ATMOSPHERIC CO_2 CONCENTRATION FORECAST WITH THE BERN-MODEL AND THE DEVELOPMENT OF THE SURFACE TEMPERATURE

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Abstract: *In Bern's model the Earth's atmosphere and oceans are considered as a system with input parameters such as CO_2 emissions on the one hand and output parameters such as atmospheric CO_2 concentration on the other hand. This make it possible to determine the impulse response function of CO2 emission and from there to calculate the corresponding CO_2 concentration in the atmosphere by convolution of the CO_2 emission with the impulse response function. The model allows numerical experiments to be carried out to investigate which future CO_2 emission scenario leads to which atmospheric CO_2 concentrations. On this base, future surface temperatures can be estimated without computationally intensive climate models. Some CO_2 emission scenarios are presented with the resulting surface temperatures.*

ПРОГНОЗИРОВАНИЕ КОНЦЕНТРАЦИИ CO2 В АТМОСФЕРЕ С ПОМОЩЬЮ МОДЕЛИ БЕРНА И ИЗМЕНЕНИЕ ТЕМПЕРАТУРЫ ПОВЕРХНОСТИ

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Резюме: *В модели Берна атмосфера и океаны Земли рассматриваются как система с входными параметрами, такими как выбросы CO_2, с одной стороны, и выходными параметрами, такими как концентрация CO_2 в атмосфере, с другой. Это позволяет определить функцию импульсного отклика эмиссии CO_2 и, исходя из нее, рассчитать соответствующую концентрацию CO_2 в атмосфере путем свертки эмиссии CO_2 с функцией импульсного отклика. Модель позволяет проводить численные эксперименты для изучения того, какой сценарий выбросов CO_2 в будущем приведет к тем или иным концентрациям в атмосфере. На этой основе можно оценить будущую температуру поверхности без использования климатических моделей, требующих больших вычислительных затрат. Были разработаны некоторые сценарии выбросов CO_2 с целью достижения климатической цели 1.5°C или 2.0°C.*

Introduction

At the 2015 climate conference held in Paris targets were defined: to hold the global average temperature well below 2 °C and to pursue efforts to limit the temperature increase to1.5°C above pre-industrial levels. Together with world economic organizations, the IPCC has developed in the past scenarios for the further development of greenhouse gas emissions and the corresponding atmospheric concentrations. This type of prediction is extremely difficult, as socio-economic developments are difficult to predict over long periods of time and the limitation of emissions is heavily dependent on political decisions. These have been constantly updated and further developed in subsequent IPCC reports (e.g. in AR5 - Representative Concentration Pathways - RCPs and in AR6 -

Shared Socio-economic Pathways - SSPs). But in a new study of a survey of 211 IPCC authors about the likelihood climate outcomes most of the authors are skeptical that warming will be limited to the Paris targets of well below 2 °C [1]. Our own study of the hemispheric and global temperature anomalies based on a regression model [2] shows an exceed of the 1.5°C and of the 2°C in the Northern Hemisphere about 2030 and 2050, respectively; in the Southern Hemisphere the exceed is expected to be later, about 2048 and 2070, and for the global temperature anomalies the exceed of the limits is to be expected about 2045 and 2060, correspondingly (see Fig. 1).

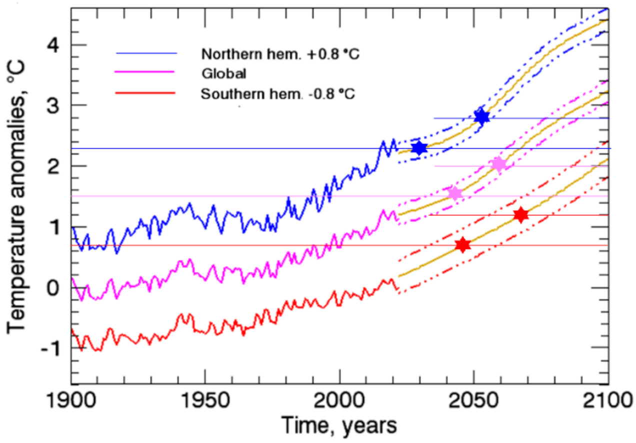

Fig. 1. Prognoses for the temperature anomalies development in the Northern and Southern hemisphere and for the global temperature anomalies. The temperature anomalies from 1900 to 2022 are in blue for the NH, in red for the SH and in magenta for the global temperatures. The prognoses are shown as yellow lines with the 95% confidence bands as double dotted dashed line. The thin lines show the limits and the stars mark the possible position of exceeding the 1.5 and 2 degree limits.

The temperature developments were forecasted under the assumption of business progress as usual. This means that the atmospheric CO_2 concentration increase exponentially in the same way as in the last decades. At present the global temperature achieved a value of 1.54±0.06 °C (https://berkeleyearth.org/global-temperature-report-for-2023) and it is for the first time over the 1.5°C limit. The global fossil carbon dioxide (CO_2) emissions responsible for climate change continue to increase in average. The global emissions of CO_2 up to about 1910 were dominated by changes in Land use [3]. However the increase of the annual global CO_2 emissions is determined basically by the global emitted CO_2 from fuel combustion, as it is shown in Fig. 2.

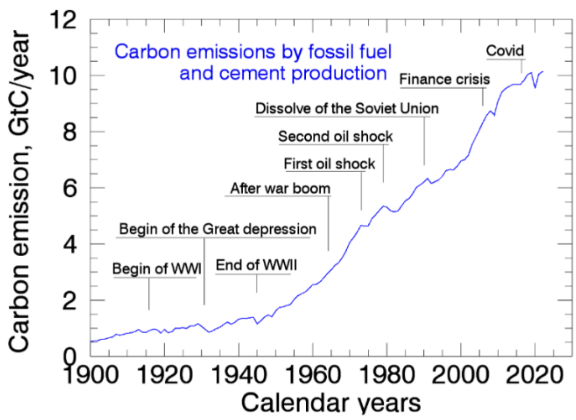

Fig. 2. Global CO_2 emissions including burning of fossil fuel and cement production meassured in GtC.. The figure is drawn based on Data of the Carbon Project (Data supplement to the Global Carbon Budget 2022 | ICOS (icos-cp.eu) and updated from [6].

The increase of the CO_2 emissions during the industrial revolution was interrupted by a period characterised by a slowdown of the emissions throughout the World Wars I and II (WWI and WWII) and the Great Depression [4, 5]. After the WWII the national economies rapidly restored and a boom of the worldwide economic development was registered. Sometimes this period is called Great Acceleration. The rapid economic growth was interrupted by the first and later by the second oil shocks. The dissolution of the Soviet Union after 1990 and during the economic crisis in 2007/2008 have caused a emission slowdown. The last minimum beginning in 2019 is related to the economic crisis caused by Covid. Since then, CO_2 emission rate has been growing again. In newer time, before covid, in 2019, the emission reached a level of 37.04 Gt CO_2/year. In 2020 it has fallen to its local minimum of 35.01 Gt CO_2/year and in 2023 it is expect to grow at 37.55 GtCO_2/year (Global CO2 emissions by year 1940-2023 | Statista.) The year to year changes of the emission rates are small like the one resulting by Covid. Of the globally emitted CO_2, around 50% end up in the atmosphere and are accumulated for a long time in different sinks. About half of the remaining 50% are stored in the world ocean, the other half in the land ecosystem. The main sinks of CO_2 are the ocean solution of CO_2, the photosynthesis by terrestrial plants and oceanic phytoplankton.

Carbon Dioxide emissions and the determination of atmospheric Carbon Dioxide concentration with the Bern model

The CO_2 concentration was estimated with the help of the Bern-model. In this model the Earth's atmosphere and oceans are considered as a system with input parameters such as CO_2 emissions on the one hand and output parameters such as atmospheric CO_2 concentration on the other hand. This makes it possible to determine the impulse response function of CO_2 emission and from there to calculate the corresponding CO_2 concentration in the atmosphere by convolution of the CO_2 emission with the impulse response function:

(1) $$CO_{2,atm}(t) = \int_{t_0}^{t} CO_{2,em}(t') * IRF(t-t')dt' + CO_{2,atm}(t_0),$$

where $CO_{2,atm}$ is the mass of CO_2 in the atmosphere (in GtCO_2 or related to carbon in GtC)
$CO_{2,em}$ is the mass of emitted CO_2 (in GtCO_2 or related to carbon in GtC)
$CO_{2,atm}(t_0)$ is the mass CO_2 in the atmosphere at the time t_0 (in GtCO_2 or related to carbon GtC)
IRF is the response function to a CO_2 impulse.

As $CO_{2,em}$ here the total CO_2 emitted by fossil burning and cement production corrected by emission from land use, is used (see Fig. 3).

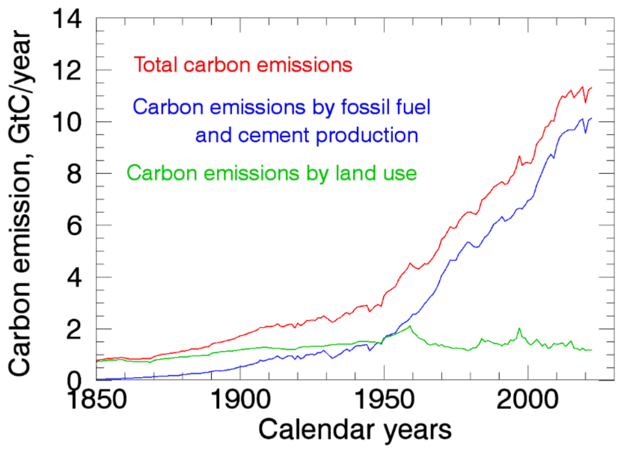

Fig. 3. Global total CO_2 emissions (red line) including burning of fossil fuel and cement production (blue line) and the emission by klans use (green line) meassured in GtC.. The figure is drawn based on Data of the Carbon Prject (Data supplement to the Global Carbon Budget 2022 | ICOS (icos-cp.eu)

Often the mass of CO_2 is given in GtCO_2 which is greater than the mass given in GtC by a factor of 3.664. On the other side the mass in GtC in the atmosphere can be easily converted in concentration of CO_2 by 1 GtC = 0.47 ppm CO_2. The impulse response function is a series of exponential functions:

(2) $$IRF(t) = a_0 + \sum_{n=1}^{k} a_n e^{-\frac{t}{\tau_n}},$$

where the coefficients a_0 and a_n are fractions of the CO_2 emissions, which the life time τ_n

characterizing the decay of the impulse. The sum of the coefficients is one. We have used the standard SAR model with the following parameters: $k=5$, $a_0=0.1369$, $a_1=0.1298$, $a_2=0.1938$, $a_3=0.2502$, $a_4=0.2086$, $a_5=0.0807$ and $\tau_1=371.6$, $\tau_2=55.7$, $\tau_3=17.01$, $\tau_4=4.16$, $\tau_5=1.33$ [7,8]. To examine the quality of the results, obtained with the model, we have calculated the $CO_{2,atm}$ from the given $CO_{2,em}$ from 1970 up to 2022. Fig. 4.

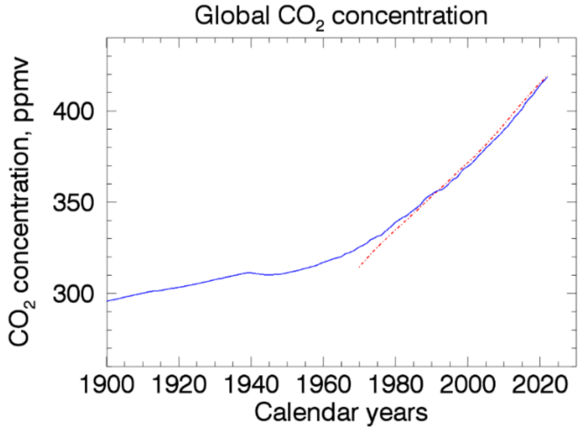

Fig. 4. Comparison of the observed CO_2 concentration (blue line) with the calculated one (red dashed dotted line) by means of the Bern-model with the total Carbon emissions as input

shows the obtained global annual $CO_{2,atm}$ (CO_2 concentration in the atmosphere) determined by measurements at Mauna Loa observatory, Hawaii in comparison with the calculated ones by the Bern-model based on the total carbon emissions (see Fig. 2, red line). The temperature anomalies are calculated using the result from our regression $T=3.3*\ln(CO_2/280ppm)+0.37$ for the global temperature [2]. In the interval from 1975 up to 2022 the calculated by the model $CO_{2,amt}$ concentration agrees very well with the observations. The errors are almost smaller than 1 ppm corresponding to and relative error of 0.3%. The errors are somewhat greater only in the region where the well-known plateau between 1940 and about 1955 effected the atmospheric CO_2 concentration. The plateau is not observed in the emissions, therefor an additional sink has to be assumed as it was done in a previous work by the authors [6]. With an additional sink, a very good agreement was achieved in the model calculation of the atmospheric CO_2 concentration over the entire time interval (not shown here).

Carbon Dioxide emission scenarios

We can determine the CO_2 concentration in the atmosphere using eq.(1) and (2) for a future model of CO_2 emissions. At first, the effect a constant in time emission and an abrupt zero-emission after 2022 will be shown, where up to 2022 the observed atmospheric CO_2 is assumed. Both scenarios are graphically displayed in fig 5a. As it is seen in Fig. 5b, the concentration of CO_2 in the atmosphere in the case of constant emission increases and consequently the temperature increases by a value of about 0.8 °C from 2022 up to 2100. The corresponding temperature anomalies are shown in Fig. 5c. The zero-emission results in a slow decrease of the CO_2 concentration and of a temperature anomaly of about 0.6°C at the end of the century. For comparison, figure 5b shows the concentration for an assumed exponential development of CO_2 growth with a constant exponent, the same as for the time interval from 1970 to 2022 (business as usual), and the resulting temperature in fig. 5c (yellow lines). Apart from the fact that we are in 2024 and that CO_2 emissions continue to grow, an abrupt 0 emissions growth is economically and politically unfeasible. Even a continuous linear decrease in annual emissions from the CO_2 level in 2022 to 0 GtC/year in 2100 is not realistic and, moreover, leads to a CO_2 concentration of about 484 ppmv and a temperature increase to 1.64 °C, and not to a temperature decrease. Therefore, models are being investigated here in which the growth of CO_2 emissions in the next decades continues as before (see Fig. 6a). In this available time, the technologies should be developed or further that are free of CO_2 emissions and that land use is also emission-free through reforestation and modern technologies, e.g. plant and animal production. We therefore consider emission scenarios here that are not based on any further restrictions on emissions until 2030. Emission rates continue to rise as until 2022 (business as usual). Only the annual increase in the emission rate is limited to 3 GtC/year for the next 8 years (until 2030). After that, the growth rate for models for model 1 and 2 is set at 3 GtC/year until 2040. Thereafter, the emission rate is assumed to remain constant at 17.3 GtC/year - for model 1 until 2070, and for model 2 until 2050. In order to

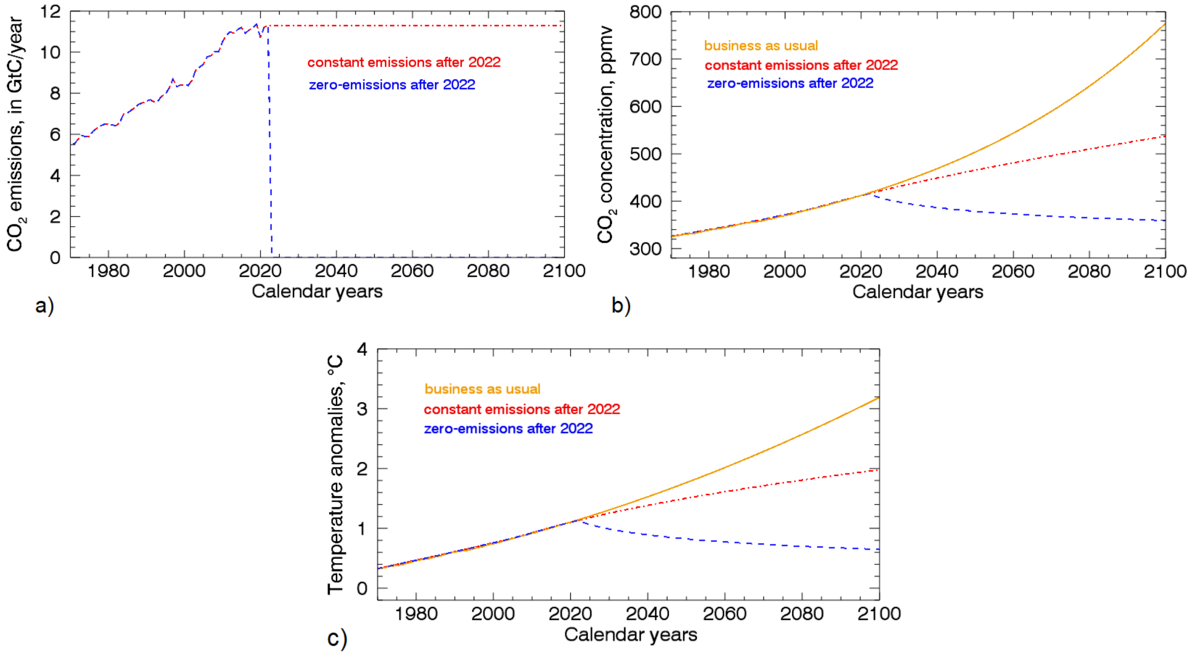

Fig. 5. a) Model of observed atmosphere CO_2 concentration up to 2022 and a constant emissions after 2022 (red line) and model of observed atmosphere CO_2 concentration up to 2022 and a zero-emissions after 2022 (blue line) and b) their atmosphere CO_2 concentration and c) surface temperature responses. For comparison the exponential grow of the atmosphere CO_2 concentration (yellow line in b) and c) resulting the temperature response.

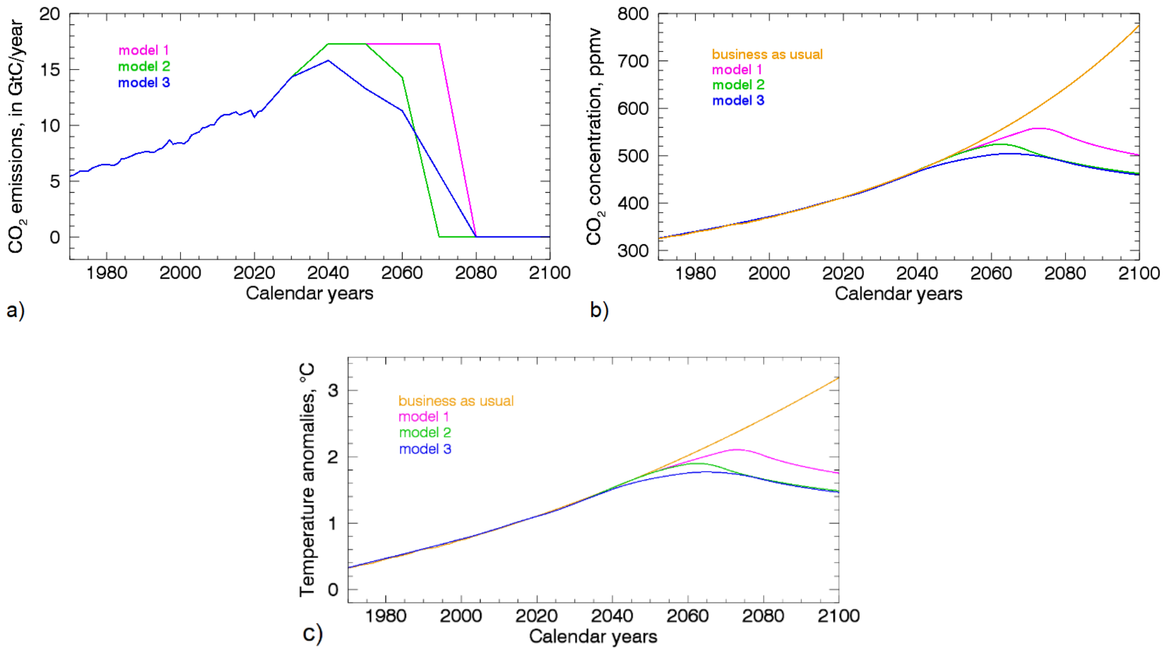

Fig. 6. Responses of atmospheric CO_2 concentration (b) and surface temperature (c) to assumed CO_2 emissions (a)

ensure compliance with the 2°C limit for model 1 an abrupt drop to the level of zero emission is necessary after the period of constant emission (see Fig. 6 model 1, magenta lines). An overshoot (a short time interval with temperatures greater than the limits) over 2°C for the model 1 results for 2060-2090 with a maximal temperature of 2.1°C. In 2100 a temperature of about 1.75°C would be achieved. A shortening of the time interval with constant emission up to 2050 allows a delay and slowing down of the emission drop (see Fig. 6 model 2, green lines). For this scenario the 2°C limit would be not achieved. However an overshoot of the 1.5°C limit would be observed from 2040 to 2090 with a maximum of about 1.9°C. For the emission model 3 an emission increase up to 2030 is assumed, as for model 1 and model 2. After this the grow rate up to 2040 is limited to 1.5 GtC/year and reaches 15.8 GtC/year in 2030. Up to 2040 the CO2 emission decrease to a value of 13.3 GtC/year. By 2060, the emission value of 2022 will be reached and after that it will fall uniformly until zero in 2080. The interval of the overshoot for the 1.5°C limit is very close to the one of model 2. Only the maximum is slightly smaller and would be 1.8°C. After 2070 the temperature anomalies obtained by model 2 and 3 would be approximately the same. For both models a temperature of about 1.5°C is reached in 2100. We have to point out that the aim of the paper is not to construct real emission scenarios. The aim was to illustrate different CO_2 emission scenarios estimating the CO_2 concentration and temperature anomalies response using the Bern-model.

Summary

The Bern-model with its CO_2 emissions and CO_2 concentration in the atmosphere is presented. The concentration and response to idealized case of constant emission and zero-emission after 2022 are determined. Three different emission scenarios were constructed with the aim of meeting the Paris climate targets. Low temperature overshoots were accepted. The scenarios are not real, but they serve more to demonstrate the possibilities of working with the Bern model. Some authors criticize temperature overshoots because the occurrence of tipping points is still vaguely known.

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