Global Environmental Change 42 (2017) 215–225

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Future growth patterns of world regions – A GDP scenario approach

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ARTICLE INFO

Article history:
Received 22 August 2013
Received in revised form 2 February 2015
Accepted 17 February 2015
Available online 31 March 2015

Keywords:
GDP scenario
Convergence
Economic growth

ABSTRACT

Global GDP projections for the 21st century are needed for the exploration of long-term global environmental problems, in particular climate change. Greenhouse gas emissions as well as climate change mitigation and adaption capacities strongly depend on growth of per capita income. However, long-term economic projections are highly uncertain. This paper provides five new long-term economic scenarios as part of the newly developed shared socio-economic pathways (SSPs) which represent a set of widely diverging narratives. A method of GDP scenario building is presented that is based on assumptions about technological progress, and human and physical capital formation as major drivers of long-term GDP per capita growth. The impact of these drivers differs significantly between different shared socio-economic pathways and is traced back to the underlying narratives and the associated population and education scenarios. In a highly fragmented world, technological and knowledge spillovers are low. Hence, the growth impact of technological progress and human capital is comparatively low, and per capita income diverges between world regions. These factors play a much larger role in globalization scenarios, leading to higher economic growth and stronger convergence between world regions. At the global average, per capita GDP is projected to grow annually in a range between 1.0% (SSP3) and 2.8% (SSP5) from 2010 to 2100. While this covers a large portion of variety in future global economic growth projections, plausible lower and higher growth projections may still be conceivable. The GDP projections are put into the context of historic patterns of economic growth (stylized facts), and their sensitivity to key assumptions is explored.

1. Introduction

The level of global environmental change, in particular climate change, depends on the scale of economic activities and the technologies employed. Scenarios of future human impact on the global environment are therefore built upon projections of economic output. The increasing demand for such projections is confronted with a shortage of available projections for the development of the world economy over the 21st century. Kemp-Benedict (2012) lists few prominent examples of available projections, among others the Special Report on Emissions Scenarios of the Intergovernmental Panel on Climate Change (Nakicenovic and Swart, 2000) and the World Energy Outlooks of the International Energy Agency (IEA, 2009). Both studies generate projections of economic output by assuming exogenous regional growth rates of gross domestic product or productivity. This assumption-based approach can be contrasted with a model-based approach, wherein a projection of the development of the global economy is produced from an economic model, e.g. WorldScan (Lejour et al., 2006).

The contribution of this paper is to develop a set of five long-term GDP projections as part of the shared socio-economic pathways (SSPs) (O'Neill et al., 2014), a major component of a new scenario framework (van Vuuren et al., 2014). The SSPs describe socio-economic futures with different challenges to mitigation and adaptation. They serve as a reference case for climate change analysis, and therefore do not include climate policies or the impact of climate change in their formulation. The GDP projections presented in this paper are based both on the underlying narratives of the SSPs (O'Neill et al., 2015) and a well understood economic model. The process of transforming the narratives into model parameters is made transparent. We use the neoclassical model developed by Abramovitz (1956) and Solow (1957), augmented with regard to human capital (Lucas, 1988; Romer, 1990; Mankiw et al., 1992; Aghion and Howitt, 1998) and the role of demographics and institutions (Acemoglu et al., 2005). The results are validated against stylized facts depicting typical economic growth patterns of the past. This paper applies a scenario approach which follows the methodology by Hawksworth (2006). We go beyond that approach, however, when deriving projections

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http://dx.doi.org/10.1016/j.gloenvcha.2015.02.005
0959-3780/

of technical progress and capital accumulation. By an empirical foundation of the former and a semi-endogenous modeling of the latter, the present approach allows for an improved regional differentiation of scenarios.

In discussing their approaches to generating long-term global scenarios and projections of economic growth, Kemp-Benedict (2012) as well as McKibbin et al. (2009) highlight the issue of convergence. As a characteristic feature, the stylized neoclassical economic models imply convergence across countries in economic output per worker over time. This implicit convergence assumption is highly debated. In a recent paper, Rodrik (2013) demonstrates evidence of unconditional convergence in manufacturing industries. On an economy-wide level, however, co-existence of stagnant economies and rapidly growing economies shows that convergence is not universal. Some authors even pointed out that divergence rather than convergence has been the dominant trend in the world economy (Durlauf, 1996; Pritchett, 1997; Easterly, 2006). Instead of assuming unconditional convergence, Galor (1996) suggests two competing convergence hypotheses: conditional convergence and club convergence. Acknowledging the importance of the convergence assumption and the discussion in the economic literature on this, we put some effort in justifying our approach. We adopted a framework that is based on the conditional convergence hypothesis applied in a neoclassical growth framework (cf. Kemp-Benedict, 2012). Specification of the convergence assumption is derived from the underlying SSP storylines.

In this paper, we establish a consistent set of GDP projections for 32 world regions and the period 2010–2100 based on a set of population and education projections for the five SSPs (see KC and Lutz, 2017). The goal is to explore key factors leading to a large spread in plausible economic futures and to provide a useful resource for the integrated assessment of climate change. The generation of GDP projections is based on a sound understanding on the drivers of economic growth. In Section 2, we provide some fundamental insights from the economic literature on growth accounting and stylized facts. Section 3 describes the method that is used to generate the GDP projections. The resulting set of five GDP scenarios is presented and evaluated in Section 4. Gross world product in the year 2100 varies by a factor of three across the scenarios. We explore the consistency of scenario assumptions, run a sensitivity analysis and confront scenario results with the stylized facts that have been established in economic literature. We end with some conclusions.

2. Theoretical and empirical foundation

The questions of what determines a country's growth rate of GDP, and why countries grow at different rates are a major concern of theoretical and empirical economic research since the beginning of modern economics. The neoclassical production function is predominantly used to answer these questions. It represents a technological relationship which expresses the level of output as a function of the level of inputs, such as labor, capital, and land. Over the last century, much of scientific effort has gone into finding a specific form of the production function. It turned out that the Cobb–Douglas production function will give the best statistical fit to empirical data, if the elasticities of output to factor inputs are constant and the technical progress is Hicksian-neutral (McCombie and Thirlwall, 1995). Assuming a constant rate of technical progress λ, it takes the form:

$$Y(t) = A(0)e^{\lambda t}K(t)^{\alpha}L(t)^{1-\alpha} \qquad \text{(I)}$$

where Y denotes output (GDP), A total factor productivity (TFP), K capital stock, L labor input and α the output elasticity on capital. An advantage of Cobb–Douglas' style production functions is the approximate correspondence of the estimated elasticities with the actual factor income shares. Based on the Cobb–Douglas production function, the growth accounting approach tries to explain output growth by the growth rates of labor, capital and technical progress. An overview of this research branch is provided as Supplementary Material S.1.

While the recent economic literature, in particular those on endogenous growth theory (Aghion and Howitt, 1998) provides alternatives and new insights, the Solow-Swan model (Solow, 1957) and the Cobb–Douglas function are still prevalent tools in exploring historic and future economic growth paths. The number of growth factors taken into account by the growth accounting literature is huge. The impact of investments, education and technological catching up is robust. Therefore, they form the basic components of the scenario approach presented in Section 3. Explanatory power of other factors varies between different studies or significance changed between early and more recent studies (e.g. R&D investments). The importance of growth factors is different between countries in general and especially between developed and developing parts of the world.

While the growth accounting approach helps to identify the most relevant variables that might have impact on regional growth paths in the future, a related branch of empirical research developed a framework that helps to evaluate simulated growth scenarios based on a number of stylized facts. Such stylized facts were derived from historical data and theoretical economic reasoning. They neglect short-term fluctuations but reveal underlying trends. In a seminal paper, Kaldor (1961) suggested six empirically observable 'stylized facts' which should be replicated by any economic growth model. Since then, these facts have been widely discussed and extended, in particular to also capture general trends and growth patterns beyond high-growth countries or to include later concepts from economic growth theory such as human capital and ideas (e.g. Dollar, 1992; Easterly, 1994; Dosi, 1995; Acemoglu and Autor, 2011). Jones and Romer (2010) presented New Kaldor facts on new variables discussed in the economic growth theory, but they also extended the set of facts that are related to technological progress and the total factor productivity, respectively. Based on a review of the empirical literature on economic growth, we selected a list of relevant stylized facts (see Table 1) to evaluate the GDP projections as well as the underlying growth model. The selection was constrained to those stylized facts that meaningfully could be tested with the developed projections and the data available. Therefore, not all stylized facts listed, e.g. in Jones and Romer (2010) or Dosi (1995), are considered in this study.

3. Scenario design

3.1. Method and data

The basic approach is an extension of the method used by PricewaterhouseCoopers (Hawksworth, 2006). Like in Hawksworth (2006) we applied a Cobb–Douglas production function as the basic tool. We also adopted the same method of introducing human capital via labor productivity. We, however, applied a different, more elaborated methodology in deriving projections of physical capital and total factor productivity (see Sections 3.5 and 3.6). These improvements allow us to integrate additional empirical data (historical development of production factors, productivity and capital intensities) into the scenario generation. Moreover, they provide the basis for a more distinct set of scenarios with an improved coverage of region-specific characteristics of the underlying narratives (e.g. convergence of developing regions with respect to overall productivity and capital intensity).

Fig. 1 shows the most important elements of the scenario design. The Solow growth model and the Cobb–Douglas production function

Table 1
Stylized facts.

Stylized fact	Description
Kaldor SF 2	Capital per worker increases continuously
Kaldor SF 4	The capital output ratio is steady over time
New Kaldor NSF 3 (Jones and Romer, 2010)	Variation in the rate of growth of per-capita GDP increases with the distance from the technology frontier
New Kaldor NSF 4 (Jones and Romer, 2010)	Large income and TFP differences. Differences in labor and capital inputs explain less than half of cross country differences in per capita GDP
New Kaldor NSF 5 (Jones and Romer, 2010)	Human capital per worker is rising throughout the world
Dosi DSF 10	Positive correlation between investment rates and economic growth
Growth Accounting GSF 2 (Quah, 1996; Acemoglu and Autor, 2011)	There is no evidence for conditional convergence across the world and the world income distribution shows an emergence of a twin-peak pattern
Growth Accounting GSF 4	There is some evidence for a hump shaped growth pattern (beta-convergence), i.e. high growth rates in a catch-up phase

are used as the basic economic tools. The gross domestic product of each country or region is, hence, formulated as a function of the production factors capital and labor which are combined with total factor productivity and the output elasticities on capital and labor. In going beyond the classical Solow approach, all of these components are derived by qualified scenarios that are either based on further economic concepts (Ramsey model, human capital), empirical foundation (historic TFP growth) or on the narratives of shared socio-economic pathways. Each component will be discussed in further detail below.

In preparing and assessing the GDP scenarios we make use of historical data from the following sources:

- Labor, population and age structure (country-based, 1950–2010):UN (2010) database
- Education, i.e. mean years of school (country-based, 1950–2005): Barro and Lee (2010)
- Physical capital (country-based, 1950–2010):King and Levine (1994), Penn World Tables (PWT) 7.1 (Heston et al., 2012)
- Labor participation (country-based, 1950–2010):International Labor Organization (ILO, 2011)
- GDP and macro-economic investments (country-based, 1950–2010):PWT 7.1 (Heston et al., 2012).

There is no complete historical dataset available for all countries from 1950 on. In order to derive datasets for aggregated regions, we applied population weighted extrapolations to fill missing data. With regard to physical capital, we used the perpetual inventory method applied to reported investment data. In case of too short investment time series, we derived an initial historical capital stock by assuming a fixed capital GDP ratio of 2.5. Historical GDP from PWT 7.1 is measured in international dollars of purchasing power parity (PPP) of the year 2005, thus reflecting growth of the economies in real terms of domestic currency. This measure also applies to the GDP scenarios to be constructed.

As major source for the future development of population, working-age population and mean years of school, we used the SSP population scenarios from IIASA (KC and Lutz, 2017).

3.2. SSP narratives

Since the GDP projections are supposed to be used as part of the SSPs, the GDP scenario design follows the underlying SSP narratives. There are five different SSPs which in the first instance are differentiated by their climate change mitigation and adaptation challenges. SSP1 ("Sustainability") characterizes a world that makes progress toward sustainability, including rapid development of low-income countries, and hence faces low mitigation and adaptation challenges. SSP2 is a kind of "middle of the road Scenario" with continuing historical trends and medium challenges in both dimensions. SSP3 ("Regional Rivalry") is a strongly fragmented world characterized by a high level of poverty, subject to high mitigation and adaptation challenges. SSP4 ("Inequality") represents a highly unequal world. The large number of poor people across countries face high adaptation challenges, while the economy catering the rich is technologically advanced and capable to reduce mitigation challenges by developing alternative technologies. Finally, SSP5 ("Fossil-fueled development") characterizes a growth-oriented world that uses conventional technologies (in particular fossil fuel based energy conversion technologies) and therefore faces high mitigation challenges. Similar to SSP1, in SSP5 per capita income across regions is expected to converge, though on a higher level and therefore within a longer time horizon.

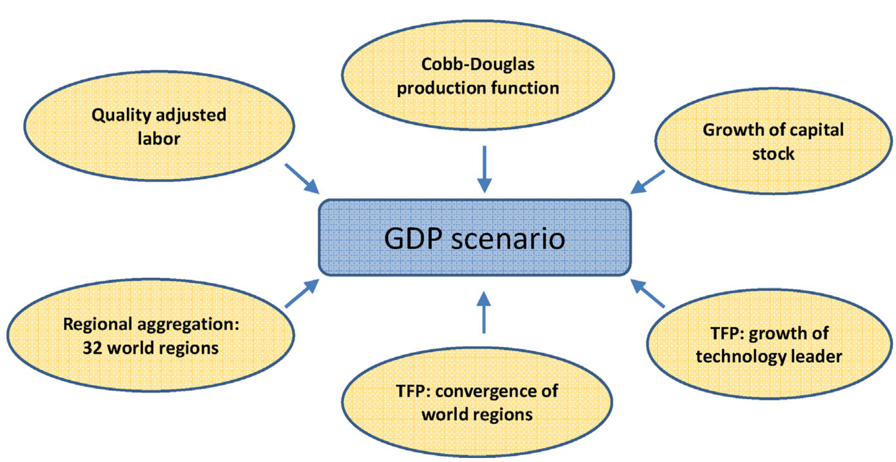

Fig. 1. Components of GDP scenario design.

Table 2 provides a summary of major assumptions for the GDP projections. The narrative elements that relate to the development of the global per capita income level were translated into assumptions on the TFP growth at the frontier. Analogously, from the level of fragmentation, globalization and development expectations in less developed countries, assumptions on the speed of convergence have been derived.

3.3. Regional breakdown

GDP scenarios are generated for 32 world regions. Table A1 in Appendix shows the country mapping. For the purpose of scenario generation, which is based on the narratives as briefly discussed in the previous section, we categorize the 32 regions according to their current income level into three income groups (partly already identified by their acronym). Details on these income groups are provided as Supplementary Material S2. This classification helps to address elements in the narratives that differentiate between income groups. This, in particular, applies to a differentiation between developing countries (i.e. middle income countries) with good prospects of catching up with high income countries and those which potentially will be left behind (i.e. low income countries).

While the regional decomposition does not allow for single-country scenarios as provided by Dellink et al. (2017) and Cuaresma (2017), the aggregation across countries with similar characteristics of economic growth and its drivers can be expected to make projections more robust. This is mainly due to the fact that for major drivers, like TFP growth, assumptions have to be made for which a country-specific differentiation is hard to justify over the scenario time horizon. However, the match with stylized facts that represent regional diversification measures (e.g. GSF4, cf. Sections 2 and 4.3) is hindered by the coarse regional resolution.

3.4. Labor and human capital

Labor input is derived from the SSP population projections (KC and Lutz, 2017). While the working age population is the basis for the production factor labor, per capita income as a major output of the GDP projections is related to the entire population. The production factor labor in the Cobb–Douglas function has three components: working age people (WAP), labor force participation rate (LFPR) and education (H):

$$L(t) = \sum\nolimits_q H(t) * \mathrm{LFPR}(q,t) * \mathrm{WAP}(q,t) \qquad \text{(II)}$$

While suppressing in the above equation the region and scenario index, we include time index t and distinguish two age classes q for the working age people: those aged 15–64 years and those aged 65 and above. Each of the two working age groups is characterized by a particular labor force participation rate. Details on the projections for the labor force participation rates across time, age groups and regions are provided as Supplementary Material S3.

By multiplying the participation rates with the respective population numbers, we arrive at the actual number of working people. The next step is to account for the quality differences that are due to different levels of education. As a measure of education we use the "Mean Years of Schooling" (MYS) provided jointly with the population projections from KC and Lutz (2017). In order to calculate human capital we use the same approach as Hawksworth (2006), which refers to Psacharopoulos (1994). Each of the first four years of education increases human capital by 13.4%, each subsequent year until the eighth mean year of schooling increases human capital by 10.1% and every year of education after that yields a return of 6.8%. Education acts as a scaling factor on labor according to the following equation:

$$H = \begin{cases} e^{0.134 \cdot \mathrm{MYS}}, & \mathrm{MYS} \le 4 \\ e^{[0.536 + 0.101 \cdot (\mathrm{MYS}-4)]}, & 4 < \mathrm{MYS} \le 8 \\ e^{[0.94 + 0.068 \cdot (\mathrm{MYS}-8)]}, & \mathrm{MYS} > 8 \end{cases} \qquad \text{(III)}$$

A hypothetical population lacking any education would therefore enter the production function with its actual number of people in the workforce, whilst for example a population with 16 mean years of schooling would enter the production function with 4.41 times the actual number of people participating in the workforce.

The given education scenarios exhibit almost no increase of MYS for SSP3 and SSP4, a moderate increase for SSP2 and a significant improvement for SSP1 and SSP5. For the latter SSPs, this results in an increase of effective labor input (quality-adjusted labor input). Nevertheless, due to the decrease of the working age population in different regions (e.g. in Japan, China, also India), the quality – adjusted labor input does not increase over time for all regions, even in these SSPs.

3.5. Physical capital stock

The original Solow model and the approach used by Hawksworth (2006) assume exogenous savings rates. While this could be based on historical data, its extensive use is hindered by the weak data quality. For some countries (like Russia and other Eastern European countries) data are not available before 1970 or even 1990, for others like China they seem not reliable (nearly constant rate over the time period 1952–2005).

In going beyond the assumption of an exogenous savings rate, here we derive a savings rate that meets some implicit optimality criteria given by applying the Cobb–Douglas production function in a growth dynamic framework. Similar to the economic growth models, this approach starts from the macro-economic accounting assumption that the amount of saving equals the amount of investment.

Investments I increase the available stock of physical capital K which is described by the following equation (with d as depreciation rate and t as time index):

$$K(t+1) = (1-d) \cdot K(t) + I(t) \qquad \text{(IV)}$$

This equation is used for estimating historical capital stocks based on available investment data. Projection of future capital stocks is based on analytical reasoning. Details are provided as Supplementary Material S4. From the analytical approach we derive the following recursive equation for the capital stock variable:

$$K(t) = \left[\frac{K(t-1)}{L(t-1)}\right]^{(1-\alpha(t-1))/(1-\alpha(t))} \cdot \left[\frac{K(t)}{Y(t)} \cdot \frac{Y(t-1)}{K(t-1)} \cdot \frac{A(t)}{A(t-1)}\right]^{(1/(1-\alpha(t)))} \cdot L(t) \qquad \text{(V)}$$

Table 2
Main assumptions for SSP GDP projections.

SSP element	SSP1	SSP2	SSP3	SSP4[a]	SSP5
TFP growth at frontier	Medium	Medium	Low	Medium	High
Speed of convergence	High	Medium	Low	LI: low MI: medium HI: medium	High

[a] In SSP4, the speed of convergence differs across country groupings with different income levels. LI: low income countries, MI: middle income countries, HI: high income countries

In order to generate scenarios for the future capital stock, and in addition to TFP and labor input (Sections 3.4 and 3.6), projections for elasticity parameter α and capital intensity K/Y are needed. We assume a long-term level for the elasticity parameter α which is different across the SSP scenarios. Parameter α also bears the economic meaning of an income share parameter which it attains as part of an equilibrium solution of a welfare or profit maximization model. Commonly, it is assumed that there is a division of income between capital and labor in the ratio of 1:2, i.e. $\alpha = 1/3$. Within African countries with low capital endowments this share is below 20%, whereas in a country like Japan it is close to 50%. Within the scenarios SSP1 and SSP5, which are characterized by a high level of international co-operation, we assume a long-term convergence to the values of 0.35 and 0.45, respectively, across all regions. We assume a much higher level for SSP5 as this high growth scenario is expected to be driven partly by large capital accumulation. A medium value of 0.35 is also assumed for SSP2. Convergence to this long-term level, however, is much slower. Slow convergence and a low level of 0.25 are assumed for this elasticity parameter in SSP3. By this assumption we model a world where national economies are rather labor intensive than capital intensive. Even slower convergence and a long-term level of 0.3 are assumed for SSP4.

The capital intensity and hence the capital stock can then be derived by using the following identity:

$$\alpha = p_K \cdot \frac{K}{Y} \qquad \text{(VI)}$$

with p_K the price of capital, i.e. the return rate on gross capital investments. We assumed a capital price level of 0.12 across all SSPs and all regions. Sensitivity analysis on this assumption is provided in Supplementary Material S7 and projection of capital intensity is shown in Table S4 (Supplementary Material S4).

3.6. Total factor productivity

Growth accounting studies demonstrated that in a Solow model framework TFP plays a dominant role, i.e. a major part of observed growth is attributed to TFP growth. The present approach of providing TFP input for GDP projections is based on the assumption that the empirically observed growth pattern in form of an exponential growth trajectory (see Fig. 2 for selected countries) is also reflected in the future dynamics of the TFP. Starting from that, this approach is based on four components: (I) Assumption on the TFP growth rate for the technological leader, (II) short term dynamics based on empirically derived initial TFP growth rate, (III) convergence rate for catching-up with the technological leader in the long run, (IV) transition time between historically dominated TFP growth and convergence-based long-term TFP growth.

According to the characterization as high, medium and low GDP growth scenario, we assumed a medium long-term TFP growth rate (g_L) for the technological leader of 0.7% per year and an increase and decrease of this rate by 50% for the high growth and low growth scenario, respectively, i.e.:

(I) SSP1, SSP2, SSP4: 0.7%
(II) SSP3: 0.35%
(III) SSP5: 1.05%.

For the TFP of the technological leader A_L it holds (with time index t, initial TFP growth rate g_A^L and transition rate γ):

$$A_L(t) = A_L(0) \cdot \{1 + [g_L + (g_A^L - g_L) \cdot e^{-\gamma t}]\}^t \qquad \text{(VII)}$$

The TFP A of all other regions r is calculated based on the following formula (β is a convergence parameter and τ the transition time between the two phases of TFP growth in units of time step length which is 5 years):

$$A(t+1,r) = \begin{cases} \dfrac{t \cdot \{A_L(t+1) - [A_L(t+1) - A(t,r)]\} \cdot e^{-t(\beta(r)/10)} + (\tau(r) - t) \cdot (1 + g_A(r))A(t,r)}{\tau(r)} & t \le \tau \\ \max\{A(t,r), A_L(t+1) - [A_L(t+1) - A(t,r)] \cdot e^{-t(\beta(r)/10)}\} & t > \tau \end{cases} \qquad \text{(VIII)}$$

For transparency reasons we still suppress the scenario index which actually applies to almost all variables and parameters. While the second formula describes the long-term convergence process (or non-convergence process if β is negative or close to zero), the first equation represents the evolution of the TFP as a

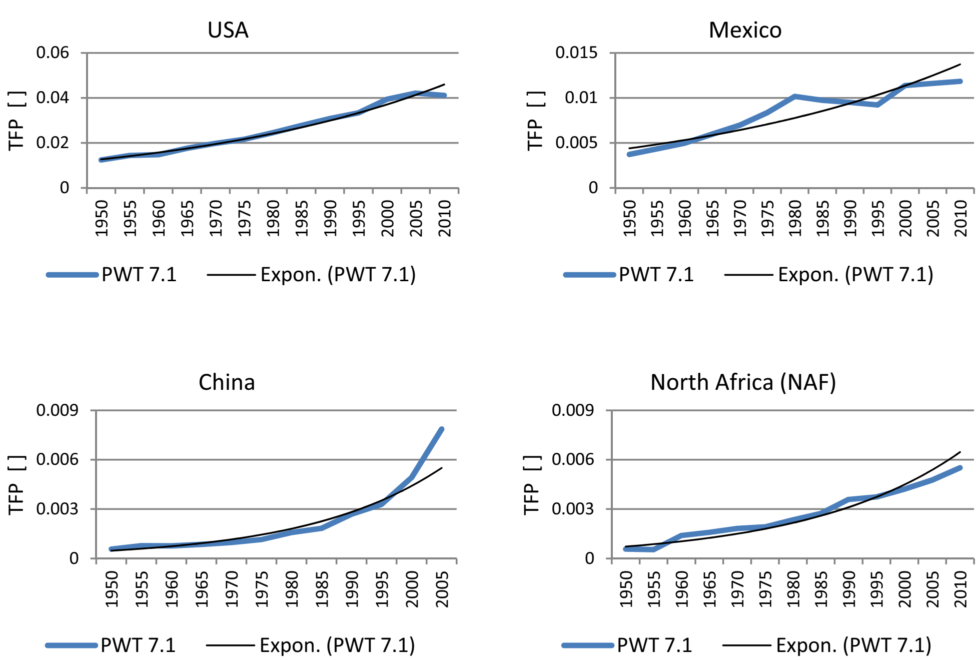

Fig. 2. Empirically derived TFP (based on PWT 7.1 data) and exponential fit.

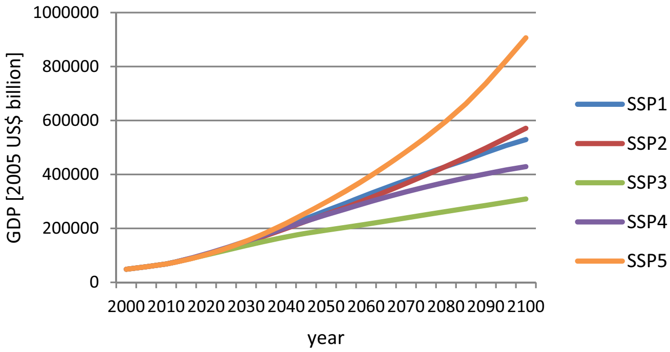

Fig. 3. World GDP (PPP).

transition from the historically based evolution toward the convergence-based TFP.

Details on the computation of initial growth rate g_A are provided in Supplementary Material S5. This material also documents the derived initial TFP levels and TFP growth rates. The estimated TFP level in 2010 is highest for Japan (0.064), the EFTA region (0.061) and the USA (0.057). Highest initial TFP growth rates of more than 17% over 5 years (weighted average) are observed in OAS-CPA, China, Korea, India and Taiwan. Limitations of the quality of the capital stock data input as well as the use of education data from two different data sources weaken the robustness of this intermediate output. Nonetheless, backward casting with the derived initial TFP growth rates fit quite well for the time span of 30–40 years. Moreover, by using initial TFP growth rates that cover a long-term trend we reduce the short-term impact of the recent financial crises on the long-term projections. Nevertheless this break in economic growth is covered in the 2010 figures of our projections (see Fig. 5, next section).

Table S5 in the Supplementary Material S5 summarizes the assumptions that have been made for the different regions and SSPs for the remaining two components: convergence rate and transition time in years. These assumptions follow the growth characteristic as given by the SSP storylines and are discussed in the Supplementary Material S5.

4. Results

GDP projections are computed for each world region and SSP based on the derived projections for the inputs capital stock, quality adjusted labor and total factor productivity as described in the previous sections. Due to size constraints, we can only provide a selection of scenario results. A comprehensive data set and a tool for visualization can be accessed via the publically available SSP database (https://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpage&page=series).

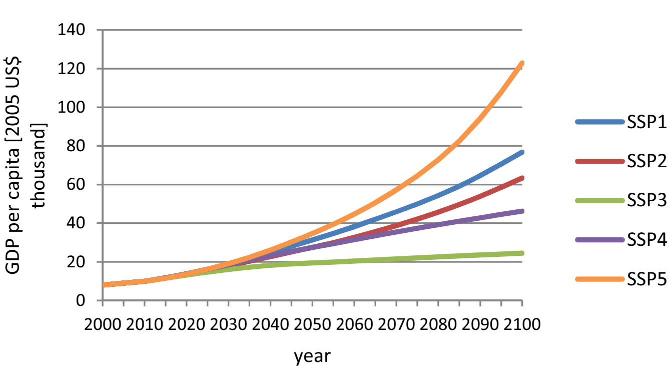

Fig. 4. World GDP per capita (PPP).

Table 3
Annual average GDP per capita growth rates.

	SSP1			SSP2			SSP3			SSP4			SSP5		
	2010–2040	2040–2100	2010–2100	2010–2040	2040–2100	2010–2100	2010–2040	2040–2100	2010–2100	2010–2040	2040–2100	2010–2100	2010–2040	2040–2100	2010–2100
High income countries	1.3%	0.9%	1.0%	1.4%	0.9%	1.1%	1.1%	0.4%	0.6%	1.5%	0.9%	1.1%	1.5%	1.7%	1.6%
Middle income countries	4.4%	1.9%	2.8%	4.0%	1.9%	2.7%	3.4%	0.9%	1.8%	4.3%	1.8%	2.7%	4.5%	2.6%	3.3%
Low income countries	4.2%	3.9%	4.1%	3.7%	3.3%	3.5%	2.7%	1.0%	1.6%	3.3%	1.8%	2.3%	4.0%	4.5%	4.4%
World	3.0%	1.8%	2.2%	2.7%	1.7%	2.0%	1.9%	0.5%	1.0%	2.7%	1.1%	1.7%	3.1%	2.5%	2.8%

4.1. GDP scenarios

Figs. 3 and 4 illustrate the global scenarios of GDP and GDP per capita, respectively. GDP is presented as real GDP measured in constant 2005 prices of purchasing power parity (PPP). World GDP increases from US$ 48.7 trillion in 2000 to a value between US$ 309 trillion for SSP3 and US$ 906 trillion for SSP5 in 2100. Assuming a constant ratio between international dollars measured in PPP and measured in market exchange rates (MER) for all 32 regions, this translates into MER values between US$ 150 and 550 trillion.

Continued growth, although on different levels across the SSP scenarios, can be observed for global output. On the regional level, however, we see a downturn of the absolute GDP level for most of the high income regions in SSP3. The small increase of total factor productivity cannot compensate the shrinking labor input. Due to demographic changes in Japan, Korea, Taiwan, Eastern Europe and above all China this also applies to SSP1 and SSP4.

Due to increasing global population until the mid of the century in nearly all SSP scenarios, growth rate of global GDP per capita is lower than that for global GDP. The ranking of the SSPs with respect to the long-term per capita income is quite distinct. The high growth scenario SSP5 exhibits the highest per capita income level in 2100 (around US$ 120,000), followed by SSP1 (US$ 77,000), SSP2 (US$ 63,000), SSP4 (US$ 46,000), and SSP3 (US$ 24,000). SSP3 is the scenario that deviate earliest from the others. Significant differences in the per capita levels can already be observed in 2030. In contrast, a significant difference between SSP2 and SSP4 cannot be observed before 2060.

However, on a regional level and in the short-term, the ranking of the SSP scenarios is not so distinct. Table 3 shows the GDP per capita growth rates separated for two time spans and the three income groups that were introduced in the previous chapter. Already on this still aggregated level it can be seen that for example in the time span between 2010 and 2040 the high and middle income countries have a slightly higher growth rate in SSP4 than in SSP2.

Table 3 also shows that the high income group countries always have the lowest average growth rates, while the growth rates are highest in the low income group for SSP1, SSP2, and SSP5, and highest for SSP3 and SSP4 in the middle income group. Across all

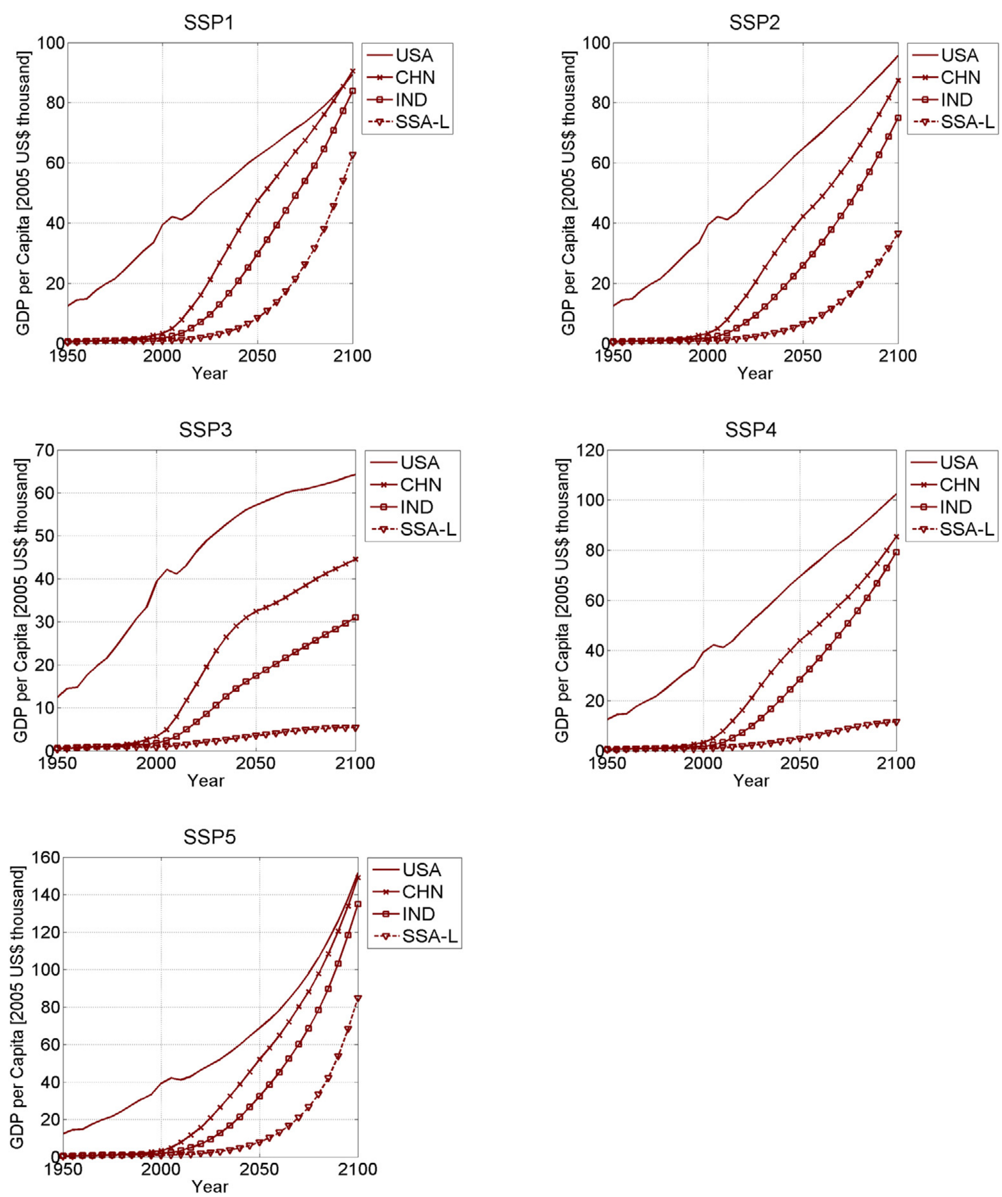

Fig. 5. Per capita income projected for USA, China, India and low income sub-Saharan Africa (each panel shows one SSP scenario).

SSP scenarios growth rates are higher in the short term than in the long term. This is explained, on the one hand, by the expectation that the relatively high growth rates achieved in the decades after World War II cannot be maintained. This is captured by the assumption on the TFP growth rates of the technological leader (Section 3.6). On the other hand, a slow-down of economic growth can be expected once the developing world regions have caught up.

In order to look at the resulting convergence properties of the scenarios, we analyze the per capita GDP development of four different regions (see Fig. 5): (i) the USA as member of the high income group, (ii) China and India as members of the middle income group, and sub-Saharan Africa (SSA-L) as representative of the low income group.

In SSP1, SSP5 and to some extent also in SSP2 we see a convergence pattern that represents a possible future in which one important aspect of the historic economic development is reflected. This is the catching-up of single countries and regions with the technological leaders. This has been observed for some of the currently advanced countries in the past, for Korea in the very recent past, it can be seen today for other south Asian countries as well as China, and is expected for India in the near future. In contrast to this, in SSP3 and SSP4 we see another development which is in line with another historical trend – that of divergence between the technologically leading countries and a majority of other countries. Although in the present scenarios this mostly applies to the four low-income regions only, due to their increasing population share at the end of the century more than half of the world population will live in countries left behind. This clearly represents the underlying storyline of the respective SSPs.

4.2. Contribution of TFP, labor, capital

Fig. 6 shows the contribution of the three factors TFP, capital and labor to the growth of per capita GDP. Based on the Cobb–Douglas production function the following decomposition holds:

$$\frac{\Delta Y}{Y} = \frac{\Delta A}{A} + \alpha \cdot \frac{\Delta K}{K} + (1-\alpha) \cdot \frac{\Delta L}{L} \qquad \text{(IX)}$$

with the weighting factors α and $(1-\alpha)$ for the capital and labor growth rates.

With respect to labor, it is the quality adjustment due to education and the ratio between population growth and working population growth that matters most. Nevertheless, except for SSA-L in the first periods this contribution is relatively small. Due to a decreasing share of working people in most of the high-income regions, even a negative contribution of the factor labor can be observed (for the USA in Fig. 6). TFP growth in general contributes most to the GDP per capita growth. It is also mostly affected when changing the assumptions on the level of economic growth. While this is not surprising, the comparison of the growth rates of SSP2 and SSP3 also shows that with the decrease of the contribution of the TFP in SSP3 compared to SSP2, also the contribution of the capital factor is reduced.

While the underlying narratives give an indication of the range and differentiation of the major parameters of the GDP projections, the chosen values bear uncertainty. Within the sensitivity analysis provided as Supplementary Material S7, we checked the robustness of the GDP projections. Sensitivity is checked against six major parameters: Labor force participation rate, return on education, long-term capital output elasticity, growth of the technological leader, initial value of TFP, and the convergence rate. Overall, we

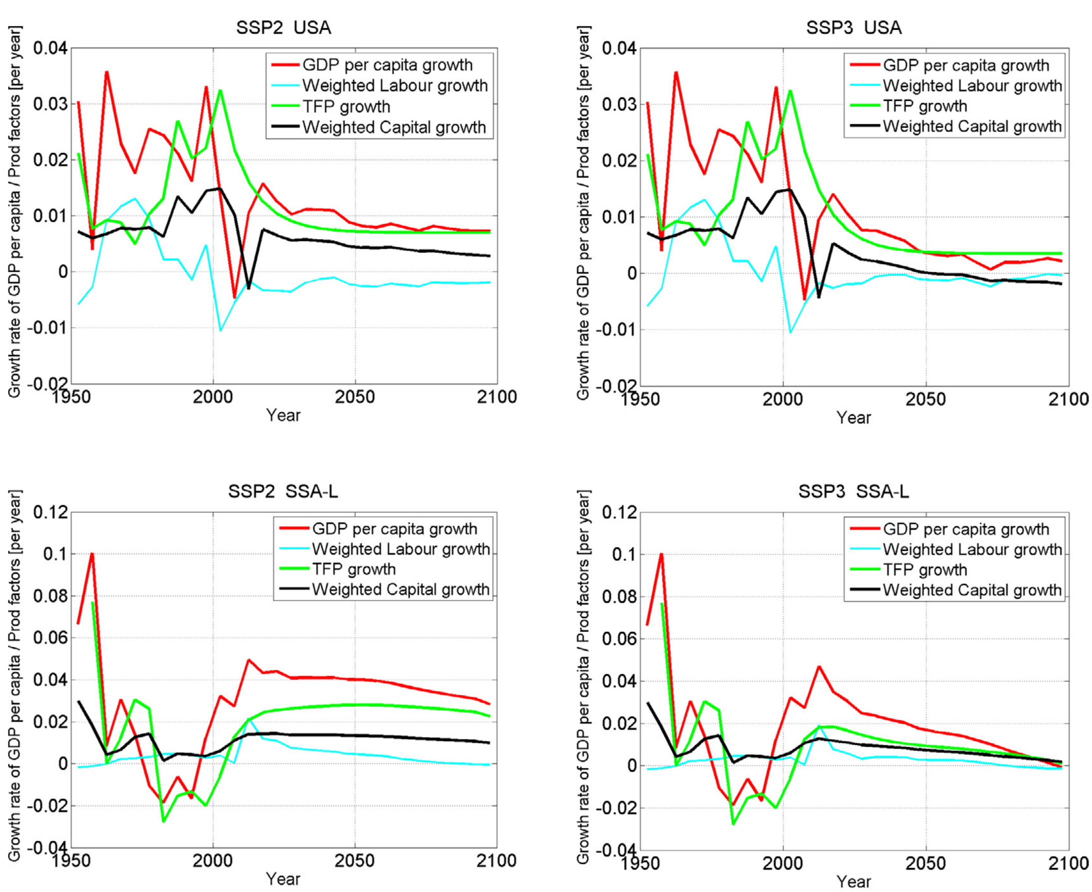

Fig. 6. Decomposition of GDP per capita growth rate for USA and SSA-L in SSP2 and SSP3.

see a moderate sensitivity of the GDP projections to the analyzed parameter changes. The magnitude of parameter variation is relatively large, but none of the experiments results in a shift of the GDP trajectory into another growth mode or changes the ranking across the SSP projections. We therefore are very confident in the robustness of our parameter choices and their representation of the narratives.

4.3. Stylized facts

How do the GDP projections perform against the stylized facts introduced in Section 2 (Table 1)? It needs to be kept in mind that the representation of a stylized fact can depend on the level of regional aggregation. Moreover, by design it cannot be expected that all projections match all stylized facts, since they all except SSP2 assume significant structural changes from past behavior.

The continued increase in the amount of capital per worker as postulated by Kaldor fact SF2 can be seen in all scenarios and is indicated by the higher growth rates of the capital compared to the labor input as illustrated in Fig. 6. Kaldor fact SF4 is discussed in the Supplementary Material S4. As part of the scenario design, we made different assumptions on the dynamics of the capital output elasticity. Although changes are slow, capital-output ratios change over time. For the majority of regions and SSPs we can observe an increasing level which is in agreement with empirical observations illustrated by Fig. S2 in the Supplementary Material S4.

A major point of interest is how the convergence pattern can be evaluated against the stylized facts. In accordance with New Kaldor fact NSF3, the variation across regions in the growth rate of per capita GDP (2015–2100) increases with the distance to the technology frontier (see Fig. 7). This feature is more pronounced in the scenarios that include low growth and divergence (SSP3 and SSP4) than in the high growth and convergence scenarios (SSP1, SSP5). Note that a 'triangle'-shape is seen historically if data are nationally disaggregated. Regional aggregation probably has an averaging effect that blurs the appearance of a stronger spread in growth rates especially for low income countries.

There is a good match of New Kaldor fact NSF4 and NSF5 across all scenarios. According to the former, income and productivity differences are large and the dominant factor of GDP growth is the Solow residual, i.e. TFP. In addition to Fig. 6 which already demonstrates the role of TFP in explaining GDP per capita growth, Fig. S3 (in Supplementary Material S6) provides further evidence by showing the correlation between GDP growth and TFP growth across all regions in two time periods (2040 and 2070) for SSP2. Regarding New Kaldor fact NSF5, the rising human capital per worker is already obeyed due to scenario construction (see Section 3.4).

The hump-shaped growth pattern as stated by GSF4 can be observed in most scenarios, but it is more pronounced in the shorter time period. Fig. S4 (in Supplementary Material S6) demonstrates this for the growth rates of the time period 2010–2030 for scenario SSP2. Differences across all scenarios are small in this short-term period.

Regional GDP growth rates and average investment shares are positively correlated across all scenarios (Dosi stylized fact DSF10). This result follows directly from the approach of scenario design based on a Solow and Ramsey growth model. Actually, this stylized fact can be used to justify the pursued approach (see Section 3.5). Correspondence with stylized fact GSF2 is restricted by scenario design which considers the convergence property as one of the distinguishing features of the SSP scenarios. Hence, all scenarios that assume convergence as part of their storyline do not match this stylized fact (SSP1, SSP2 and SSP5). Fig. 5 indicates that in SSP3 and SSP4 per capita income does not always converges. However, the twin-peaking of world income distribution disappears in both

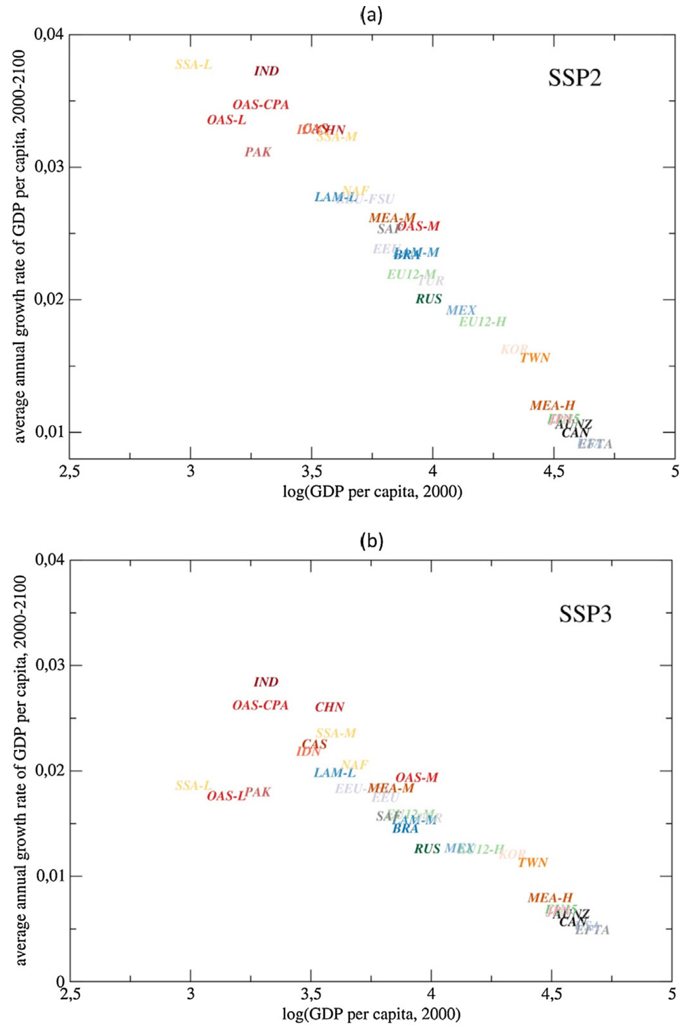

Fig. 7. Representation of New Kaldor fact NSF3: (a) SSP2 and (b) SSP3.

scenarios in the coming decades and returns only very moderately in SSP4. Fig. 8 shows the development of the Gini coefficient in all SSP scenarios. According to this, world income is most equally distributed in SSP1, followed by SSP5 and SSP2. Due to growth stagnation in SSP3, there is no further reduction of the income disparity. In SSP4 the convergence of middle income countries first narrows the range of income distribution, but in the long-run the income gap to the low-income group, which gains in population share, widens again.

In summary, with the exception of GSF2, we find a reasonable match with the stylized facts reported in the literature. The match with some of the stylized facts is better in the short term than in the long term. This can be seen as a consequence of the principle limitation (lack of time persistence) of socio-economic trends. Convergence assumptions are quite strong for most of the projections, but the span of average growth rates of per capita income fits well to the historical observation. A combination of higher growth of the technological leader and lower convergence rates would be an alternative for generating projections within a comparable global range, but with an even larger spread in regional per capita incomes. The adoption of more extreme assumptions (e.g. negative growth rates) would either lead to projections with implausible global long-term income levels or would assume a highly arbitrary process of selecting countries and regions to be subjected to extreme assumptions. In the end, the

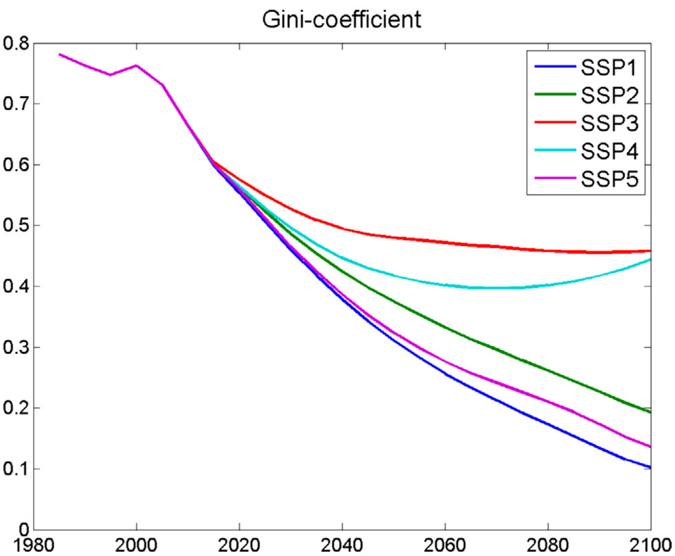

Fig. 8. Inter-region Gini coefficient.

presented set of projections will have a good chance of covering the variety of global future GDP but will probably not represent the diverse development the future will confront us with on the regional or national level.

5. Summary and conclusions

This paper presents a set of GDP projections consistent with the narratives of new shared socio-economic pathways (SSP). By using an economic growth model for the scenario design, the spread between the GDP projections is determined by five factors: labor input, capital input, output elasticities, long-term growth of the economy at the technology frontier, and convergence of total factor productivity in economies below the technology frontier. GDP projections are provided for 32 countries and world regions. While thus the projections bear less information than the country-based projections provided by Cuaresma (2017) and Dellink et al. (2017), data reduction by country aggregation facilitates consistency checks, sensitivity analyses and interpretation of results. At the global average, per capita GDP is projected to grow annually in a range between 1.0% (SSP3) and 2.8% (SSP5) from 2010 to 2100. The study demonstrates the robustness of the scenarios by successfully testing the scenario results against stylized facts from empirical economic literature and by demonstrating low sensitivity to the choice of input parameters in terms of their ability to shift pathways into other domains.

The underlying SSP narratives are translated into different economic futures. The sustainable world of SSP1 is accompanied by a medium to high per capita income growth of 2.2% annually at the global average over the whole century. Average growth is particular high in today's low income countries (4.1%). This reflects rapid technological change in these countries facilitated by international cooperation, technology diffusion and progress in education. While the "Middle of the Road" projection SSP2 achieves at the global level similar absolute income levels like SSP1, the per capita income is significantly lower (growth rate 2.0%). This is mainly due to less international cooperation, slower technological change and hence less convergence between the advanced world regions and the developing world regions. Per capita income growth in the low income group is 3.5% over the century. Technical progress ceases in the fragmented world of SSP3. Restrictions in international trade, technology and knowledge transfers reduce the per capita income growth rates to the very low end of historical growth rates (1.6% for low income countries and 0.6% for high income countries). SSP4 is characterized as an unequal world. This is reflected in the GDP scenario by the fact that the low income regions, which in other scenarios show the highest growth rates, substantially fall behind the middle income group. Increasing inequality is also shown by an increasing Gini coefficient in the second half of the century. The increasing population share of the low income regions lead to a global average income growth rate of 1.7% which is lower than those of the other medium growth scenarios SSP1 and SSP2. Finally, the high growth projection in SSP5 is accompanied by global per capita income growth of 2.8%. Most remarkably, this is the only projection which for a particular income group shows higher growth rates in the long run than in the short run. Due to the strong growth orientation and continued fast technological progress in the advanced world regions, the convergence process of the developing world regions takes longer. Average per capita income growth of 4.0% in the first half of the century is followed by 4.5% in the second half for the low income countries.

The GDP projections developed here provide an essential input for the integrated assessment of global environmental change, in particular climate change. The different growth trajectories across the SSPs will trigger assessment studies with different levels of greenhouse gas emissions and climate change impacts. Different mitigation and adaptation strategies have to be explored to deal with resulting climate change. The strong linkage of the GDP projection design to the SSP storylines allow for combining the GDP assumptions with other assumptions (e.g. on energy demand and land use) that follow these storylines and which are needed for a comprehensive integrated assessment of climate change.

Acknowledgement

Funding from the German Federal Ministry of Education and Research (BMBF) within the call Economics of Climate Change (funding code 01LA1105A, CliPoN) is gratefully acknowledged.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2015.02.005.

Appendix B

Table A.1 Region mapping.

SINGLE-COUNTRY REGIONS	
Brazil (BRA); Canada (CAN); Indonesia (IDN); India (IND); Japan (JPN); Korea, Rep. (KOR); Mexico (MEX), Russian Federation (RUS), South Africa (SAF); Turkey (TUR); Taiwan (TWN)	
AGGREGATED REGIONS	
Region	Countries
AUNZ	Australia; New Zealand
CAS	Armenia; Azerbaijan; Georgia; Kazakhstan; Kyrgyz Republic; Tajikistan; Turkmenistan; Uzbekistan
CHN	China; Hong Kong, SAR; Macao, SAR
EEU	Albania; Bosnia and Herzegovina; Croatia; Macedonia FYR; Serbia; Montenegro
EEU-FSU	Belarus; Moldova; Ukraine
EFTA	Switzerland; Norway; Iceland
EU12-H	Cyprus; Czech Republic; Estonia; Hungary; Malta; Poland; Slovak Republic; Slovenia
EU12-M	Bulgaria; Latvia; Lithuania; Romania
EU15	Austria; Belgium; Denmark; Finland; France; Germany; Greece; Ireland; Italy; Luxembourg; Netherlands; Portugal; Spain; Sweden; United Kingdom
LAM-L	Haiti; Belize; Guatemala; Honduras; Nicaragua

Appendix B (*Continued*)

SINGLE-COUNTRY REGIONS	
Brazil (BRA); Canada (CAN); Indonesia (IDN); India (IND); Japan (JPN); Korea, Rep. (KOR); Mexico (MEX), Russian Federation (RUS), South Africa (SAF); Turkey (TUR); Taiwan (TWN)	
AGGREGATED REGIONS	
LAM-M	Argentina; Bolivia; Chile; Colombia; Costa Rica; Cuba; Dominican Republic; Ecuador; El Salvador; Jamaica; Paraguay; Panama; Peru; Trinidad and Tobago; Uruguay; Venezuela, RB; Antigua and Barbuda; Bahamas, The; Barbados; Bermuda; Dominica; Grenada; Guyana; St. Lucia; St. Vincent and the Grenadines; St. Kitts and Nevis; Suriname; Martinique; Guadeloupe; Netherlands Antilles; French Guiana
MEA-H	Israel; Kuwait; Oman; Qatar; United Arab Emirates; Saudi Arabia; Bahrain
MEA-M	Iraq; Jordan; Lebanon; Syrian Arab Republic; Yemen, Rep.; Iran, Islamic Rep.; Occupied Palestinian Territory
NAF	Algeria; Egypt, Arab Rep.; Libya; Morocco; Tunisia; Western Sahara
OAS-CPA	Cambodia; Vietnam; Lao PDR; Mongolia
OAS-L	Nepal; Bangladesh; Micronesia, Fed. Sts.; Papua New Guinea; Philippines; Samoa; Solomon Islands; Timor-Leste; Tonga; Vanuatu; Fiji; Korea, Dem. Rep.; Myanmar
OAS-M	Brunei Darussalam; French Polynesia; Singapore; Malaysia; Maldives; Thailand; Bhutan; Sri Lanka; New Caledonia; Guam
PAK	Pakistan; Afghanistan
SSA_L	Benin; Cameroon; Congo, Dem. Rep.; Cote d'Ivoire; Congo, Rep.; Eritrea; Ethiopia; Ghana; Kenya; Mozambique; Nigeria; Senegal; Sudan; Tanzania; Togo; Zambia; Zimbabwe; Burkina Faso; Burundi; Cape Verde; Central African Republic; Chad; Comoros; Djibouti; Gambia, The; Guinea; Guinea-Bissau; Lesotho; Liberia; Madagascar; Malawi; Mali; Mauritania; Niger; Rwanda; Sao Tome and Principe; Sierra Leone; Somalia; Swaziland; Uganda;
SSA-M	Angola; Botswana; Gabon; Equatorial Guinea; Mauritius; Namibia
USA	United States; Puerto Rico; United States Virgin Islands

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