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The Challenge of the Paris Agreement to Contain Climate Change

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ABSTRACT
Climate change due to anthropogenic CO_2 and other greenhouse gas emissions has had and will continue to have widespread negative impacts on human society and natural ecosystems. Drastic and concerted actions should be undertaken immediately if such impacts are to be prevented. The Paris Agreement on climate change aims to limit global mean temperature below 2 °C compared to the pre-industrial level. Using simulation and optimization tools and the most recent data, this paper investigates optimal emissions policies satisfying certain temperature constraints. The results show that only if we consider negative emissions coupled with drastic emissions reductions, temperature could be stabilized at about 2.5 °C, otherwise higher temperatures could possibly occur. To this end, two scenarios are developed based on the national emissions reduction plan of China and the USA. According to the simulation results, the objective of keeping temperature rise under 2 °C cannot be met. Clearly, negative emissions are needed if the Paris targets are to be given a chance for success. However, the feasibility of negative emissions mainly depends on technologies not yet developed. Reliance on future technological breakthroughs could very well prove unfounded and provide excuses for continued carbon releases with possible severe and irreversible climate repercussions. Thus, the Paris Agreement needs immediate amendments that will lead to stronger mitigation and adaptation commitments if it is to stay close to its goals.

KEYWORDS
Climate Change; Paris Agreement; Nationally Determined Contributions; Integrated Assessment Model

1. Introduction

It is a scientifically proven fact that the climate is changing mainly due to CO_2 emissions from burning fossil fuels. Climate change has a multitude of adverse consequences; environmental, economic, and social, among others. Temperature rise has been associated with a lot of dangerous phenomena such as changes in weather and climate, hot spells, floods, droughts, hurricanes, acidification of oceans, sea level rise, melting of icecaps, reappearance of old diseases, landslides, etc. Climate change is already having negative economic and health impacts on a global scale in the form of property damages, loss of agricultural production, hunger, spread of disease vectors, injuries, and fatalities, among others. Climate change, simply phrased, is a major security threat to all countries and drastic and concerted action should be undertaken immediately to alleviate this global problem (Grigoroudis, Kanellos, Kouikoglou, & Phillis, 2016).

A new global agreement to combat climate change was adopted under the United Nations Framework Convention on Climate Change (UNFCCC) in December 2015 in Paris. The Paris Agreement on climate change is the result of significant efforts and negotiations by the international community to reach a universal deal on global warming. Albeit it is a step forward, its effectiveness is questionable (Stavins, 2016).

The main goal of the Paris Agreement is "… *holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels…*" (UNFCCC, 2016). These temperature targets are the outcome of intense international negotiations aiming to prevent dangerous interference with the climate system, while ensuring sustainable food production and economic development (Rogelj et al., 2016).

The Paris temperature targets raise two important questions: Can national intentions as expressed in the agreement achieve these targets by the end of this century and if not, what should be done next? Since temperature increase depends on cumulative emissions, not only short or mid-term, but also long-term emissions reduction plans are required.

The Paris Agreement is based on national plans submitted by the participating countries that outline their intentions about targets and actions to reduce CO_2 emissions. However, the individually promised targets by governments are not given in a universal form. Some countries give their contribution in rather clear and precise numerical terms, while others use relative targets based on possible per capita emissions or emissions intensity per unit of economic output. For some, the mitigation problem is connected with economic fairness. Economically advanced nations have reached a high standard of living thanks to their high emissions, whereas others are currently struggling to join the club of developed countries and in the process are increasing their emissions when mitigation is needed by all. Going one step further, many developing countries that will be hit hard by the effects of climate change expect aid from the rich countries. The latter made in Paris promises of economic aid to the former, but it remains to be seen to what extent these promises will be kept.

A serious problem of the Paris Agreement is that it relies on negative emissions. The Agreement aims to reach a global peak in CO_2 emissions as soon as possible and a balance between

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anthropogenic emissions and removals in the second half of this century (Rogelj et al., 2016). This balance can be realized, besides reforestation and afforestation of land, through biofuel production, carbon capture and storage technologies. However, the feasibility of such solutions has been widely questioned, because for example, no large scale carbon capture and storage technologies exist today and biofuel production competes with food production.

The objective of this paper is twofold. First, it investigates optimal emissions policies using the most recent data. The analysis is based on simulation and optimization tools and estimates of optimal emissions trajectories under certain constraints in 2015-2100. Second, it assesses the implications of the Paris Agreement, focusing on the two largest emitters, China and the USA. As noted by several researchers, the window for limiting warming to below 1.5 °C with high probability already seems to have closed (Rogelj et al., 2016), while currently, a large part of the available carbon budget that would keep global warming to below 2 °C has already been emitted. It turns out that a 2.5 °C target is more realistic. However, even this modest goal has a chance of succeeding only under very strong international cooperation and deep emissions cuts.

The remainder of this paper is organized as follows: Section 2 presents the key elements of the Paris Agreement and an overview of studies assessing its implications. Section 3 describes analytically the applied optimization model, while the results of the examined scenarios are given in Section 4. Finally, Section 5 makes some concluding remarks.

2. Adoption and Implications of the Paris Agreement

2.1. Key Elements of the Paris Agreement

The Paris Agreement adopted at the Paris Climate Change Conference (COP21) in December 2015 is a global mechanism to address climate change. During COP21, 195 countries agreed a universal global climate deal, recognizing the necessity of climate change response, and low-carbon, climate-resilient, and sustainable development (UNFCCC, 2016).

According to the agreement, countries should cooperate in a global action plan in order to limit global warming to well below 2 °C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels. The most important key elements of the Paris Agreement include the following (Dimitrov, 2016):

(a) Global objective of limiting global warming to well below 2 °C and pursuit of efforts to limit the temperature increase to 1.5 °C (Article 2);
(b) Reach global peak of emissions as soon as possible (Article 4.1);
(c) Each party shall prepare, communicate and maintain successive nationally determined contributions that it intends to achieve to be revised every five years (Article 4.2);
(d) Developed countries should continue taking the lead with economy-wide absolute emissions reduction targets, while developing countries are under weaker obligations and should continue enhancing their mitigation efforts, and are encouraged to move over time toward reductions of economy-wide emissions or limitation targets in light of different national circumstances (Article 4.4);
(e) Developed countries shall provide financial resources to assist developing countries, while other parties are encouraged to provide such support voluntarily (Article 9).The Intended Nationally Determined Contributions (INDCs) are one of the most important elements of the Paris Agreement. They express national pledges that contribute to "*…stabilizing the greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system…*", which is the ultimate objective of the UNFCCC. In addition, the Paris Agreement includes a 5-year revision process for INDCs in order to measure and monitor ongoing progress.

The INDCs represent a "bottom-up" decentralized and transparent set of climate commitments. Several researchers, however, although they recognize the positive side of INDCs, note the high risk of implementing them. For example, Kennel, Briggs, and Victor (2016) note that INDCs rely on complex and highly decentralized decision processes that should engage all levels of government and the private sector. Moreover, there is no coordination between countries, and thus it is difficult to determine if the sum of all INDCs is consistent with the objectives of the UNFCCC (Peters, Andrew, Solomon, & Friedlingstein, 2015). It should be noted that the published INDCs span a short period until 2025 or 2030, although temperature rise depends on cumulative emissions over the entire century. Thus, INDCs are just a first step in a process of monitoring, evaluation, and revision (Fawcett et al., 2015).

Other articles of the Paris Agreement emphasize the increasing necessity of adaptation to the adverse impacts of climate change (UNFCCC, 2016). The signatories of the Agreement have invited the Intergovernmental Panel on Climate Change (IPCC) to assess the impacts of a global temperature rise of 1.5 °C above pre-industrial levels and global greenhouse gas emission pathways leading to this target.

2.2. Studies on the Implications of the Paris Agreement

Several implications of the Paris Agreement have been exposed in recent studies (see Rogelj et al., 2016, for a relevant review). Most of them examine whether the global target of limiting average temperature rise below 2 °C is achievable, while others analyze the aggregate effect of the published INDCs. Although the results of these studies are mainly focused on the global emissions till 2030, it is widely accepted that the target of 2 °C requires rapid emissions reductions and adoption of a low-carbon energy policy over long periods of time.

The objective of limiting temperature rise to 1.5 °C is considered rather unrealistic given the present global temperature rise of about 0.85 °C with respect the pre-industrial period and the current trend of greenhouse gases emissions (GHG). As noted by Boucher et al. (2016), focusing on a 1.5 °C scenario constitutes a form of hypocrisy, since it sustains false hope to the most vulnerable countries.

Jeffery et al. (2015) examined 158 published INDCs (94% of global emissions) using the Climate Action Tracker (CAT) approach, which estimates global warming consequences and emissions gaps. According to CAT, temperature will rise by about 2.7 °C by 2100 (with a range of 2.2–3.4 °C) if all INDCs are fully respected. The same model predicts a 3.6 °C rise by 2100, if current policies are not changed. Similarly, Rogelj et al. (2016) estimated a median warming of 2.6–3.1 °C by 2100,

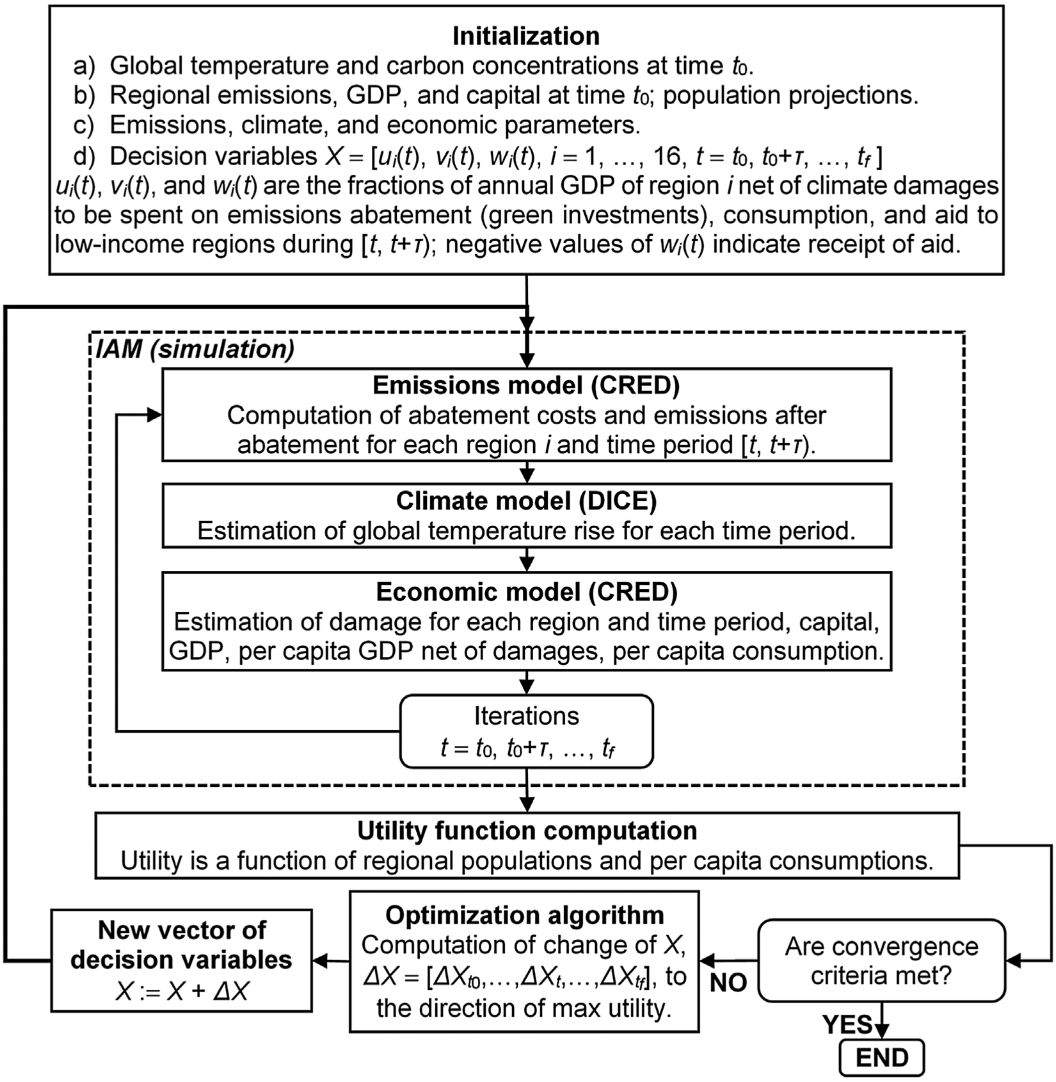

Figure 1. Simulation and Optimization Algorithms.

again based on the INDCs. Fawcett et al. (2015), Benveniste et al. (2015), and den Elzen et al. (2016) have reported similar results.

Fujimori et al. (2016), using the Dynamic Integrated Climate-Economy (DICE) integrated assessment model (IAM) argue that the current INDCs are not consistent with the 2 °C objective. Sharper emissions cuts coupled with negative emissions are needed to stay within target (see also Meinshausen et al., 2015). Schleussner et al. (2016) concluded that the temperature targets of the Paris Agreement of 1.5 or 2 °C are unrealistic even if zero global emissions are reached by 2100 given the agreed near-term mitigation targets between 2020 and 2030. Hof et al. (2015) demonstrated that negative emissions are necessary to reach the Paris Agreement targets and all existing coal-fired power plants should be practically retired by 2040. In the same vein, Iyer et al. (2015) noted that, if no action is undertaken until 2030, drastic reductions must be imposed between 2030 and 2035 by prematurely retiring fossil fuel power plants of a total capacity of 2,300 GW and by installing up to 2,900 GW of additional low-carbon power plants.

We now proceed with the analysis and simulation of various scenarios to test the feasibility of the Paris Agreement targets. Mitigation of GHG is done in an optimal fashion so that a suitable utility function is maximized. Then we examine possible trajectories of GHG emissions, the resulting warming, and economic repercussions. We start with the optimization model.

3. Optimization Model

3.1. Overview

The optimization procedure uses models of climate, economy, and emissions to simulate climate change and economic development on a time interval $[t_0, t_f]$, which in our simulations is [2015, 2100] using 5-year steps, $\tau = 5$. The reason for choosing t_0=2015 and not a later year is that the models we use contain initial conditions, such as carbon content and temperature rise, for this year. The economy and emissions models are based on the Climate and Regional Economics of Development (CRED) IAM by Ackerman, Stanton, and Bueno (2012, 2013). Sixteen world regions are considered: South Africa, Rest of Africa, China, India, South-East Asia and the Pacific, Other Developing Asia, Brazil, Mexico, Rest of Latin America and the Caribbean, Middle East, Eastern Europe, Western Europe, Other Europe, Japan, USA, Other high-income regions (i = 1, 2, …, 16).

The computational procedure is depicted in Figure 1 and summarized in the following steps:

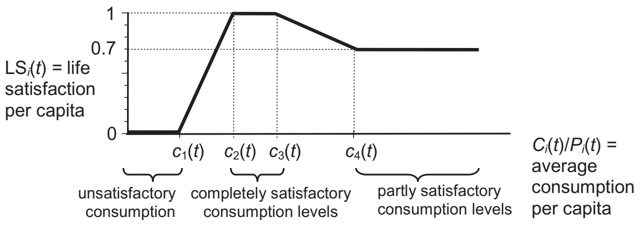

Figure 2. An Empirical Function for Assessing Life Satisfaction.

(a) The model uses three control variables for each region i and year t, all expressed as fractions of GDP net of global warming damages[1]:

u: Regional CO_2 emissions abatement cost, i.e., the amount of money each region pays for climate abatement.
v: Regional consumption.
w: Net regional economic aid provided to other regions (if $w > 0$) or received from other regions (if $w < 0$).

(b) Climate model
The anthropogenic CO_2 emissions raise the carbon concentration in the atmosphere, thereby causing higher solar energy absorption that raises average climate temperature T.
(c) Economy model

- The output (GDP) of each region is estimated by a production function involving capital, K, and the projected population.
- K depreciates over time and grows by annual investments.

- Annual investments equal GDP less the costs of global warming damages, CO_2 abatement, the economic aid offered or received, and consumption C. Climate damages are appropriate functions of T and GDP. The remaining quantities are fractions of GDP.

(d) Emissions model
The annual regional emissions E equals the sum of industrial emissions and the carbon balance from land-use change minus the abated emissions. Industrial emissions are estimated from GDP generation and the population of each region while land-use emissions are assumed to be fixed. The emissions abatements are calculated using a dynamic pricing model that involves the relative abatement expenditure u and the marginal abatement cost (MAC) curve of each region (more details are given in the Appendix).
(e) By repeating steps (b)–(d) for all years in $[t_0, t_f]$ and all regions, we obtain time series of GDP, consumption, and carbon emissions for each region and the average global temperature; these outputs depend on the control variables u, v and w.
(f) Optimization

- The overall utility is a measure of life satisfaction based on the per capita consumption for each region.
- The objective is to maximize utility subject to dynamic constraints on GDP, emissions E, and global warming T, imposed by the economy and climate models.
- Additional constraints are imposed on the control variables so that the regional emissions reductions and the regional net per capita GDP meet certain fairness principles.

Steps (b)–(d) of the above algorithm simulate the climate, economy, and CO_2 emissions over the period $[t_0, t_f]$ and are detailed in the Appendix.

3.2. Utility Function and Convergence Criteria

A common objective in IAMs and policy analyses is the maximization of a utility function. The utility function is generally taken as the present value of the logarithm of the per capita consumptions:

$$U(u, v, w) = \sum_{t=t_0+\tau}^{t_f} (1+\rho)^{-(t-t_0)} \sum_{i=1}^{16} P_i(t) \ln \frac{C_i(t)}{P_i(t)} \qquad (1)$$

where ρ is the rate of pure time preference used for discounting future utilities, $P_i(t)$ is the population of region i in year t and $C_i(t)$ the total consumption of region i. The default value of ρ in CRED is 0.1 percent per year, the same as in the Stern Review (Stern, 2007). The objective function (1) is increasing in the consumption. Grigoroudis et al. (2016) have proposed an alternative utility function for measuring life satisfaction (LS), which is increasing for small levels of per capita consumption, becomes flat at higher levels, and finally declines in the richest countries. This function is derived by assigning a value $LS_i(t)$ from 0 (completely dissatisfied) to 1 (completely satisfied) to each individual, based on the average per capita consumption of each region as shown in Figure 2. Its use is justified by a survey data analysis reported in Proto and Rustichini (2013) and by experimental results in Grigoroudis et al. (2016) indicating that LS-based optimal abatement policies are fairer for the developing world. Indeed optimal abatement policies using the LS criterion allow a 7% higher consumption per capita in the poorest region (Rest of Africa) than policies under optimal logarithmic utility, with just 0.3% corresponding reduction in the richest country (USA). The LS utility function has the form

$$\mathrm{LS}(u, v, w) = \sum_{t=t_0+\tau}^{t_f} (1+\rho)^{-(t-t_0)} \sum_{i=1}^{16} P_i(t) \mathrm{LS}_i(t) \qquad (2)$$

As in Grigoroudis et al. (2016), the thresholds c_j in Figure 2 are assumed to have an annual growth rate of 1.25%, same as the average annual growth rate of the global economy (GDP) over the past decade, i.e., $c_j(t) = 1.0125^{t-2010} c_j(2010)$ with base values (in $US): $c_1(2010) = 4{,}980$, $c_2(2010) = 32{,}220$, $c_3(2010) = 37{,}957$, and $c_4(2010) = 44{,}200$.

The next section reports the numerical results obtained from the maximization of $\mathrm{LS}(u, v, w)$. The following constraints are considered in the optimization procedure:

(a) *Temperature rise*: The optimal solution should not lead to a temperature rise above 2.5 °C at the end of the examined period t_f.
(b) *Temperature stabilization*: The difference of temperature rise at the end of the examined period should not exceed 0.025 °C, i.e., $T_{t_f} - T_{t_f-\tau} \le 0.025$.
(c) *Equity constraint*: The per capita consumption of the poorest region in t_f should be no less than 2.5% the highest per capita consumption. This value is the current lowest to highest consumption ratio.

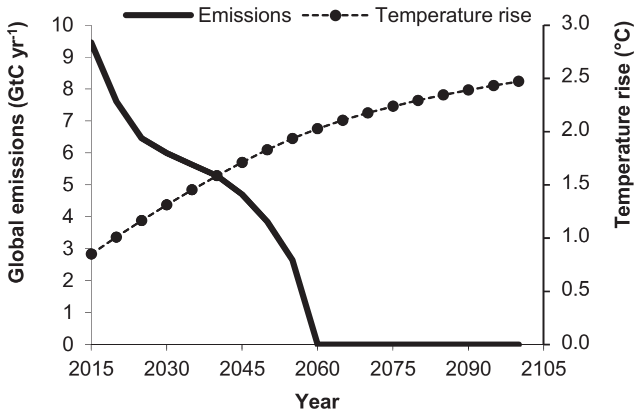

Figure 3. Global Emissions and Temperature Rise for the Optimal Scenario.

4. Results

4.1. Optimal Results

Now a number of possible emissions and temperature scenarios are examined based on the models described in the previous section. Figure 3 shows the global CO_2 emissions and the corresponding temperature rise for the period 2015–2100. Optimal emissions reductions are quite sharp in the period 2015–2060, with an average abatement of 1.05 GtC per 5 years. After 2060, global emissions remain at zero in order to satisfy the temperature rise constraint of 2.5 °C. However, although T_{2100} = 2.47 °C, the temperature stabilization constraint is not satisfied, since $T_{2100} - T_{2095} = 0.04 > 0.025$. Under this optimal scenario, climate damages rise from 0.48% of the global GDP in 2015 to 4.08% in 2100. No optimal scenario leads to 1.5 or even 2 °C. This and the remaining scenarios use the initial conditions of 2015 and thus action is assumed to start at 2015, but in reality no sharp reductions are expected before 2020 or even later, thus making the 2-degree target even more remote.

The estimated regional emissions are presented in Figure 4. The largest overall emissions reductions should be undertaken by China, the world's biggest polluter, followed by the USA, one of the biggest polluters per capita. China's emissions should decrease from 2.66 GtC in 2015 to about 2 GtC in 2020, while the USA's and Western Europe's emissions should decrease from 1.63 and 0.91 GtC in 2015 to 1.38 and 0.73 GtC in 2020, respectively. Regional per capita emissions have similar trends. The annual per capita emissions in the USA must decrease from 4.91 tons C per capita in 2015 to 4 tons in 2020. In other regions with high per capita emissions, like Eastern Europe, South Africa, Japan, and Middle East, reductions vary from 2.5 tons C per capita in 2015 to 1.5 up to 2.3 tons in 2020.

As was already mentioned, the optimal scenario leads to a rise of 2.5 °C, but does not stabilize temperature. Even this less ambitious goal, however, requires immediate, strong and concerted action.

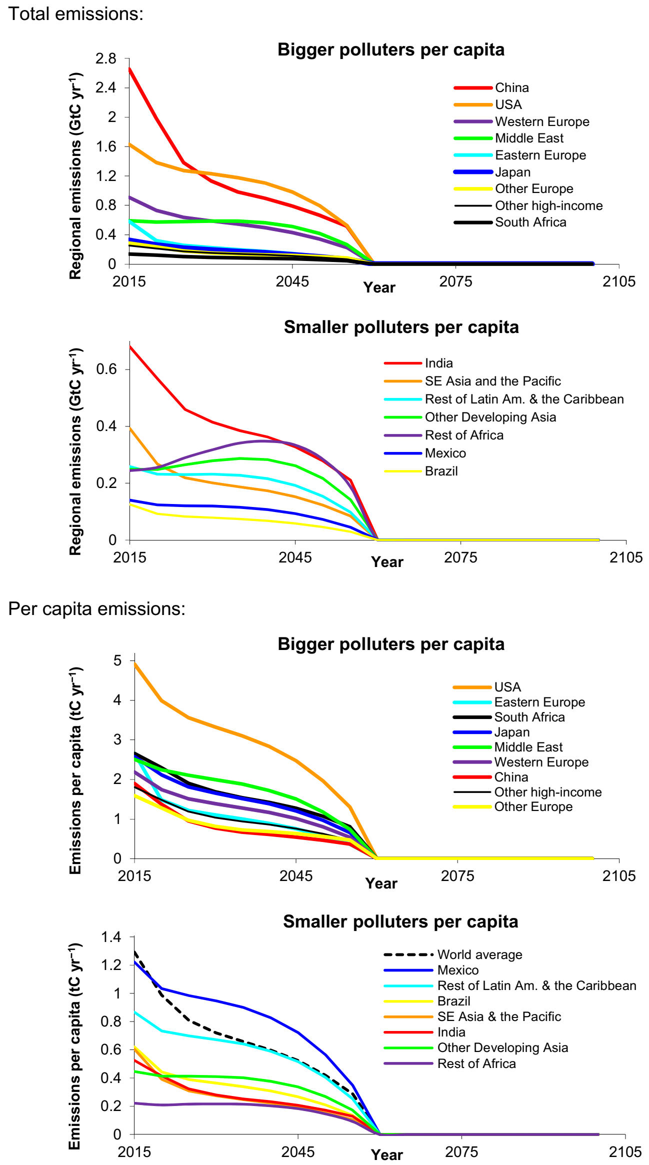

Figure 4. Estimated Total and Per Capita Regional Emissions for the Optimal Scenario.

4.2. Optimal Results with Negative Emissions

Next LS is maximized allowing negative emissions. In the model, this is realized by allowing emissions abatements to be higher than the corresponding industrial emissions. The global CO_2 emissions and the corresponding temperature rise between 2015 and 2100 are shown in Figure 5. Both constraints regarding temperature are now satisfied. Temperature rise is estimated at 2.47 °C in 2100 and exhibits a rather stable pattern about this value, because now $T_{2100} - T_{2095} = 0.02 < 0.025$.

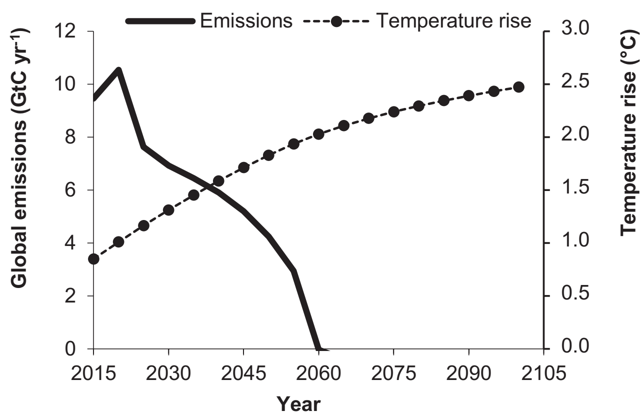

Figure 5. Global Emissions and Temperature Rise for the Optimal Scenario with Negative Emissions.

Contrary to the previous scenario, here the initial mitigation time is postponed for the year 2020, because negative emissions permit a less drastic abatement policy. Global optimal emissions increase from 9.45 GtC per year in 2015 to 10.53 GtC in 2020. Then substantial mitigation action should be undertaken

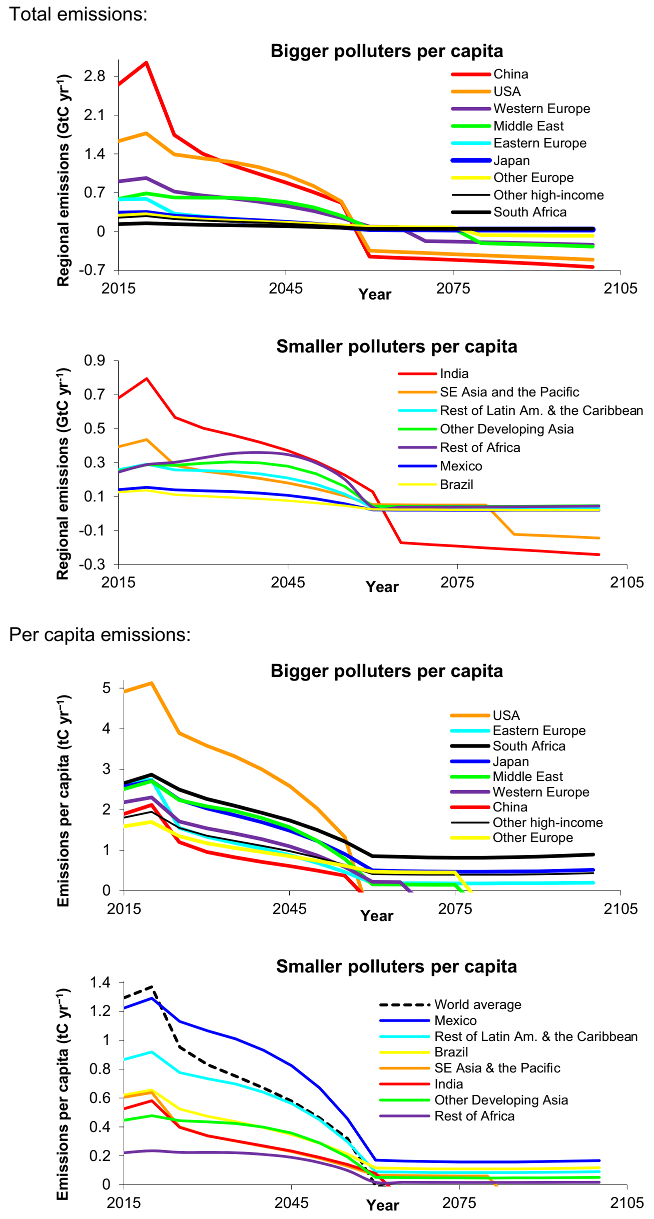

Figure 6. Estimated Total and Per Capita Regional Emissions for the Optimal Scenario with Negative Emissions.

in order to reduce global emissions in 2060 to zero. Emissions between 2020 and 2025 should be reduced by 27.5%. Past 2060 global emissions become negative all the way to 2100, reaching −1.77 GtC per year at the end of the period.

In Figure 6, the detailed estimated regional emissions are shown. Overall and per capita emissions reductions start at 2020, they reach zero in 2060 and assume negative values for USA and China and, five years later, they also become negative for India, which is a large emitter due to its population size despite its low per capita emissions. Most regions progressively become negative emitters except developing areas in South-East Asia and the Pacific, Rest of Africa, and South Africa, which are allowed positive, but near zero emissions in 2100. The estimated global climate damages are similar to the optimal scenario with positive emissions (0.48–4.2% of global GDP).

According to Figure 6, China's emissions should decrease from 3.05 GtC in 2020 to −0.64 GtC per year in 2100, while the USA's and Western Europe's emissions should decrease from 1.77 and 0.97 GtC in 2020 to −0.51 and −0.24 GtC per year in 2100, respectively. The largest per capita reductions occur in the USA, Middle East, and Western Europe from 5.12, 2.71, and 2.31 tons C in 2020 to −1.31, −0.70, and −0.62 tons C in 2100, respectively.

At first glance, the negative emissions scenario appears promising, but in reality it is based on future technological advances that might prove to be false. Several authors question if large-scale negative emissions are technically, economically, and socially viable (see example Anderson & Peters, 2016). The most important current negative emissions technologies include:

(a) Reforestation and afforestation (conversion of land into forest): They are not technologies in the strict sense, but they are important mitigation strategies. Although trees can draw an amount of carbon from the atmosphere, the process is slow and it requires large land areas in order to make a significant difference to global CO_2 concentrations (Ashcroft, 2013).

(b) Bioenergy with carbon capture and storage (BECCS): Currently, it is the most widely known negative emissions technology included in several IAMs. At the moment no large-scale BECCS can be deployed, while their potential is not limitless. As noted by Ashcroft (2013), BECCS is limited by the supply of sustainable biomass, since capturing CO_2 by burning existing biomass that would otherwise have been untouched, would do nothing to reduce atmospheric CO_2.Other negative emissions technologies are currently in different development stages, but their cost and energy intensity would likely be high (e.g., direct air capture process).

4.3. The USA Scenario

The USA is the second largest GHG emitter globally. Its INDCs are summarized below[2]:

- Reduce GHG emissions by 17% below 2005 level by 2020.
- Reduce GHG emissions by 26–28% below 2005 level by 2025.

The above targets were incorporated into the optimization model, assuming in addition a constant emissions reduction of 0.03 GtC per year or 0.15 per five years, starting from an emissions level of 1.636 GtC in 2015 and ending with zero emissions just before 2070. The results are thus based on a fixed emissions pathway for the USA and optimized carbon emissions for the remaining regions, which are stricter than their INDCs. No negative emissions are allowed.

The global CO_2 emissions and the corresponding temperature rise under this scenario are shown in Figure 7. The emissions pathway is similar to the optimal one shown in Figure 3 except for 2060 where all regions become carbon-free with the exception of the USA, which has one more decade to eliminate CO_2 emissions. Global emissions should be reduced significantly in 2015–2020, from 9.46 GtC in 2015 to 7.49 GtC per year in 2020. The temperature rise constraint is satisfied with T_{2100} = 2.46 °C, but the optimization model also fails to satisfy the temperature stabilization constraint as $T_{2100} - T_{2095} = 0.04 > 0.025$. As in Section 4.1, climate damages exhibit a rising trend from 0.48% of the global GDP in 2015 to 4.06% in 2100.

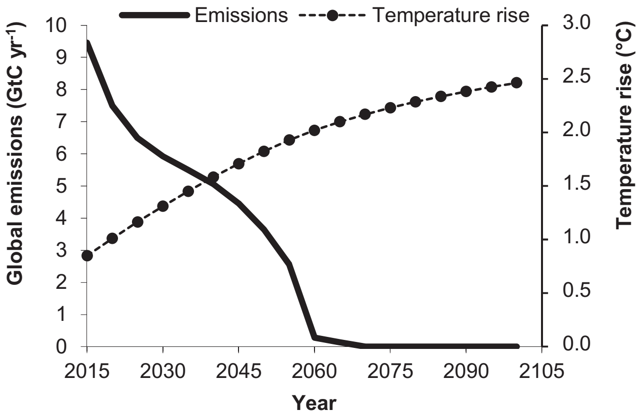

Figure 7. Global Emissions and Temperature Rise for the USA Scenario.

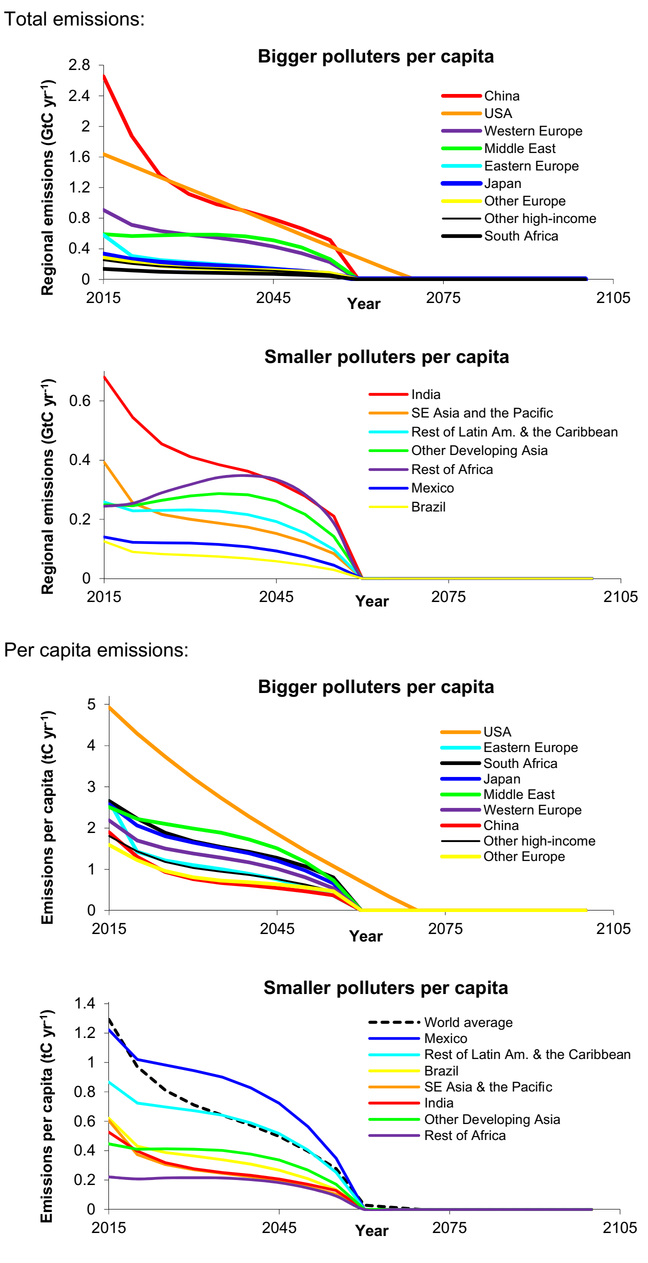

Figure 8. Estimated Total and Per Capita Regional Emissions for the USA Scenario.

Figure 8 shows the estimated regional emissions. USA per capita emissions decrease from 4.93 tons C in 2015 to zero in 2070 at declining rates from 0.63 to 0.33 GtC per 5 years per capita. The emissions pathways for all other regions are almost the same as those in Section 4.1.

We observe that inclusion of the US INDCs as an additional constraint in the optimization model does not alter the overall or regional emissions pathways, except for a small change in the US emissions. As in Section 4.1, the temperature rise is limited to 2.5 degrees in 2100 but not stabilized.

4.4. The China-USA Scenario

The INDCs of both the USA and China are next incorporated into the model. China's INDCs are as follows:

- Peaking of CO_2 emissions around 2030 and making best efforts to peak early.
- Lowering CO_2 intensity (CO_2 emissions per unit of GDP) by 60–65% from the 2005 level.
- Increasing the share of non-fossil fuels in primary energy consumption to around 20%.
- Increasing the forest stock volume by around 4.5 billion m^3 from the 2005 level.If the intended emissions intensity reduction is met, then $E_{2030}/GDP_{2030} = 0.4[E_{2005}/GDP_{2005}]$. In 2015 China's emissions intensity was reduced by 33% compared to 2005 levels. Therefore, $E_{2015}/GDP_{2015} = 0.66[E_{2005}/GDP_{2005}]$ and

$$\frac{E_{2030}}{GDP_{2030}} = 0.4\frac{E_{2005}}{GDP_{2005}} = \frac{0.4}{0.66}\frac{E_{2015}}{GDP_{2015}}$$

We assume that China's economy will grow by 75% in 2015–2030, which corresponds to an annual GDP growth of 3.8%, the current growth rate of the group of low and middle income countries in which China belongs. This is a rather low value given the country's current growth rate of 6.8%, but we use it to generate an optimistic emissions scenario. From the previous equation we obtain

$$E_{2030} = \frac{0.4}{0.66}\frac{E_{2015}}{GDP_{2015}}GDP_{2030} = 1.06E_{2015},$$

which implies that China's emissions will increase by just 6% in the period 2015–2030.

An estimate of China's emissions in 2015 is $E_{2015} = 2.66$ GtC. Even with this estimate, additional information is necessary for defining a plausible emissions trajectory from now until 2100. We make the following assumptions in accordance with China's INDCs:

- We assume that peaking of CO_2 emissions will take place in 2025.
- Taking into account the current emissions and emissions growth rate in 2010–2015 (16% increase of emissions per 5 years), we assume that this growth rate will gradually decrease to zero until 2025 as emissions peak in this year. Accordingly, the maximum of China's emissions will amount approximately to 3.01 GtC for the year 2025.
- China's emissions in 2030 for a 75% GDP increase (6% increase of emissions compared to 2015 level) will be 2.82 GtC. Hence, emissions decrease in 2025–2030 at a rate of 0.19 GtC per 5 years. This rate is assumed constant until 2100.

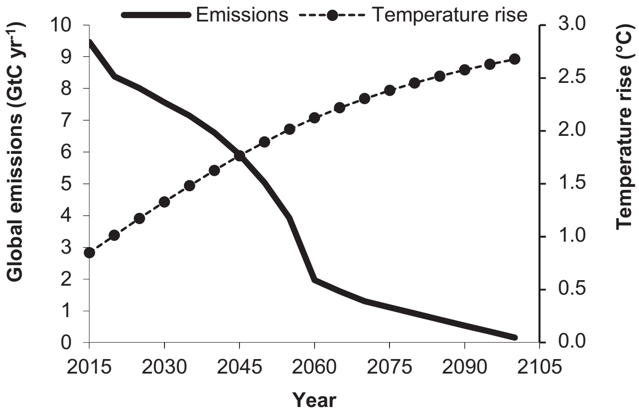

Figure 9. Global Emissions and Temperature Rise for the China-USA Scenario.

Other studies adopt a similar approach to estimate future emissions of China, assuming a gradually declining GDP growth between 2015 and 2030. For example, Peters et al. (2015) use an exponential decay function to fit GDP historical data. They estimate an emissions peak in 2021 (optimistic scenario under a 65% intended CO_2 intensity reduction) or 2026 (pessimistic scenario for 60% intensity reduction) and corresponding annual emissions of 2.7–2.86 GtC in 2030.

China's INDCs are in consonance with its purported right to economic growth relative to developed countries and the consequent obligation of the developed countries to cut their emissions first.

We next combine China's emissions pathway in 2015–2100 with that of the USA from the previous section and incorporate both into the optimization model, while all other regions are optimized.

Figure 9 shows the global CO_2 emissions and the corresponding temperature rise. The optimal pathway is very different from the pathways of Figures 3 and 7, since China is the world's biggest CO_2 emitter and its impact is noticeable. This scenario leads to a reduction of global emissions from 9.46 GtC in 2015 to 8.37 GtC in 2020 and 1.97 GtC in 2060. The temperature rise in 2100 will be T_{2100} = 2.65 °C and it will continue to increase at a rate T_{2100}—T_{2095} = 0.05 °C. The global damages are larger in this scenario reaching 4.35% of the world GDP in 2100.

The estimated regional emissions are given in Figure 10. In this scenario, the USA has the same emissions path as in Figure 8; China's emissions increase from 2.66 GtC in 2015 to 2.80 GtC in 2020, and decrease at a rate of 0.19 GtC/5 years afterwards, reaching 0.15 GtC in 2100. A similar pattern may be observed in China's per capita emissions; they rise from 1.90 tons C in 2015 to 2.07 tons in 2025 and then decline at a rate of 0.11 to 0.14 tons C per 5 years, reaching 0.13 tons C in 2100. The estimated global and per capita emissions for the remaining regions are similar to those of Section 4.1.

Based on the China-USA scenario, the assumed action plan of China significantly affects the optimal solutions presented in Sections 4.1 and 4.3. China's emissions reduction rate is assumed almost constant, and this leads to linear emissions in 2025–2100. Although the optimal emissions for all other regions are zero past 2070, China's emissions remain positive. Most importantly, the estimated global and regional emissions fail to satisfy the temperature constraints of stabilizing global warming at about 2.5 °C.

Of course, China's INDCs are more vague and uncertain than the targets set by other countries, because China's

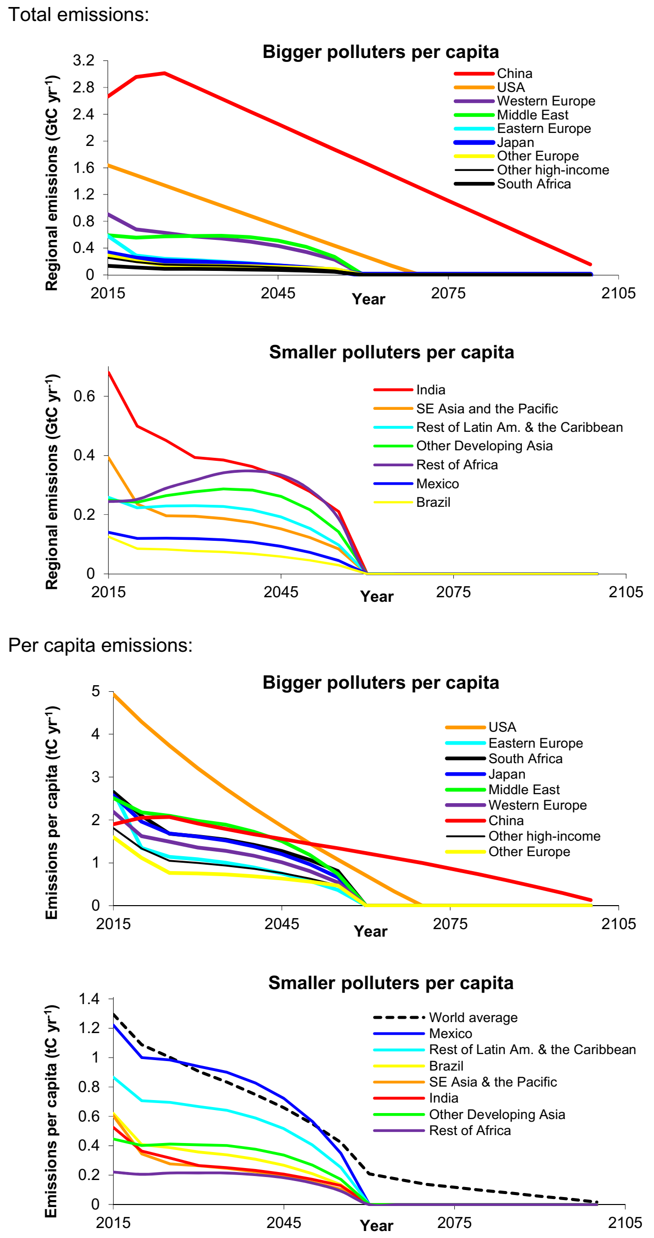

Figure 10. Estimated Total and Per Capita Regional Emissions for the China-USA Scenario.

emissions depend on the country's future GDP. Alternative assumptions of GDP growth alter the optimal emissions pathways. For example, den Elzen et al. (2016) noted that a 1% change in China's average annual economic growth would result in a target emission level change of approximately 0.68 GtC. Despite this, the INDCs can still give a picture of the implications of the Paris Agreement.

5. Concluding Remarks

In this paper, we used two models of climate and economy to analyze several scenarios of carbon emissions for different world regions in 2015–2100. This approach combines simulation and optimization tools to find optimal emissions trajectories and estimate the temperature rise by the end of the century under certain assumptions and constraints.

Our first finding from the numerical experiments is that, without negative emissions, the temperature rise might be 2.5 °C above pre-industrial levels by 2100, but it cannot be stabilized, although drastic measures are taken (complete abatement of emissions by 2060 and large emissions reductions between 2015 and 2020).

By allowing negative emissions, the optimization model gives different results. Only in this case commencement of emissions mitigation can be delayed until 2020 and temperature will be stabilized in 2100 at about 2.5 °C. This scenario is based on the effectiveness and wide usage of negative emissions technologies. Currently, it is questionable whether these technologies are technically, economically, and socially viable. Moreover, several researchers emphasize the "moral hazard" when negative emissions technologies are considered as an alternative to deep cuts in emissions (Ashcroft, 2013): *"if we know we can effectively remove CO_2 from the atmosphere will we be less inclined to cut emissions in the first place?"* Thus, negative emissions may discourage mitigation actions or even give the illusion that emissions can be increased without catastrophic consequences.

Next we discuss the implications of the Paris Agreement using the same model. We focused on the USA and China, which are the two greatest overall CO_2 emitters. We assumed that these two countries would fulfill their commitments (INDCs) under the Paris Agreement, while the rest of the world regions would take even more drastic measures. The results show that the global objective of the agreement (limiting global warming to well below 2 °C) cannot be met in any optimal way or under the INDCs of the two greatest polluters, even if negative emissions are accepted. This is a bleak prospect for the climate and should be taken into account by the negotiators when they meet in 2020 to review progress of the Agreement. In particular, the measures announced by China lead to a global warming of 2.65 °C by 2100. Contrary to the US INDCs, China's commitments are linked to its economic growth, and thus they are uncertain. Currently, China appears to have a high emissions growth compared with other large emitters.

The key finding from the above and other studies is that an optimal emissions pathway consistent with the 2 °C target requires a very drastic acceleration of the current decarbonization rates.

The Paris Agreement is a real progress towards the solution of the global warming and climate change problem, but it is not sufficient. The policies adopted by countries to achieve the emissions targets included in their INDCs are mostly not clear. It is questionable if the stated targets will be met, since several factors and circumstances may influence future emissions policies. Political or economic developments might have unexpected impacts on the Paris Agreement such as the recent US election and a possible abandonment of the US INDCs or the economic problems of southern Europe. The findings of this work as well as those of others demonstrate that the Paris Agreement, hopeful as it might be, must be strengthened if a high temperature rise is to be avoided with unprecedented in historical time impacts on climate, the environment and the society.

Notes

1. For simplicity, the temporal and regional variables *t* and *i* are dropped from the notation. Equivalently, all symbols used herein represent nested vectors indexed by both *t* and *i*.
2. INDCs are available at http://www4.unfccc.int/submissions/indc/Submission Pages/submissions.aspx.
3. DICE 2016R version available at *http://aida.wss.yale.edu/~nordhaus/homepage/DICEmodels09302016.htm*
4. This expression follows by equating the gross industrial emissions-to-GDP ratio and formula (11) of Ackerman et al. (2012).

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix 1.

Below we provide details of the models used to simulate the climate, economy and emissions.

1.1. Climate Model

The climate model uses as input a time series of annual anthropogenic CO_2 emissions and computes the resulting increase in atmospheric temperature. We adopt the climate model used in the latest version[3] of the Dynamic Integrated Climate-Economy (DICE) model (Nordhaus & Boyer, 2000). The dynamics of CO_2 concentration in the atmosphere is approximated by difference equations describing the exchange of carbon among the atmosphere (reservoir 1), the upper ocean and biosphere (reservoir 2), and the lower ocean (reservoir 3). Let $M_j(t)$ be the carbon content of reservoir j at time t and TE(t) the total annual anthropogenic CO_2 emissions (after abatement) into the atmosphere, both in GtC (billion tons of carbon). The model is

$$\begin{bmatrix} M_1(t+\tau) \\ M_2(t+\tau) \\ M_3(t+\tau) \end{bmatrix} = \begin{bmatrix} \varphi_{11} & \varphi_{21} & 0 \\ \varphi_{12} & \varphi_{22} & \varphi_{32} \\ 0 & \varphi_{23} & \varphi_{33} \end{bmatrix} \begin{bmatrix} M_1(t) \\ M_2(t) \\ M_3(t) \end{bmatrix} + \tau \begin{bmatrix} \mathrm{TE}(t) \\ 0 \\ 0 \end{bmatrix} \quad (3)$$

It is assumed that the emissions rate TE(t) is constant throughout the interval $[t, t+\tau)$, where t and τ are measured in years. Regional CO_2 emissions are computed using the CRED model (Ackerman et al., 2013), based on economic growth and emissions scenarios for each region. The following values are used for $\tau = 5$: $\phi_{12} = 0.12$, $\phi_{11} = 1—\phi_{12} = 0.88$, $\phi_{21} = 0.196$, $\phi_{23} = 0.007$, $\phi_{22} = 1—\phi_{21}— \phi_{23} = 0.797$, $\phi_{32} = 0.001465116$, $\phi_{33} = 1—\phi_{32} = 0.998534883$. Initial values for 2015 are $M_1(2015) = 851$ GtC, $M_2(2015) = 460$ GtC, and $M_3(2015) = 1{,}740$ GtC. Estimates of CO_2 emissions are given in the next section.

The atmospheric concentration M_1(t) relative to the corresponding pre-industrial value (588 GtC) is used to compute the total anthropogenic radiative forcing, measured in W/m^2 and given by:

$$F(t) = 5.311\ln\left(\frac{M_1(t)}{588}\right) + F_o(t)\ W/m^2 \tag{4}$$

where $F_o(t)$ is an estimate of the radiative forcing due to non-CO_2 GHGs. In DICE, it is assumed that $F_o(t)$ increases linearly from 0.5 in 2015 to 1.0 in 2100 and remains constant thereafter; thus,

$$F_o(t) = \begin{cases} 0.5 + (1-0.5)\frac{t-2015}{2100-2015} = 0.5 + 0.5\frac{t-2015}{85} & t \in [2015, 2100] \\ 1 & t > 2100. \end{cases} \tag{5}$$

Finally the mean atmospheric temperature rise $T(t)$ in °C and the mean lower ocean temperature rise $T_O(t)$ since pre-industrial times are coupled as follows:

$$T(t+\tau) = T(t) + 0.1005[[F(t+\tau) - 1.187516T(t)] + 0.088[T_O(t) - T(t)]] \tag{6}$$

$$T_O(t+\tau) = T_O(t) + 0.025\left[T(t) - T_O(t)\right] \tag{7}$$

With initial values $T(2015) = 0.85$ °C and $T_O(2015) = 0.0068$ °C, estimated from existing climate models and historical data.

1.2. Economy Model

Following the CRED model (Ackerman et al., 2013), the GDP of each region in year t is approximated by a Cobb-Douglas utility function with a capital exponent 0.3:

$$Y_i^*(t) = TFP_i(t)K_i^{0.3}(t)P_i^{0.7}(t) \tag{8}$$

where $Y_i^*(t)$ is the GDP of region i at time t; $\mathrm{TFP}_i(t)$, $K_i(t)$ and $P_i(t)$ are the corresponding total factor productivity, capital, and population of region i (a proxy for labor supply). Projections for the regional populations $P_i(t)$ are taken from CRED. It is assumed that $\mathrm{TFP}_i(t)$ grows at a constant rate of 1 percent per year; thus,

$$\mathrm{TFP}_i(t) = \mathrm{TFP}_i(t_0)e^{0.01(t-t_0)} \tag{9}$$

where, $\mathrm{TFP}_i(t_0)$ is estimated by calibrating (6) against initial year data:

$$TFP_i(t_0) = Y_i^*(t_0)K_i^{-0.3}(t_0)P_i^{-0.7}(t_0). \tag{10}$$

The capital $K_i(t)$ accumulated in region i by time t comprises standard capital $S_i(t)$ (public utilities, factories, and other means for productivity) and green capital $G_i(t)$ (investments, technologies, and infrastructures for implementing carbon mitigation policies). Capital is given by

$$K_i(t) = S_i(t) + \alpha_K G_i(t) \tag{11}$$

where, α_K is a constant in [0, 1] representing the productivity of green capital, measured by its impact on GDP, relative to the productivity of standard capital. CRED uses $\alpha_K = 0.5$; other models use $\alpha_K = 0$ thus ignoring the contribution of green capital to the economy. All monetary values are in US dollars converted from national currency using 2010 average exchange rates. Capital accumulation will be discussed later in this section.

Let $Y^*(t)=\sum_{i=1}^{16} Y_i^*(t)$ be the world annual GDP in year t. The total cost of damages due to the rise $T(t)$ of mean atmospheric temperature is expressed as $Y^*(t)D(t)$, where $D(t)$ is a global damage function. An exact prediction of the scale and frequency of such damages and the associated costs is not possible. Commonly used damage functions involve powers of $T(t)$. CRED provides the following choices for $D(t)$:

$$D(t) = 1 - \frac{1}{1 + \alpha_D T^2(t) + \gamma_D T^{\delta_D}(t)} \tag{12}$$

where α_D, γ_D and δ_D are tuning parameters chosen so that the damage function meets certain assumptions. In this paper, we use the values $\alpha_D = 0.006724$, $\gamma_D = 2.635 \cdot 10^{-6}$, and $\delta_D = 7.02$, based on the following three estimates: Global climate damages are expected to be 4.2% of the world GDP when $T(t) = 2.5$ °C; 50% at 6 °C, and 99% at 12 °C. Ackerman et al. (2012) provide justifications for employing these values.

The world output net of damages is given by $Y^*(t)[1—D(t)]$. Regional damages are given by $Y^*(t)D_i(t)$, where $D_i(t)$ is a damage function for region i in year t. In the latest version of CRED, $D_i(t)$ is estimated by the formula

$$D_i(t) = \frac{\mathrm{VI}_i^{[1-D(t)]^2}\,Y_i^*(t)}{\sum_{k=1}^{16}\mathrm{VI}_k^{[1-D(t)]^2}\,Y_k^*(t)}D(t) \tag{13}$$

where VI_i is a regional vulnerability index obtained by combining three indicators (Stanton, Cegan, Bueno, & Ackerman, 2012). The contribution of tourism and agriculture (climate-sensitive sectors) to GDP, the fraction of population living at less than 5 meters above sea level, and the unavailability of freshwater resources. The output of region i net of damages is given by

$$Y_i(t) = Y_i^*(t) - Y^*(t)D_i(t). \tag{14}$$

The net annual output of region i is spent on abatement (green capital investment), consumption, aid donation, and standard capital investment, thus, $u_i(t)Y_i(t)$, $v_i(t)Y_i(t)$ and $w_i(t)Y_i(t)$ and $[1—u_i(t)—v_i(t)—w_i(t)]Y_i(t)$, respectively. If $w_i(t)$ is negative, then region i is a net aid receiver. The following constraints are imposed
nonnegative expenditures:

$$u_i(t) \ge 0, v_i(t) \ge 0, \text{ and } 1 - u_i(t) - v_i(t) - w_i(t) \ge 0 \text{ for all } (i,t), \tag{15}$$

equality of total annual aid donated and aid received:

$$\sum_{i=1}^{16} w_i(t)Y_i(t) = 0 \text{ for all t.} \tag{16}$$

Standard capital and green capital, $S_i(t)$ and $G_i(t)$, are both assumed to depreciate at a constant annual rate δ and increase by the corresponding investments. CRED uses an annual depreciation rate $\delta = 0.05$. The dynamics of capital accumulation for τ-year time steps is modeled by

$$S_i(t+\tau) = (1-\delta)^\tau S_i(t) + \tau\left[1 - u_i(t) - v_i(t) - w_i(t)\right]Y_i(t) \tag{17}$$

$$G_i(t+\tau) = (1-\delta)^\tau G_i(t) + \tau u_i(t)Y_i(t) \tag{18}$$

and, in view of (11),

$$K_i(t+\tau) = (1-\delta)^\tau K_i(t) - \tau(1-\alpha_K)G_i(t) + \tau\left[1 - u_i(t) - v_i(t) - w_i(t)\right]Y_i(t) \tag{19}$$

Finally, the annual consumption is given by

$$C_i(t) = v_i(t)Y_i(t). \tag{20}$$

1.3. Emissions Model

Net annual emissions equal anthropogenic emissions minus abated emissions, all in GtC. The anthropogenic CO_2 emissions result from industrial activities and changes in the use of land. Industrial sources include electric power generation, transportation, industries, commercial businesses, residences, and so on. Land-use sources include forestry and agriculture, which could have a positive or a negative overall effect, depending on whether the land areas in a region absorb more CO_2 from the atmosphere than they emit. Deforestation and reforestation are examples of such cases.

The industrial emissions of region i in year t are approximated by $\alpha_{Ei}[Y_i^*(t)]^{0.9}P_i^{0.1}(t)$, which is a Cobb-Douglas type function[4]. With industrial emissions, GDP, and population in t_0 obtained from available data, the parameters α_{Ei} are given by
α_{Ei} = (industrial emissions in GtC of region i in year t_0) $\times[Y_i^*(t_0)]^{-0.9}P_i^{-0.1}(t_0)$.
The net annual emissions in region i are given by

$$E_i(t) = \alpha_{Ei}\left[Y_i^*(t)\right]^{0.9}P_i^{0.1}(t) + \beta_{Ei} - Q_i(t) \tag{21}$$

where β_{Ei} is an estimate of CO_2 emissions (in GtC) due to land-use change in region i, assumed to be constant over time at the t_0 level, and $Q_i(t)$ is the annual amount of emissions abated. For the sake of simplicity, only industrial emissions abatements are considered (CRED considers abatements and abatement costs for land-use changes as well). Next, we provide expressions linking the annual emissions abatements $Q_i(t)$ and the corresponding costs $u_i(t)Y_i(t)$.

Abatements are assumed zero for all years prior to 2020, i.e., $Q_i(t) = 0$ for all $t \le 2015$. Abatement costs and maximum feasible abatements for each region are based on the McKinsey marginal abatement cost (MAC) curves. CRED makes several approximations about the cost of a unit decrease in emissions, the annual emissions abated, $Q_i(t)$, and the corresponding abatement (green) capital $G_i(t)$. The final approximation is

$$G_i(t) = \varepsilon_i Q_i(t) + \varphi_i(t) Q_i^2(t). \tag{22}$$

Parameters ε_i and the time series $\varphi_i(t)$ are estimated as in Ackerman and Bueno (2011) assuming that full abatement of industrial emissions is feasible by 2060.

Upon combining equations (18) (replacing $t + \tau$ by t) and (22) one obtains $Q_i(t)$ and, using (21), the net annual emissions in region i. Finally, summing the regional annual emissions yields the total annual anthropogenic CO_2 emissions into the atmosphere,

$$\mathrm{TE}(t) = \sum_{i=1}^{16} E_i(t), \tag{23}$$

Which is the feedback to the climate model (3).