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# Causes of climate models uncertainty and implications for economic policy

**Alfred Greiner** 

Bielefeld University P.O. Box 10 01 31 33501 Bielefeld – Germany

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## Causes of climate models uncertainty and implications for economic policy

Alfred Greiner\*

#### Abstract

In this paper it is shown that climate models are characterized by uncertainty and its causes are pointed out. It is well known that a higher greenhouse gas concentration raises the radiative forcing of the earth and the physics behind it is well understood. However, as regards the feedback effects of higher temperatures, parameter uncertainty, model uncertainty and the chaotic nature of the climate system give rise to a considerable degree of ignorance regarding the climate system. Given this uncertainty costly  $CO_2$  abatement measures are difficult to justify with the currently available technology. But, due to technical progress more efficient technologies are expected to reduce abatement costs in the future such that a net zero emission policy could be justified to avoid possible, but uncertain, climate damages. In any case, fixing a deadline by which the net zero goal must be met is not welfare maximizing and more flexibility is needed to avoid prohibitive costs.

Keywords: Global warming, uncertainty, technology, policy implications JEL: E61, Q54

<sup>\*</sup>Department of Business Administration and Economics, Bielefeld University, P.O. Box 100131, 33501 Bielefeld, Germany, e-mail: agreiner@uni-bielefeld.de

#### 1 Introduction

The concentration of greenhouse gases (GHGs) in the atmosphere, such as carbon dioxide ( $CO_2$ ), methane ( $CH_4$ ), nitrous oxide ( $N_2O$ ) just to mention the most important ones, has been rising since the beginning of the industrialization in the 18th century. For example, the  $CO_2$  concentration increased from about 316 parts per million (ppm) in 1959 to 425 in 2024 according to the measurements of the National Oceanic and Atmospheric Administration (NOAA).<sup>1</sup> Simultaneously, the average temperature of the earth has been rising over time. Thus, the temperature of the lower troposphere reached higher levels with an increase of about 0.15-0.23 °C per decade since 1979, when the satellite based temperature measurements began, see https://www.nsstc.uah.edu/climate/ and https://images.remss.com/msu/msu\_time\_series.html, respectively.

Since it is generally known that the GHG concentration in the atmosphere crucially determines the temperatures on earth, with larger concentrations giving rise to higher temperatures, 196 countries committed themselves in the so-called Paris agreement to reduce the net emissions of GHGs to zero in the second half of the 21st century (see UN, 2016, Art. 4), the so-called net zero goal. By this, the world intends to limit global warming to 2 °C relative to preindustrial levels (ibid. Art. 2). The 2 degree goal goes back to Nordhaus (1977) who argued that temperatures more than 2 °C or 3 °C above the current average temperature would take the climate outside of the range of observations which have been made over the last several hundred thousand years (for an exhaustive discussion of the 2 degree goal see Jaeger and Jaeger, 2011). The Paris agreement is legally binding, but, in case of violation countries do not have to fear sanctions (UN, 2016, Art. 4).

The scientific foundation for the Paris agreement was laid by the 5th assessment report of the Intergovernmental Panel on Climate Change (IPCC), see IPCC (2014). However, there is large uncertainty as regards the climate sensitivity of the earth with respect to higher GHGs (cf. Meinshausen et al., 2009, Meinshausen et al., 2011, section 4.1.3, Sherwood et al., 2020), despite the high technical sophistication of the climate models. Therefore, predictions of future temperatures are to be considered with caution.

The goal of this paper is to summarize the knowledge that exists on the relation between the GHG concentration on earth, on the one hand, and the rise of the global surface temperature, on the other hand, and to identify the causes for climate model

 $<sup>^{1}</sup>$ See https://gml.noaa.gov/ccgg/trends/data.html.

unertainties. Given that uncertainty, implications for economic policy are derived and the net zero goal is critically scrutinized.

The rest of the paper is organized as follows. Section two presents facts on the relation between the GHG concentration on earth and global warming and points out uncertainties inherent in climate models. The following section three provides the policy implications and section four, finally, concludes the paper.

#### 2 Facts on GHGs and uncertainty of climate models

The radiative forcing of the most important GHGs is demonstrated in detail in Etminan et al. (2016). For  $CO_2$  it is given by the natural logarithm and for  $CH_4$  and  $N_2O$  by the square root function, where interactions between the gases must be taken into account. For  $CO_2$  those interaction terms play a role for concentrations larger than 2000 ppm, which is about 4.7 times higher than the current concentration, whereas the impact of the interactions for methane is stronger compared to the situation when methane is considered in isolation. The physics behind radiative forcing is presented in the paper by Wijngaarden and Happner (2020), for example, who show that a doubling of  $CO_2$  implies a reduction of the outgoing long wave radiation (OLR) of 3 W/m<sup>2</sup> which implies a rise of the average surface temperature of about 1.4 to 2.3 °C in equilibrium (see Wijngaarden and Happner, 2020, p. 34).

To get an idea of the radiative effects of the atmospheric  $CO_2$  concentration, table 1 is presented that depicts the change in the OLR as a result of different concentrations of that GHG. The values were obtained from the computer code MODTRAN (moderate resolution atmospheric transmission) that is available, for example, at the following internet site https://biocycle.atmos.colostate.edu/shiny/modtran/

Table 1:  $CO_2$  concentrations, OLR and radiative forcing ( $\Delta F$ ) relative to the preceeding line, using MODTRAN from https://biocycle.atmos.colostate.edu/shiny/modtran/

$CO_2$	OLR	$\Delta F$
280 ppm	$238.6 \mathrm{~W/m^2}$	
425  ppm	$236.8 \mathrm{~W/m^2}$	$\Delta F = 1.8 \; \mathrm{W/m^2}$
560  ppm	$235.7~\mathrm{W/m^2}$	$\Delta F = 1.1 \; \mathrm{W/m^2}$
800  ppm	$234.1 \mathrm{~W/m^2}$	$\Delta F = 1.6 \ \mathrm{W/m^2}$

Table 1 shows that the effect of raising the  $CO_2$  concentration from the preindustrial

Table 2:  $CO_2$ , OLR and  $\Delta F$  with a surface temperature rise of 0.3°C and a 5% increase in  $H_2O$ , using MODTRAN from https://biocycle.atmos.colostate.edu/shiny/modtran/

$CO_2$	OLR	$\Delta F$
425 ppm	$236.8~\mathrm{W/m^2}$	
$560 \mathrm{~ppm}$	$236.0 \mathrm{~W/m^2}$	$\Delta F = 0.8 \ \mathrm{W/m^2}$

level of 280 ppm to the current value of about 425 ppm reduces the OLR by  $\Delta F = 1.8$  W/m<sup>2</sup>. A further rise to 560 ppm generates another decline of  $\Delta F = 1.1$  W/m<sup>2</sup>. According to Lan et al. (2025) the average growth of the global  $CO_2$  concentration amounted to about 2.4 ppm from 2010 to 2020. Assuming an accelerating growth of the emissions, mainly due to fast growing economies in Asia with a population of about 4.8 billion people, and taking an average value of 3 ppm, the first doubling of the  $CO_2$  concentration, from 280 to 560 ppm, will be reached in 45 years going along with the aforementioned radiative forcing of 1.1 W/m<sup>2</sup>, compared to the current value of 425 ppm.

It should be mentioned that the results in table 1 hold ceteris paribus, i.e. for unchanged values of the temperature and of the water content of the atmosphere. Table 2 gives the radiative forcing of raising the  $CO_2$  concentration from 425 ppm to 560 ppm for an increase of the surface temperature by 0.3 °C and with a 5% percent increase in the water content of the atmosphere. The resulting lower value of the radiative forcing compared to table 1 is due to the higher temperature. This holds because the radiation of the earth follows the Stefan-Boltzman law that states that the emission is a function of the fourth degree of the temperature. This effect overcompensates the one of the higher water content of the atmosphere that tends to raise the radiative forcing.

Comparing tables 1 and 2 shows that feedback effect matter quite a lot. Besides physical feedbacks there are other feedbacks such as biological and chemical ones and from clouds that may be affected by higher temperatures. These are taken into account in complex climate models, but, give rise to considerable uncertainties making quantitaive predictions doubtful.

One source of uncertainty is of methodological nature. Complex climate models are based on physical laws and on heuristic methods that are resorted to in case the underlying physical relationship is not known. In order to get models to work with, calibration or tuning is necessary to obtain those parameter values that are unknown. This tuning, however, can mask structural deficiencies of the climate models, as pointed out by Mauritsen et al., 2012, p. 14 and Hourdin et al., 2017, p. 591. To determine parameters Bayesian estimation is used, where the result may be crucially determined by the selection of the prior distribution. Thus, Lewis (2023) demonstrates that the outcome of the influential study by Sherwood et al. (2020) changes significantly, when an objective Bayesian method with mathematically computed priors is used.

Two other sources of uncertainty are due to the fact that the parameters are uncertain just as the model.<sup>2</sup> Parameter uncertainty means that the true value is not known, but, there exists an informed guess of the upper and lower bound. The model, then, is run for different constellations of the uncertain parameters giving rise to a marginal probability density of the temperatures. A related aspect is the dependence of model parameters on the surface temperature. For example, the albedo of the earth may crucially decline as the temperature rises and it has been shown in a couple of papers that this can give rise to multiple equilibria in the long run (see e.g. Greiner and Semmler, 2005, Greiner et al., 2010, Bondarev and Greiner, 2025). Model uncertainty means that the climate model does not correctly reflect the actual climate, such that deviations of model predictions from observations are not Gaussian. But even if the model can replicate the past climate reasonably well, this does not imply that the future climate can be predicted, too. This holds because the above mentioned tuning may mask structural errors such that the future climate cannot be predicted even if the models replicate the past well.

The last and a very important aspect to be pointed out is that the climate of the earth is a nonlinear dynamic system that is characterized by deterministic chaos. The dynamics of the atmosphere and oceans are described by the Navier–Stokes equations, a system of nonlinear partial differential equations in space and time. The model by Lorenz (1963) is based on the Navier-Stokes equations and represents a highly simplified model of the dynamics in a fluid layer. It is a three dimensional ordinary differential equation system that displays chaotic behaviour for a specific constellation of the underlying parameters. An important aspect of chaotic systems is their sensitivity with respect to initial conditions, meaning that minor changes at the starting time can generate large differences in the respective time paths.

Thus, Kay et al. (2015) run their Community Earth System Model (CESM) model with 30 different initial conditions that differ by the factor  $10^{-14}$ . They find that the difference in the temperature change over 34 years amounts up to 6 °C. The following figure 1 shows the temperature trend for the winter months December, January, February

<sup>&</sup>lt;sup>2</sup>Those two aspects are discussed in detail in Frigg et al. (2015) with regard to the United Kingdom Climate Impacts Program (UKCP09).

(DJF) over the years 1979-2012 for the 30 different runs, the ensemble mean (EM) and the actual temperatures (OBS) based on GISTEMP (see Hansen et al. 2010). It can be realized that the differences between the individual simulation runs are partly quite large. Further, the shape of the chaotic attractor may crucially depend on the parameter values. An example in economics is provided by Greiner and Kugler (1994) who analyze a simple two dimensional economic system that is characterized by chaos. There, it turns out that the bifurcation parameter determines the shape of the attracor and, thus, the upper and lower bounds the variables take on and the distribution.

The considerations up to now have shown that climate models are characterized by uncertainty. Hence, the question of arises how valid their projections are. Screening the literature, one finds quite a lot of contributions that cast doubt on the general validity of climate models. We do not intend to give an exhaustive survey of those papers, but, just point out a few of them.<sup>3</sup> For example, Irving et al. (2021) describe significant problems in the latest Coupled Model Intercomparison Project Phase 5 and Phase 6 (CMIP5 and CMIP6) models regarding not only energy conservation in the ocean but also at the top of the atmosphere. Heuzé et al. (2023) analyze 14 representative CMIP6 models with regard to their performance for the Arctic region and find that those models are biased. They point out that "These models are very biased: too cold where they should be warm, too warm where they should be cold, not stratified enough, not in contact with the surface as they should, moving the wrong way around the Arctic, etc." (Heuzé et al., 2023, p. 2551). The bias is confirmed by Winkelbauer et al. (2024) who study 39 CMIP6 models and detect large inter-model spreads and systematic biases in the representation of annual cycles and long-term averages for the Arctic. Finally, McCarthy and Caesar (2023) analyze whether the ensemble of CMIP5 and CMIP6 models can replicate the Atlantic Meridional Overturning Circulation (AMOC) that crucially determines the climate of the earth, especially in the northern hemisphere. They show that both the magnitude of the trend in the AMOC and often even the sign of the trend differ between observations and the climate model ensemble mean. The authors, then, ask whether one can trust AMOC projections of models that cannot replicate the past. Additionally, one could wonder how reliable model projections of the entire global climate are if those models are not capable of replicating the evolution of an important subsystem.

<sup>&</sup>lt;sup>3</sup>More studies are presented in Greiner (2024).



Figure 1. Global maps of historical (1979-2012) boreal winter (DJF) surface air temperature trends for each of the 30 individual CESM-LE members, the CESM-LE ensemble mean (denoted EM), and observations (denoted OBS based on GISTEMP), Kay et al. (2015, p. 1341).

Climate models are highly complex technically sophisticated models and the best available tools to understand the climate of the earth and have considerably helped to understand climatic phenomena. The scientists involved are doing excellent work. Nevertheless, the models are uncertain because of the complex nature of the real global climate and skepticism is appropriate with regard to statements concerning the future climate. Probability based statements do not improve the situation either, but, suggest a degree of knowledge and precision that the models cannot deliver due to the inherent uncertainty of the models.

## **3** Policy implications

In the last section it was pointed out that a rise in greenhouse gases increases the backradiation of the earth and leads to higher temperatures. Rising temperatures may go along with more extreme weather events because a warmer atmosphere absorbs more water and leads to higher humidity. When the earth warms by 1 °C the atmosphere can absorb around 7 percent more moisture which follows from the Clausius-Clapeyron equation. However, this is only a partial effect and over the last four decades, near-surface water vapor has not risen over arid and semi-arid regions. That observation is in contrast to climate model simulations that predict an increase at a rate close to theoretical expectations (see Simpson et al., 2024). Ma et al. (2025) use satellite observations and show that two thirds of the ocean have experienced weakened evaporation suggesting that a warmer climate does not always result in increased evaporation, a trend that is primarily attributed to wind stilling.

In addition, the evidence for more extreme weather events is not that obvious up to now. For example, according to table 12.12, column 3, in the last IPCC report (see Ranasinghe et al., 2021, p. 1856) there is no or only low evidence for more extreme weather events except for heat waves, besides the well known observations, such as a higher surface temperature, a decline in sea ice and increased ocean temperatures. This is in line with other contributions, such as Alimonti and Mariani, 2023, or Zhang et al., 2023, who consider losses from tornadoes in the USA. Figure 2 and figure 3 exemplarily show the number of hurricanes world wide from 1980 to 2024 and the intensity measured by the accumulated energy. Using ordinary least squares to compute the trend line, it can be seen that there is no positive trend in those time series.

As regards the economic effects of global warming there exist quite a lot of them and a



Figure 2: Number of global hurricanes, H, from 1980 to 2024 and the trend line. Data Source: Department of Atmospheric Science from the Colorado State University, https://tropical.atmos.colostate.edu/Realtime/index.php?arch&loc=global



Figure 3: Accumluated cyclones energy, N, from 1980 to 2024 and the trend line. Data Source: Department of Atmospheric Science from the Colorado State University, https://tropical.atmos.colostate.edu/Realtime/index.php?arch&loc=global

survey of approaches and studies can be found in Kolstad and Moore (2020), for example. However, often the results are not robust and the empirical estimations lack a sound theoretical foundation and calculate regressions without economic explanatory variables.<sup>4</sup> Barker (2022, 2023, 2024, 2024a) reanalysis four, partly frequently cited, studies that find negative growth effects of higher temperatures and carefully points out flaws that heavily question the outcome of those papers. Greiner et al. (2025) analyze the relationship that exists between the growth of the surface temperature and economic growth for European countries and find no statistically significant relationship between those variables, while the rule of law, which reflects bureaucracy, the output gap and the fiscal variable are statistically significant and robust. Tol (2023) compares the global costs and benefits of a climate policy that achieves net zero emissions by 2050 and finds that the benefits exceed the costs only if the discount rate is low and the risk aversion is high. For the EU the costs of such a policy exceed its benefits by a factor of ten (see Tol, 2021).

The considerations up to now have shown that the effects of global warming are highly uncertain, both as regards the global climate as well as regards its economic consequences. In particular, no robust evidence exists that global warming has had a negative impact on economic output. Nevertheless, it cannot be excluded that the ongoing climate change will do so in the future and that climate catastrophes may occur. Hence, from an economic perspective it is reasonable to abate GHG emissions due to the precautionary motive. Then, two questions arise: First, how should that be done and, second, by how much should GHG emissions be reduced.

The first question can easily be answered since it is obvious that the reduction should be done in a cost efficient way. This clearly results from the economic principle stating that certain goals should be reached in a way such that no resources are wasted. Even if that requirement is self-evident for economists it should be mentioned because in the real world often environmental policy measures are implemented that violate it. An example is provided by the German renewable energy law that subsidizes so-called renewable energies. But, since the energy market is regulated by the EU Emission Trading System (EU ETS) any additional regulation only causes costs without yielding benefits. Thus, Schmalenbach and Stavins state that "... the EU ETS illustrates the perverse outcomes that result when "complementary" policies are applied to reduce emissions that are also covered under the cap, particularly in the absence of a price floor. ... they relocate emissions, drive up aggregate abatement costs, and depress allowance prices." (Schmalensee and Stavins,

<sup>&</sup>lt;sup>4</sup>See Greiner (2024a) for a brief discussion of that shortcoming.

2017, p. 70).<sup>5</sup>

The second question is more difficult to answer. To address that question it should be noted that the share of anthropogenic to non-anthropogenic  $CO_2$  emissions is about 3% to 5% (see Yurak and Fedorov, 2024). Denoting by E total  $CO_2$  emissions, one can write  $E = E_{\bar{a}} + E_a = E_{\bar{a}}(1+u)$ , with  $E_{\bar{a}}$  non-anthropogenic emissions,  $E_a$  anthropogenic emissions and u the share of anthropogenic to non-anthropogenic emissions which amounts to  $3/97 \approx 3.1\%$  to  $5/95 \approx 5.26\%$ .

Denoting the atmospheric  $CO_2$  concentration by C(t) its evolution over time t is described by  $dC(t)/dt = \dot{C}(t) = \beta E_{\bar{a}}(t)(1+u) - \mu C(t)$ , with  $\beta \in (0.4, 0.5)$  that share of emissions that is not absorbed by plants, the oceans and the land and  $\mu$  the decay rate of  $CO_2$ . According to IPCC (2001) the 1/e time is between 200 and 5 years giving a value for  $\mu$  between 0.184% and 7.36%. Hard (2019) and Manning et al. (1990) report the 1/etime of (radioactive) <sup>14</sup> $CO_2$  as 15 and 17 years, respectively, giving a value for  $\mu$  of 2.5% and 2.2%. In steady state one has  $\dot{C}(t) = 0 \Leftrightarrow C_{st} = c_1 E_{\bar{a}}(1+u)$ , with  $C_{st}$  denoting the  $CO_2$  steady state value and  $c_1 = \beta/\mu$ . The share of anthropogenic to non-anthropogenic emissions u has been assumed to be time constant. However, the time series for that variable is characterized by a slightly rising trend which can be realized from figure 2 in Yurak and Fedorov (2024). Hence, it seems to be justified to consider different values of that parameter.

In table 3 it is assumed that the  $CO_2$  concentration in the atmosphere has stabilized and realized its steady state value. We denote by  $C_{st}^{nz}$  the net zero  $CO_2$  steady state concentration, i.e. that concentration that is realized for zero anthropogenic  $CO_2$  emissions, u = 0. We do that for the two values  $C_{st}^{nz} = 500$  ppm and  $C_{st}^{nz} = 800$  ppm, respectively. Column 2-4 in table 3 show the increase in radiative forcing when anthropogenic emissions amount to 5.26%, 10% and 15%, respectively, relative to net zero anthropogenic emissions. The additional forcing resulting from the deviation from the net zero target ranges from  $0.2 \text{ W/m}^2$  to  $0.6 \text{ W/m}^2$  for a stabilization of  $CO_2$  at 500 ppm and 800 ppm. For example, if mankind manages to keep the share of anthropogenic to non-anthropogenic emissions constant at 5.26%, which roughly corresponds to the current value, radiative forcing is  $0.3 \text{ W/m}^2$  higher than radiative forcing with net zero anthropogenic emissions when  $CO_2$ emissions stabilize at 500 ppm.

<sup>&</sup>lt;sup>5</sup>Already in 2004 and 2014 the German Scientific Advisory Board at the Ministry of Economics and Labor and the Commission of Experts for Research and Innovation, respectively, stated that the renewable energy law should have been abolished.

Table 3:  $C_{st}^{nz}$  and radiative forcing ( $\Delta F$ ) relative to u=0 (MODTRAN)

$C_{st}^{nz}$ , u=0	u = 0.0526	$u{=}0.1$	$u{=}0.15$
500  ppm	$0.3 \mathrm{~W/m^2}$	$0.5 \ \mathrm{W/m^2}$	$0.6 \mathrm{~W/m^2}$
$800 \mathrm{~ppm}$	$0.2 \mathrm{~W/m^2}$	$0.4 \mathrm{~W/m^2}$	$0.6 \mathrm{~W/m^2}$

Table 3 demonstrates that the radiative forcing of slightly larger steady state atmospheric  $CO_2$  concentrations is relatively small. To get insight into the question of under which conditions it is optimal to achieve a net zero  $CO_2$  emissions policy a world that consists of two countries is considered. Deleting the time argument t, the costs of reducing  $CO_2$  emissions  $K_i$  in country i, i = 1, 2, and of deviating from an optimal  $CO_2$  level  $\overline{C}$ are specified as follows,

$$K_i = (\sqrt{u_i + b_i})^{-1} + \delta_1 (\bar{C} - C)^2 + \delta_2 (\bar{C} - C)^2, \ i = 1, 2, \delta_1 = 1, \delta_2 = 0, \tag{1}$$

with  $b_i \in \mathbb{R}$ , i = 1, 2. The variable  $u_i$ , i = 1, 2, denotes the share of anthropogenic emissions in country *i* relative to non-anthrogenic emissions  $E_{\bar{a}}$ . For  $b_i = 0$  the marginal and the total costs of emissions reduction tend to infinity as net zero is approached, i.e. for  $u_i \to 0$ . Marginal costs that approach infinity reflect the fact that it becomes more and more difficult to further reduce emissions as one approaches net zero. Loosely speaking, one can state that the low-hanging fruits have already been picked. As regards the costs of the  $CO_2$  concentration, those are strictly positive in country 1 when the  $CO_2$ concentration deviates from a certain value, i.e. for  $C \neq \bar{C}$ , whereas country 2 does not incur costs,  $\delta_2 = 0$ . The evolution of the  $CO_2$  concentration is,

$$\dot{C} = \beta E_{\bar{a}} \left( 1 + u_1 + u_2 \right) - \mu C.$$
 (2)

Minimizing the stream of discounted costs over an infinite time horizon, the following insight can be derived as regards the cooperative solution.<sup>6</sup> The marginal abatement costs in the country are decisive as to the question of how much is invested in abatement. In particular, when the marginal costs of abatement u converge to infinity as u approaches zero, it is not optimal to pursue a net zero policy. That holds independent of whether  $CO_2$ causes costs in a country or not. When the abatement costs of net zero in one country approach infinity while they are finite in the other country, the following policy is optimal.

<sup>&</sup>lt;sup>6</sup>Details regarding the derivation of the optimal solution are given in the Appendix.

The first country has strictly positive emissions and the latter sets either  $u_{i,st} > 0$ , i.e. it does not pursue a net zero policy, or  $u_{i,st} < 0$  depending on its marginal abatement costs. Again, that policy is independent of in which country the climate damages occur. The result  $u_{i,st} < 0$  means that  $CO_2$  emissions are negative that can be achieved by carbon dioxide removal from the atmosphere. The outcome that the abatement policy in a country only depends on its own marginal costs and is independent of whether a country incurs costs from  $CO_2$  is due to the fact that the cooperative solution is considered, where the joint costs are to be minimized.

As regards policy implications the above considerations demonstrate that the marginal costs of net zero are decisive with respect to the optimal abatement policy. It must be underlined that the abatement cost function is not a function that depends on time only, but, rather on the available technology. Hence, setting a fixed date at which net zero is to be achieved is to be seen skeptical. Given the currently prohibitive costs of abatement to meet the net zero goal, it is more reasonable to invest in technical progress generating new technologies rather than to incur high costs today and to abate  $CO_2$  in the future at lower costs. The Paris agreement stating that net zero emissions should be achieved in the second half of this century is indeed relatively flexible. But, some countries set fixed deadlines that are to be met, such as the EU stating that net zero should be reached by 2050 and that GHGs should be reduced by at least 55% relative to 1990 until 2030. Rather, the optimal policy depends on the prevailing state of the technology, determining the abatement costs, and the pace of technical progress is decisive as to the question of whether marginal abatement costs can be made equal to marginal damages of  $CO_2$ , where it should be recalled that the warming effect of additional  $CO_2$  in the atmosphere is declining as its concentration rises. Once  $CO_2$  free energy sources will be available in sufficient quantities, the abatement costs will decline rapidly and the switch to  $CO_2$ free production methods will be easy to achieve, i.e. at low costs. In addition to those considerations, it must be underlined that the damages going along with global warming are difficult to estimate, if not impossible, just as the consequences of climate change itself. Therefore, the benefits of today's abatement are difficult to measure so that incurring large costs is even more unjustifiable.

#### 4 Conclusion

In this paper it was shown that climate models are uncertain and the warming effect of additional  $CO_2$  declines as its atmospheric concentration increases. Given the large degree of uncertainty, it is difficult to justify costly measures using the currently available technology. Nevertheless, it cannot be excluded that damages can occur in the future as  $CO_2$  continues to increase. Hence, it seems justified to reduce GHG emissions, but, the question of by how much depends on the marginal abatement costs. Since current abatement costs necessary to achieve large emissions reductions are prohibitively high, shifting abatement into the future when  $CO_2$  free production techniques will be available at lower costs seems to be economically reasonable. Instead of investing huge amounts in inefficient  $CO_2$  reductions today it would be preferable to invest those resources in technical progress allowing future abatement at lower costs. In any case, setting a fixed date when net zero is to be achieved is definitely not welfare maximizing and flexibility in reducing  $CO_2$  emissions is needed.

### Appendix

Denoting the discount rate by  $\rho > 0$ , the intertemporal optimization problem reads as  $\max_{u_1,u_2} \left(-\int_0^\infty e^{-\rho t} (K_1 + K_2) dt\right)$  subject to (2) and with the costs given by (1). Forming the current-value Hamiltonian (for a short introduction see e.g. Greiner and Fincke, 2015, Appendix B),

$$H(\cdot) = -\left(\sqrt{u_1 + b_1}\right)^{-1} - \left(\sqrt{u_2 + b_2}\right)^{-1} - \left(\bar{C} - C\right)^2 + \lambda \left(\beta E_{\bar{a}}(1 + u_1 + u_2) - \mu C\right),$$

with  $\lambda$  the shadow price of the atmospheric  $CO_2$  concentration, the necessary and sufficient<sup>7</sup> optimality conditions are obtained as,

$$u_{i} = -b_{i} + (2(-\lambda)\beta E_{\bar{a}})^{-2/3}, \ i = 1, 2$$
  
$$\dot{\lambda} = \lambda(\rho + \mu) - 2(\bar{C} - C)$$

The first equation states that the marginal costs of abatement,  $(1/2)(u_i + b_i)^{-3/2}$ , equals its marginal benefits,  $(-\lambda)\beta E_{\bar{a}}$ , in the two countries with benefits meaning the avoided

<sup>&</sup>lt;sup>7</sup>They are sufficient if in addition the transversality condition  $\lim_{t\to\infty} e^{-\rho t} \lambda C = 0$  holds.

damages of  $CO_2$ . For  $C > (<) \overline{C}$  the shadow price of  $CO_2$  is negative (positive) stating that a rise (decline) causes costs. At the steady state  $\dot{C} = \dot{\lambda} = 0$  holds.

To get additional insight, numerical values for the parameters are specified. The discount rate is set to 3.5%, i.e.  $\rho = 0.035$ , the share of emissions entering the atmosphere is 45% and the decay rate is 2.5%,  $\beta = 0.45$ ,  $\mu = 0.025$  and  $\bar{C}$  is set to  $\beta E_{\bar{a}}/\mu$ , i.e. to the value with zero anthropogenic emissions without loss of generality. The following table 4 gives the optimal steady state abatement rates  $u_{1,st}$  and  $u_{2,st}$  for different values of the abatement costs modelled by  $b_i$ , i = 1, 2. Setting  $b_i = 0$  implies that the marginal costs of abatement converge to infinity as abatement converges to zero, i.e. for  $u_i \to 0$ .

	$b_1 = 0$	$b_1 = 0.1$	$b_1 = -0.1$
$b_2 = 0$	$u_{1,st} = 0.0612$	$u_{1,st} = -0.0136$	$u_{1,st} = 0.1455$
	$u_{2,st} = 0.0612$	$u_{2,st} = 0.0864$	$u_{2,st} = 0.0455$
$b_2 = 0.1$	$u_{1,st} = 0.0864$	$u_{1,st} = -0.0218$	$u_{1,st} = 0.1612$
	$u_{2,st} = -0.0136$	$u_{2,st} = -0.0218$	$u_{2,st} = -0.0388$
$b_2 = -0.1$	$u_{1,st} = 0.0455$	$u_{1,st} = -0.0388$	$u_{1,st} = 0.1359$
	$u_{2,st} = 0.1455$	$u_{2,st} = 0.1612$	$u_{2,st} = 0.1359$

Table 4: Optimal  $u_{1,st}$ ,  $u_{2,st}$  for different values of abatement costs  $b_i$ , i = 1, 2.

Table 1 shows that the outcome is symmetrical stating that the abatment is identical when both countries have the same marginal costs, independent of the fact that there is no damage in country 2. This results from the joint optimization of the costs. Setting  $b_1 = 0.2, b_2 = 0.21817$  the optimal abatement rates are  $u_{1,st} = 0.0182, u_{2,st} = 1.2 \cdot 10^{-6}$ , i.e. country 2 pursues a net zero policy and country 1 emits 1.8% of non-anthropogenic emissions.

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