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Modelling Dependence of Climate System on Carbon Dioxide Emissions from Fossil Fuel Combustion

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Preliminary note

We have developed a model for investigating the dependence of the climate system on the concentration of carbon dioxide in the atmosphere. This model was constructed in the STELLA program, which makes use of Systems Dynamics Modelling as a methodology. It consists of two main sectors: climate sector and carbon dioxide emissions sector, and studies interactions between climate system and carbon dioxide emissions from coal, oil, natural gas. Together, the interacting climate and carbon dioxide emissions provide approximate predictions of both Earth and atmosphere temperature as a function of time. Our simple model predicts a gradual increase in atmosphere and Earth temperatures. The increase of mean temperatures for the time interval of 100 years is about 5 K, which is in accordance with the data obtained from IPCC where the range of projected global temperature change, for the same time interval, for all scenarios is from 1.4 K to 5.8 K

Modeliranje ovisnosti klimatskog sustava od emisije ugljičnog dioksida iz izgaranja fosilnih goriva

Prethodno priopćenje

Napravljen je model za istraživanje ovisnosti klimatskog sustava od koncentracije ugljičnog dioksida u atmosferi. Ovaj model je konstruiran s programom Stella koji za metodologiju upotrebljava modeliranje dinamičkih sustava. On sadrži dva glavna sektora: klimatski sektor i sektor emisije ugljičnog dioksida, i istražuje interakciju između klimatskog sustava i emisije ugljičnog dioksida iz ugljena, nafte i prirodnog plina. Interakcija između klimatskog sustava i emisije ugljičnog dioksida daje približno predviđanje za temperaturu Zemlje i atmosfere kao funkcije vremena. Naš jednostavan model predviđa postepeni rast temperature Zemlje i atmosfere. Rast srednje temperature za interval vremena od 100 godina je oko 5 K koji je u suglasnosti s dobivenim podacima iz IPCC gdje se za isti interval vremena, projektirane promjene globalne temperature, za sve scenarije, kreću od 1.4 K do 5.8 K.

1. Introduction

The Earth's climate system is a complex type of energy flow system in which solar energy enters the system, is absorbed, reflected, stored, transformed, and released back into the outer space. When the amount of energy received equals the amount given back to space, the Earth is in a steady state in terms of energy, expressed by a constant mean temperature of the Earth [1]. In reality, the Earth's climate is changing and human activities are contributing to this change. Human activities: burning of fossil fuels (coal, oil, and natural gas) for industries, transportation, and heating purposes, as well as cutting down of trees and forests, agricultural activities, and change in land use, result in increase of the concentration of greenhouse gases, in particular carbon dioxide. Most climate change scenarios project that greenhouse gas concentrations will increase through 2100 with a continued increase in average global temperatures [2].

The response of the climate system to anthropogenic forcing includes the potential for 'rapid climate change'. The rapid climate changes can be associated also with nonlinear responses of economic and ecological factors [3]. One way to react to potential climate change is halting growth in global warming pollution by reducing emissions. This reduction can be achieved using energy from biomass, solar, wind and other renewable sources and/or nuclear energy seems to be a viable alternative [4].

In order to investigate the above phenomena, we have created a model that has the following aims:

1. Evaluating the physical processes that contribute to the Earth's temperature, as well as developing a model that accurately predicts equilibrium temperature which keeps the Earth's energy balance (climate sector).
2. In order to project the impact of human perturbations on the climate system, developing a model which

Symbols / Oznake

H	- water heat capacity, $Jkg^{-1}\cdot K^{-1}$ - toplinski kapacitet vode
Q	- total energy stored in the ocean, J - ukupna energija uskladištena u ocean
T_o	- the ocean's average temperature, K - srednja temperatura oceanima
I_A	- insolation absorbed by atmosphere, J/s - insolacija absorbirana od atmosfere
S_0	- solar input, J/s - solarni input
T_e	- Earth's temperature, K - temperatura Zemlje
T_A	- atmosphere's temperature, K - temperatura atmosfere
I_S	- insolation reflected by surface, J/s - insolacija reflektirana s površine
R_{SA}	- radiation from sun to atmosphere, J/s - radijacija od Sunca do atmosfere
I_c	- reflected insolation by clouds, J/s - insolacija reflektirana s oblaka
R_{SE}	- radiation from sun to Earth, J/s - radijacija od Sunca do zemlje
S	- Earth's surface, m^2 - površina Zemlje
P	- cloud cover, % - pokrivenost oblacima
A_e	- Earth's albedo, const - Zemljin albedo
α	- atmospheric absorption coefficient, const. - atmosferski koeficijent absorpcije

Indices/Indeksi

C	- cloud - oblak
A	- atmosphere - atmosfera
E	- Earth - Zemlja
S	- solar - sunce
S_p	- space - prostor
s	- surface - površina

explores global temperature change in response to carbon dioxide emissions

For achieving these aims, usually the energy balance models are used [5-7]. Such a model, designed in this work, uses the program STELLA [8], which makes use of Systems Dynamics Modelling as a methodology. In this model, the carbon dioxide emission sector is linked with the climate sector. In the climate sector, the Earth's reservoirs are linked with atmosphere's reservoirs describing thermal energy stored in the atmosphere and the Earth's surface (a combination of land and water). The reservoirs are also linked by a number of flows that transfer energy from one reservoir to another as well as to and from outer space.

While this is a very simple model, which neglects many difficult issues, we show that it allows for quantitative estimates which are in good agreement with the IPCC models.

2. Modelling Climate System

The physical principle used in this model is - conservation of energy. This model for Earth's energy system conserves the energy flowing to and from the Earth. The main task of this sector is to determine the Earth's temperature at which the incoming and outgoing flows are balanced.

The determination of the Earth's radiation budget is essential to atmospheric modelling and climate studies. The average of the total amount of solar energy received by the Earth is $55.6\ 10^{24}$ J/year [8]. Of the total sunlight falling on Earth, about 70 % is absorbed by the Earth and atmosphere and 30 % is reflected back to space. The atmosphere's dust and clouds absorb 23 %. The remaining 47 % is absorbed by land and ocean surfaces. This part is used by the climate and serves for keeping the temperature. Almost all of the reflected sunlight (26 %) is reflected by clouds, which covers 60 % of the Earth's surface. In cloud-free areas, 4 % of the sunlight is reflected by the surface.

The surface is heated by absorbing 47 % of the sunlight. For this reason, the surface of the Earth emits an amount of energy (116 %), greater than the total from the sun (100 %). Of this emission the total heat loss by radiation is only 14 %. The other 102 % of incident sunlight is absorbed by greenhouse gases in the atmosphere and converted into heat energy and then into atmospheric emissions of long wave radiation..

The atmosphere emits 161 % of long wave energy, 65 % of which is lost directly to space, whereas 96 % travels downward towards the surface to the Earth's surface where it is absorbed and transferred into heat energy (Figure 1).

We have assumed that the oceans cover 70 % of the surface S (an area of about $3.57 \cdot 10^{14}$ m^2) and about h=35 meters of water is actively involved in the heat exchange with the surface on a time scale of a few years, the total mass of water $m=10^{20}$ kg. Total energy stored in the oceanic part of the reservoir is: $Q=1.5 \cdot 10^{25}$ J. The water heat capacity:

$$H = \pi \cdot d^2 h \cdot \rho \cdot c, \tag{1}$$

where d=12742 10^3 m is Earth's diameter and c – specific heat capacity of water. The ocean's average temperature is:

$$T_o = \frac{Q}{H}, \tag{2}$$

By analogous calculations we find the amount of energy conserved on the Earth. If the continental area is $1.53 \cdot 10^{14}$ m^2, assuming that only one meter of soil or rock is involved, using a density of 1500 kg/m^3 and a heat capacity of 1000 J/kg K, we end up with $6.6 \cdot 10^{22}$ Joules. The same calculations are carried out for the atmosphere, assuming a mass of $5.14 \cdot 10^{18}$ kg, an average temperature of -18 °C, and a heat capacity of 700 J/kgK, which results in $9.17 \cdot 10^{23}$ J.

Below, we briefly describe how each flow is defined. (Note: Expressions used in the model are written in brackets, whereas symbols represent respective radiations.)

Radiation from sun to Earth (**Solar to Earth** - R_{SE}) -This is the solar energy that reaches and is absorbed by the land surface, which is strongly dependent on solar input (S_0), insolation reflected by surface (I_S), reflected insolation by clouds (I_C) and the portion of the insolation that is absorbed by the atmosphere (I_A) A simple formulation for this is:

$$R_{SE} = S_0 - I_C - I_S - I_A, \tag{3}$$

where I_A – insolation absorbed by atmosphere, and represents absorption of incoming solar radiation by the atmosphere defined by:

$$I_A = S_0(1-\alpha), \tag{4}$$

where α = 0.82 – atmospheric absorption coefficient, and insolation reflected by surface:

$$I_S = A_E(S_0 - I_C - I_A), \tag{5}$$

A_e - Earth's albedo – is the average albedo of the surface (dominated by water in the oceans) and is entered as 0.074, a bit less than 0.1, I_c - reflected insolation is the solar radiation reflected back into space by clouds, which is strongly dependent on solar input (S_0) the percentage of the surface covered by clouds, but also on the cloud albedo:

$$I_C = S_0 \cdot P \cdot A_C, \tag{6}$$

P - cloud cover is the fraction of the Earth's surface covered by clouds, initially set at 0.60, equivalent to 60%, and A_c – cloud albedo is set at 0.074.

Radiation from sun to atmosphere (**Solar to atmosphere -** R_{SA}**) -** This flow is defined using the same approach as in previous case:

$$R_{SA} = (1-\alpha) \cdot S_0, \tag{7}$$

Radiation emitted from surface lost to space (**Earth to space** - R_{ESp}) – The heated Earth's surface emits infrared radiation part of which, passing through atmosphere, is lost into the space. The value of this flow depends on atmospheric absorption coefficient and can be determined according to the Stefan-Boltzmann law:

$$R_{ESp} = (1-\alpha) \cdot F_E, \tag{8}$$

F_e – Stefan Boltzmann law applied for the case of Earth

$$\begin{aligned} F_e &= k S_0 \sigma T_e^4 = \\ &= 55.6 \cdot 10^{14} \cdot 5.67 \cdot 10^{-8} \cdot 3.155 \cdot 10^7 \frac{s}{yr} T_e^4, \end{aligned} \tag{9}$$

σ - Stefan-Boltzmann's constant. Here, T_e - is the Earth's temperature in K at any time during the model run. Using a time unit of a year requires that we convert all physical parameters (i.e. Solar constant and Stefan-Boltzmann constant) from units containing seconds to years. One average year is 31.557.600 s, which includes the leap-year effect.

$$k = 31557600 \frac{s}{yr} = 3.155 \cdot 10^7 \frac{s}{yr}. \tag{10}$$

Long wave radiation emitted from atmosphere lost to space (**Atmosphere LW to Space -** R_{ASp}**).** Analogous to the previous flow, this one is designed to change as the temperature of the atmosphere changes:

$$R_{ASp} = F_A, \tag{11}$$

F_A – Stefan-Boltzmann law applied for the case of atmosphere,

$$F_A = k \cdot S_0 \cdot \sigma \cdot T_e^4. \tag{12}$$

Here, $\sigma = 5.67 \cdot 10^{-8}$ Js^{-1}m^{-2}K^{-4} and T_A-is the atmosphere's temperature in K at any time during the model run.

Radiation emitted from surface to atmosphere (**Earth_IR_to_Atmosphere** - R_{EA}) – Mathematical formulation of the flow of the infrared radiation emitted from the Earth's surface into the atmosphere can be

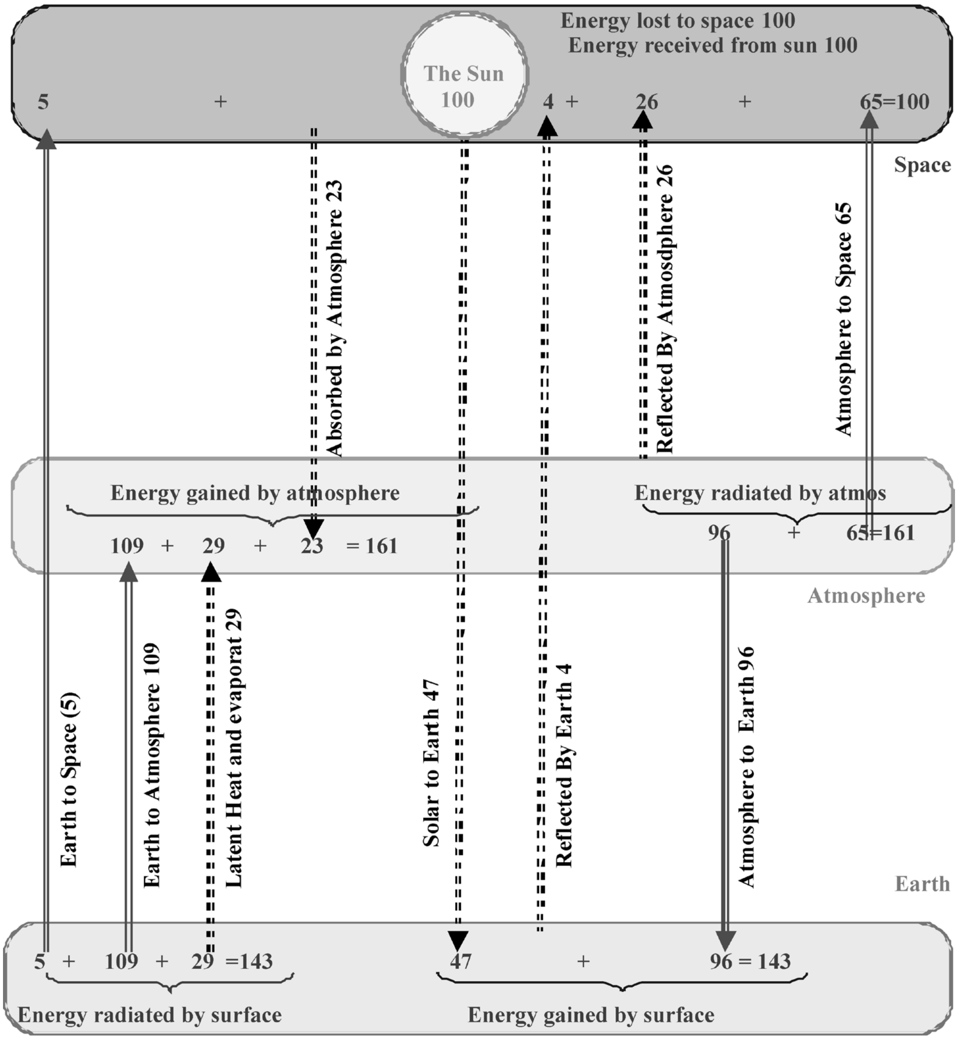

Figure 1. The Earth's global energy balance, source: [9]. Here, the units of energy are equivalent to the percentage of solar energy received by the Earth each year. Solid arrows represent infrared radiation, while the dashed arrows represent short wave radiation

Slika 1. Globalna bilanca energije Zemlje [9]. Jedinice energije su ekvivalentne s postotkom sunčeve energije primljene od Zemlje svake godine. Pune strelice pokazuju infracrvenu radijaciju dok isprekidane strelice pokazuju kratko valnu radijaciju

represented in a quite simplified manner: apply the assumption that all of these processes will depend on the temperature of the Earth surface in a relatively simple fashion:

$$R_{EA}= \alpha \cdot k \cdot S_0 \cdot \sigma \cdot T_e^{\,4}, \tag{13}$$

Long wave radiation emitted from atmosphere to surface (**Atmosphere LW to Earth -** R_{AR}) – If we denote by T_A the temperature of the atmosphere, then applying the Stefan-Boltzmann law, we can determine the long-wave radiation emitted from atmosphere to surface, R_{AS},:

$$R_{AE}= k \cdot S_0 \cdot \sigma \cdot T_e^{\,4}, \tag{14}$$

This radiation causes the greenhouse effect. In this model the way in which cloud cover is defined, could be modified, making it dependent on the global temperature. The reasoning here is that when the Earth is very cold, there will be less evaporation, therefore less water vapor to form clouds in the atmosphere, and conversely, when it is warmer, there will be a greater percentage of the Earth covered by clouds. In reality, as the water content of the atmosphere changes, we would have to change the part of the system that relates to the greenhouse efficiency and the latent heat transport (through evaporation and condensation of water) if we wanted a model that is as realistic as possible.

Climate system in this model will have only two reservoirs where energy is stored - the atmosphere and the Earth's surface linked by six flows (Figure 2).

3. Modelling Carbon Dioxide Emissions

The relative contributions of different fossil fuels to total energy-related carbon dioxide emissions have changed over time. In 1990, emissions from the combustion of liquids and other petroleum made up an estimated 42 % of the world total; in 2005 their share was 39 %; and in 2030 it is projected to be 35 %. Carbon dioxide emissions from natural gas combustion, which accounted for 19 % of the total in 1990, increased to 20 % of the 2005 total [10].

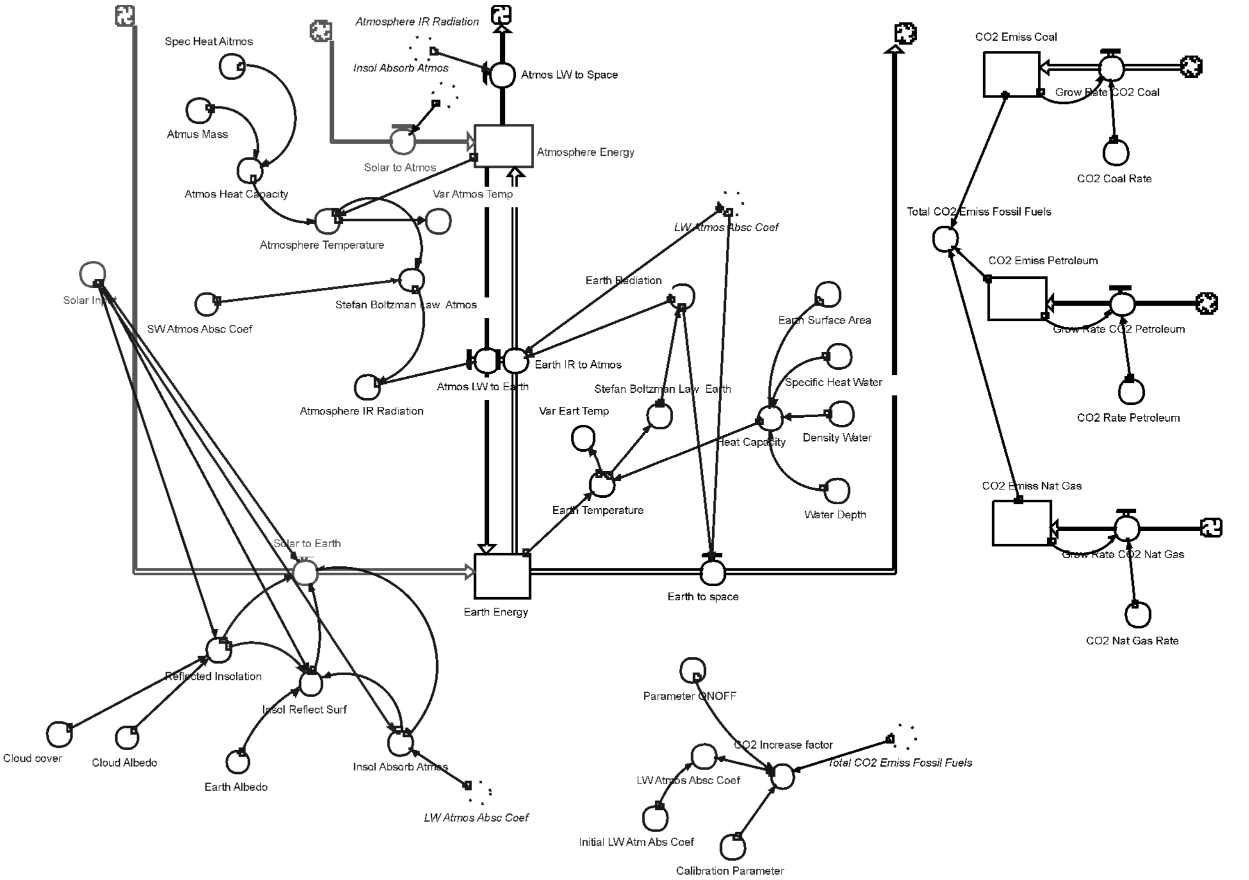

Figure 2. Representation of the model

Slika 2. Reprezentacija modela

World carbon dioxide emissions from the consumption of liquid fuels are projected to grow at an average annual rate of 1.2 % from 1980 to 2100. Carbon dioxide emissions from natural gas combustion worldwide are projected to increase on average by 1.7 % per year, to 117, 5 billion metric tons in 2100. Total carbon dioxide emissions from the combustion of coal throughout the world are projected to increase by 2.0 % per year on average. Carbon dioxide emissions from fossil fuels obtained from the model are represented in the Figure 3.

Carbon dioxide emissions in this sector have only four reservoirs: carbon dioxide emissions from petroleum, carbon dioxide emissions from coal, carbon dioxide emissions from natural gas and carbon dioxide emissions from fossil fuels (Figure 3).

4. Results and Model Simulations

After the running of the climate model (i.e. global model in which the influence of carbon dioxide emissions

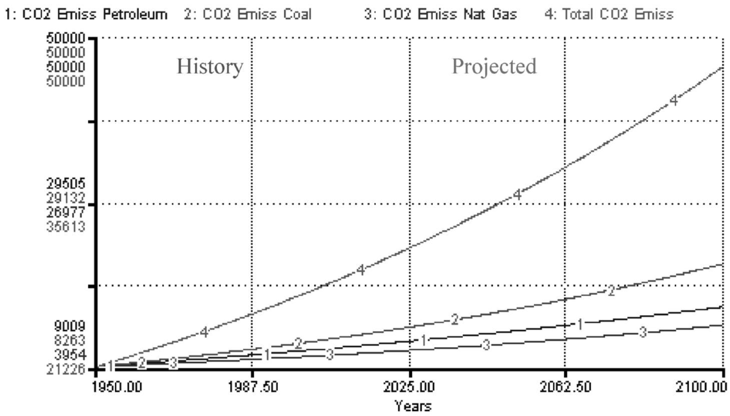

Figure 3. World carbon dioxide emissions of fossil fuels from petroleum, coal, natural gas, and total, obtained from the model. History: Energy Information Administration [10]. Projections: from the model

Slika 3. Svjetska emisija ugljičnog dioksida iz fosilnih goriva: iz nafte, ugljena, prirodnog plin i totalna. Povijest: Energy Information Administration [10]. Projekcije: iz modela is not taken into consideration), the graph as in Figure 4 are obtained. In this case, constant temperatures are obtained, for the temperature of the atmosphere 255 K = -18 ^{0}C and 288 K = 15 ^{0}C for the temperature of the Earth.

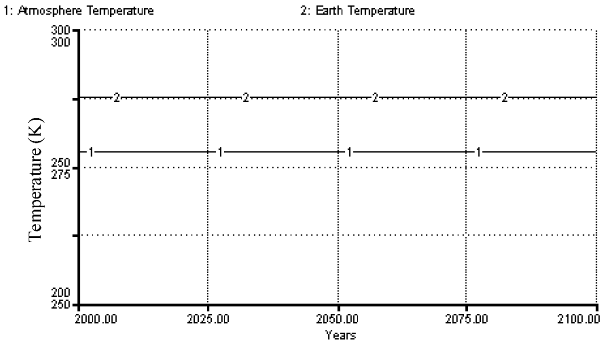

Figure 4. Values obtained from the model (CO_2 emission is not taken into consideration). Global Earth's temperature, which is a constant and has the value 288 K and global Earth's temperature, which is a constant and has the value 255 K

Slika 4. Vrijednosti dobivene iz modela (emisija CO_2 nije uzeta u obzir). Globalna temperatura Zemlje koja je konstantna i ima vrijednost 288 K i globalna temperatura atmosfere koja je konstantna i ima vrijednost 255 K

A graph (Figure 5a) is obtained after the execution of the model. (in which the influence of carbon dioxide emissions is taken into consideration). From these graphs we see a gradual increase in the atmosphere's and Earth's temperatures. This increase is due to the connection between the sectors of carbon dioxide emissions and climate system. This increase in temperature is a consequence of the increase of carbon dioxide emissions in the atmosphere, which is released from the fossil fuel combustion. In this case the GHG effect is taken into consideration. Increase of mean temperature for the time interval of 100 years is about 5 K (±0.7 K), which is in accordance with the data obtained from [11] for the same time interval, which is 1.4 K to 5.8 K. For these temperature changes of the Earth and atmosphere to be more discernible graphically, the temperature change of Earth and atmosphere compared to their temperatures where the influence of carbon dioxide emission is not taken into consideration is shown in Figure 5b.

5. Conclusions

In this work, the model which links the carbon dioxide emission sector with the climate sector is presented. This model consists of two sectors: climate sector and carbon dioxide emission sector. These sectors consist of different reservoirs and fluxes.

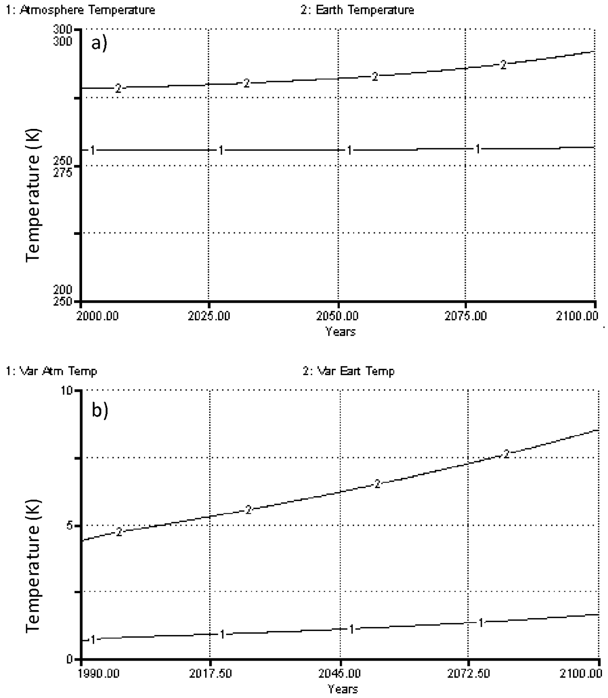

Figure 5. Values obtained from the model (CO_2 emission in atmosphere is taken into consideration): a) Global atmosphere's temperature and global Earth's temperature, b) Variations of global atmosphere's temperature and variations of global Earth's temperature

Slika 5. Vrijednosti dobivene iz modela (emisija CO_2 je uzeta u obzir). a) Globalna temperatura atmosfere i globalna temperatura Zemlje b) Varijacije globalna temperature atmosfere i varijacije globalne temperature Zemlje

After running the climate model (i.e. global model in which the influence of carbon dioxide emissions is not taken into consideration), constant temperatures are obtained; for the temperature of the atmosphere 255 K = -18 ^{0}C and 288 K = 15 ^{0}C for the temperature of the Earth. In the case, in which the influence of carbon dioxide emissions is not taken into consideration, results from this model show that until the year 2100, the Earth's temperature will be increased by 5 K (±0.7 K), for predicted values of the increase in energy consumption from fossil fuels and the increase of carbon dioxide emission for the business as usual case. Results obtained for the increase of the Earth's temperature are in agreement with predicted results of [12], where the range of projected global temperature change between 1990 and 2100 for all scenarios is 1.4 K to 5.8 K. Predicted rates of the increase in energy consumption and carbon dioxide emission are close to the predicted rates of the increase in energy consumption and carbon dioxide emission in the latest predictions made in this field.

According to the results obtained here, we can conclude that although this models very simple, it gives results for the depedence of Earth’s and atmosphere’s temperature on carbon dioxide emission which are in good agreement with the IPCC models. Our model is thus applicable to various scenarios of interest.

With this model the dependence of increase in the Earth's temperature and the impact on the Earth's climate, on the increase of the energy and carbon dioxide emission at different rates can be investigated, for example by replacing the fossil fuel energy with renewable energy.

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