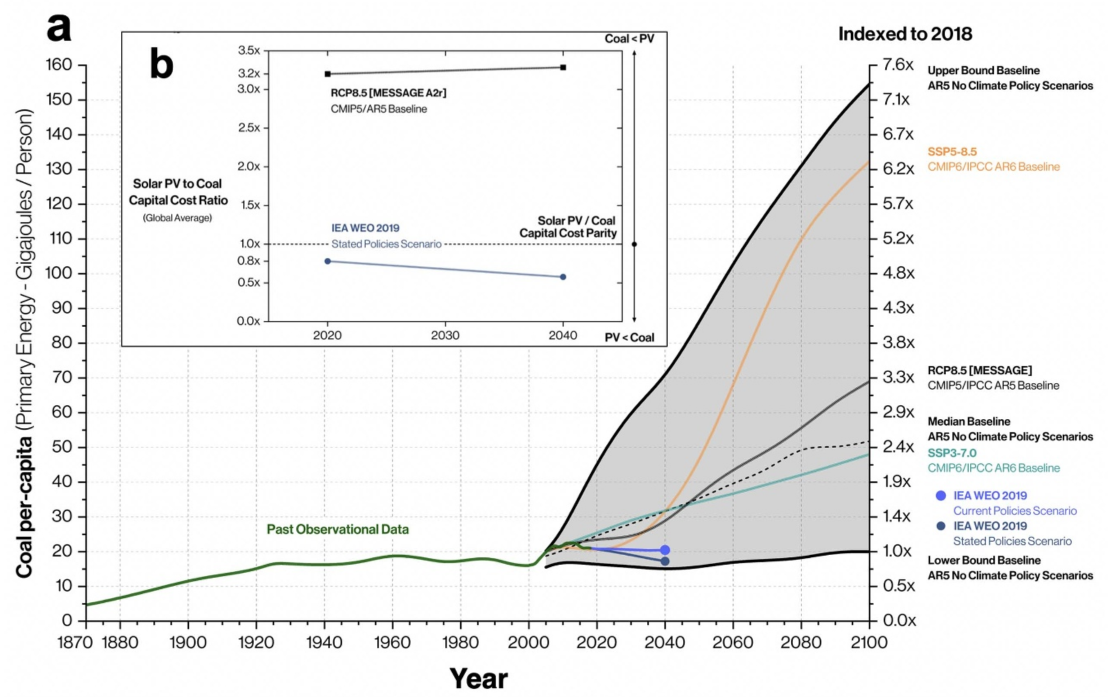

Figure 5. (a) A comparison of global coal demand per capita: historically (green), under AR5 baseline (no-policy) scenarios (grey), under high-emission SSP baselines (SSP5-8.5, orange; SSP3-7.0, teal) (IPCC WGIII 2014, IIASA 2018), and under IEA (2019a) 'Current Policies' (lighter blue) and 'Stated Policies' (darker blue) scenarios. (b) A comparison of the solar-to-coal capital cost ratio between RCP8.5 and the IEA (2019a) Stated Policies scenario.

of the Road') and SSP4 ('Inequality') is slightly slower than the IEA's projections (figure 1(b)) (Dellink *et al* 2017, Riahi *et al* 2017).

Most AR5 baselines project higher energy intensity growth than IEA (figures S3(a) and (b))—a difference larger than explained by GDP unit differences (see footnote 7). Energy intensity growth (or decline) in the SSPs diverges from IEA projections in opposite directions from per-capita GDP divergences, as GDP is the denominator in energy intensity. These divergences offset each other in SSP1 and SSP3 baselines relative to the IEA's Current Policies scenario (figure 1(b), table S2), meaning they project similar growth rates in energy per capita (i.e. per-capita GDP × energy intensity). However, remaining SSP baselines project faster energy-per-capita growth than IEA's Current Policies scenario; and all SSPs project faster energy-per-capita growth than IEA Stated Policies scenario (table S2, figure S3(c)).

Baselines of all SSP scenarios project higher carbon intensity growth than both IEA scenarios (figures 1(b) and (S3)). Most AR5 and SSP baseline scenarios project that carbon intensity would not decline (in the absence of climate policies), whereas experience of the past decade suggests that factors beyond climate policy lead to carbon-intensity declines. Figure 5(a) illustrates the case of coal (see also Ritchie and Dowlatabadi 2017): high-emission baselines, such as RCP8.5 and SSP5-8.5, project multiple-fold increases in coal demand per capita to 2100, while the IEA (2019a) projects declining coal per capita, even under Current Policies. One reason for this discrepancy is that high-emission baseline scenarios substantially over-projected the cost of renewable energy sources that have been realized such as solar power relative to coal and other fossil fuels (figure 5(b)). This divergence in projected coal use also drives some of the divergence in energy intensity, as coal is a relatively inefficient energy source (e.g. Farquharson *et al* 2016).

3.3. Per-capita GDP 'catch-up' rates and future outlook

In the OECD and Asia, per-capita GDP growth rates needed to catch-up to AR5 and SSP baseline scenarios by 2040 are higher on average than baseline projections and the range of expert projections reported by Christensen *et al* (2018), but also largely overlapping in their distributions, even if COVID-19 impacts turn out to be double what the IMF projected in April 2020 (figure 4). In the other regions (LAM, MAF, and REF), catch-up by 2040 would require growth rates at the extreme high ends of, or above, the baseline and Christensen *et al* (2018) ranges (figure 4). Looking ahead to 2100, catch-up per-capita GDP growth rates are higher on average than baseline projections, and have higher medians than the Christensen *et al* (2018) expert range in all regions except Asia, but also with high degrees overlap between the catch-up ranges and baseline and Christensen *et al* (2018) ranges in all regions. Christensen *et al* (2018) report higher extremes, looking to 2100, in most regions and globally (figure 4).

4. Discussion

Projected CO_2 emissions from AR5 to SSP baseline scenarios diverge from post-2005 observations and energy agency projections to 2040 (see Hausfather and Peters 2020). Our analysis shows projected per-capita GDP growth and carbon intensity are key drivers of this divergence, with per-capita GDP growth the predominant driver of past divergence from observations, and carbon intensity a key driver of projected 2020–2040 divergence from energy outlooks. Given that projecting energy systems—not GDP or population—is the IEA's main focus, it is neither surprising nor illuminating that the IEA's 2020–2040 per-capita GDP projections do not diverge from the AR5 and SSP baselines. Indeed, projections of GDP growth by the IMF are the basis for both the IEA's 2020–2040 projections, and the SSP baselines' 2005–2018 projections (Dellink *et al* 2017, IEA 2019a). Though previous studies have also noted these CO_2 emission and carbon intensity divergences (e.g. Ritchie and Dowlatabadi 2017, Hausfather and Peters 2020), our results identify and quantify the important role of slower-than-projected economic growth.

Beyond 2040, if the trends anticipated by energy agency forecasts continue, carbon intensity will continue diverging from AR5 and SSP baselines—especially from higher-emission scenarios such as RCP8.5, due to the assumptions about fossil-fuel expansion in these scenarios that are increasingly implausible. Ritchie and Dowlatabadi (2017) explore these assumptions in detail. The IEA's BAU-like scenarios (Current Policies and States Policies) project a gradual decline in coal demand, in contrast to a dramatic increase in most baseline scenarios (figure 5). Moreover, in recent years the IEA and other energy agencies have underestimated rates of coal decline and solar and wind growth (e.g. Carrington and Stephenson 2018). Thus, continuing carbon intensity divergence from baseline projections would contribute to growing CO_2 emission divergence from the median AR5 and SSP ranges, even if per-capita GDP growth eventually catches up to baseline projections.

In assessing whether the observed divergence of per-capita GDP growth (figure 3) from AR5 and SSP baseline projections foreshadows a longer-term divergence, we consider two broad questions. First, to what extent do possible causes of scenarios' past per-capita GDP growth over-projections indicate a potential for future over-projections? Second, to what extent does past per-capita GDP growth over-projection directly imply longer-term over-projection by requiring implausibly high catch-up rates (figure 4)?

It is impossible to definitively answer the first question. There is large uncertainty, and economists disagree about the growth outlook to 2100. Some anticipate higher growth rates than AR5 and SSP baseline scenarios project in many regions (Christensen *et al* 2018), while others anticipate growth slowing dramatically across the developed world, for structural reasons (e.g. aging populations, debt, innovation slowdowns) unrelated to climate change (Gordon 2016, Jackson 2019). Recent statistical economic growth projections to 2100 (Müller *et al* 2019, Startz 2020) found similar uncertainty ranges as Christensen *et al* (2018) (global per-capita GDP growth between ∼1%/y and ∼3%/y), which make catch-up to the AR5 and SSP baselines by 2100 appear possible. We identify six important qualifications to interpreting this analysis.

First, the period over which we evaluated per-capita GDP growth projections (2005–2017) is relatively short and contained the Great Recession of 2008–2009. The COVID-19 crisis adds an additional global recession to the dataset when including 2018–2020 estimates. Although this may suggest 2005–2020 is a historically unusual period, there will be other global recessions in the 2020–2100 period, which will result in positive bias in scenario-projected future growth rates if the possibility of such negative shocks is not accounted for in projections (Burgess *et al* 2020).

Second and relatedly, authoritative economic growth forecasts, including the IMF's (upon which IEA's 2020–2040 and SSPs' pre-2018 projections are largely based; Dellink *et al* 2017, IEA 2019a), have historically tended to over-project growth on average, partly due to under-projecting business-cycle fluctuations (de Resende 2014, CBO 2019), where negative fluctuations (recessions) tend to be larger than positive fluctuations (Bekaert and Popov 2019, Burgess *et al* 2020). Other reasons for positive economic forecast biases include over-projecting productivity growth, assuming GDP will converge to potential GDP, and political biases (e.g. de Resende 2014, Congressional Budget Office (CBO) 2019).

Third, even if the 2008–2009 recession is anomalous, it cannot fully explain the baseline scenarios' 2005–2017 over-projections of per-capita GDP growth in developing regions. The over-projection magnitudes in these regions are larger (∼1%–3%/y over 12 years) than the 2008–2009 recession alone can explain (figures 2 and S2), and their timing (figure 4) is more indicative of other events, such as the Arab Spring and Syrian civil war in the MAF and the Venezuelan inflation crisis in LAM. The likelihood of future periods comparably tumultuous as the past decade should factor into emission scenario uncertainty ranges, especially given the likelihood of climate change causing economic, social, and political upheavals (Carleton and Hsiang 2016).

Fourth, AR5 and SSP baseline projections do not consider economic damages from climate change, which could be sizeable and induce feedbacks that depress emissions (Woodard *et al* 2019). Indeed, such feedbacks create obvious internal inconsistencies in high-emission baseline scenarios. For instance, the SSP5-8.5 baseline projects currently-developing regions will have substantially higher GDP per-capita by 2100 than currently-developed regions have today (Dellink *et al* 2017, IIASA 2018), while at the same time other studies project that a forcing level of 8.5 W m^{-2} in 2100 would render many of these same regions uninhabitable by 2100 (Mora *et al* 2017). In contrast, other recent models project smaller economic damages relative to GDP than the above comparison suggests (e.g. 8.5% at 6° of warming; Nordhaus 2018; but see also Keen (2020), which argues that such estimates are biased low for reasons similar to those discussed above).

Fifth, some demographers now anticipate substantially slower population growth than previous UN projections suggested (e.g. only 6–9 billion people, not 10–12 billion, by 2100; Vollset *et al* 2020), due to falling birth rates, especially in developing countries (Bricker and Ibbitson 2019). Slower population growth could further reduce per-capita GDP growth by exacerbating the economic pressures of aging populations and public debt.

Lastly, the current COVID-19 crisis may accelerate and entrench longer-term reductions in trade and immigration flows, as countries become more cautious about the potential for disease spread or the security of their supply chains for essential goods such as energy products. Such a scenario would have parallels to the SSP3 storyline—which projects slower economic growth than the other SSPs (figure 3). The recovery from the COVID-19 also seems likely to be much slower in many regions than the rapid V-shaped recovery the IMF projected in April 2020 (figure 3) (e.g. see revised projections for the U.S. in CBO 2020).

Whether inertia will keep per-capita GDP growth below 2040 or 2100 projections, even assuming baseline projections of post-2020 growth rates are accurate, our results (figure 4) suggest that per-capita GDP growth is unlikely to catch up to baseline scenarios by 2040, but catch-up is possible by 2100 under strong economic growth. Indeed, the range of expert projections from Christensen *et al* (2018) includes growth rates that would allow per-capita GDP to exceed the highest baseline scenario projections by 2100. However, this does not suggest CO_2 emissions exceeding high-emission baseline scenario projections are necessarily plausible, given the carbon intensities in these scenarios would still be implausible.

5. Conclusion

Recent (post-2005) trends and energy outlook projections (to 2040) of global CO_2 emissions are substantially lower than projected by baseline scenarios used in the IPCC's Fifth (AR5) and Sixth (AR6) Assessment Reports, and are well off-track from widely-cited high-emission marker scenarios such as RCP8.5. We show that this divergence owes largely to per-capita GDP and carbon intensity growth slower than projected in baseline scenarios. The gap between observed and projected carbon intensity is very likely to continue to increase throughout the 21st century due to the implausible assumptions high-emission scenarios make about future fossil-fuel expansion (Ritchie and Dowlatabadi 2017). The gap between observed and projected per-capita GDP is unlikely to close by 2040 due to inertia but is more uncertain to 2100.

We see three immediate implications of our analysis. First, if scenarios underpin research used to inform policy, such scenarios should be kept up-to-date and corrected when divergences from real-world trends or improved projections are identified. It is unsurprising that scenarios used by the IPCC—many developed over a decade ago—are diverging from the real world. They should be updated more regularly. Second, policy-relevant climate research, including evaluations of near-term policy options, should use or consider near-term energy scenarios (including but not limited to the IEA's), which are updated on an annual basis. These provide a more reliable guide to the next several decades than century-long scenarios, which are appropriate in exploratory climate research. Finally, in a world where climate policy is now BAU, the historical distinction of policy and no-policy scenarios may be obsolete, and a new approach to scenario planning may be needed (e.g. Pielke and Ritchie 2020).

Our analysis supports the conclusions drawn by previous studies (Hausfather and Peters 2020, Pielke and Ritchie 2020) that high-emission AR5 (RCP8.5) and high-emission AR6 (i.e. SSP3-7.0 and SSP5-8.5) baselines should not be utilized as reference scenarios in climate research. Our findings also suggest that future scenario development efforts should consider wider ranges of assumptions regarding economic growth due to high uncertainty in growth futures, and the possibility that the current pandemic will bring lasting changes to the economic system.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://github.com/mattgburgess/climatekaya.

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