A DYNAMIC SIMULATION MODEL OF CARBON CIRCULATION AND METHANE FEEDBACKS IN ANTHROPOGENIC CLIMATE CHANGE

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ABSTRACT

The human induced climate change is one of the most serious and difficult environmental issue to manage that has emerged in the recent decades. Although the severity of the problem and the need for urgent action are unquestionable today, people usually prefer 'wait and see' policies instead of prompt action. One reason of this tendency is inherent difficulties of understanding the dynamics of anthropogenic climate change and anticipating the possible future results of today's actions. Climate change is a good example of a dynamic systems problem. It embodies several delays, feedbacks, nonlinearities and uncertainties in its dynamically complex structure. Therefore, the need for and the usefulness of descriptive and simple models explaining these dynamic complexities are undisputed. The aim of this study is to construct a dynamic simulation model for this end. The model integrates several components of the climate system. It includes the carbon cycle, radiative forcing of CO_2, CH_4, N_2O and induced temperature change as well as the temperature feedback affecting carbon exchange between land and the atmosphere. It also proposes a representation of the permafrost melting and methane feedback processes. The model aims at enabling the user to test the effects of these feedbacks, the emission scenarios and parameter uncertainty on greenhouse gas concentrations and related temperature change. Model structure is validated with indirect structure tests. Historical emissions and temperature change data are used to calibrate the model behavior. For future work, we aim to transform the model to an interactive learning environment that can be reached from the web to be used by the general public so as to improve their understanding of the dynamics of anthropogenic climate change.

Keywords: anthropogenic climate change, carbon circulation, methane feedback, permafrost melting

1. INTRODUCTION

Of all the environmental issues that have emerged in the past few decades, global climate change is the most serious, and the most difficult to manage (Dessler and Parson, 2007). Although climate change in IPCC usage refers to "any change in climate over time, whether due to natural variability or as a result of human activity", activities of mankind have surely precipitated it with disastrous results. Today, increased emissions of greenhouse gases (GHGs), especially of carbon dioxide, are known to be the main cause of this.

Climate change carries higher stakes than other environmental issues, both in the severity of potential harms if the changes go unchecked, and in the apparent cost and difficulty of reducing the changes. In this sense, climate change is the first of a new generation of harder environmental problems that human society will face over the 21st century, as the increasing scale of our activities puts pressure on evermore basic planetary-scale processes.

Climate change presents a classical dynamic systems problem. The effects of changes in emission and absorption processes of greenhouse gases can only be observed with very long time delays. There are uncertain destabilizing feedbacks, such as methane, water vapor, soil decomposition and sea ice/albedo processes (Ford, 2007). There are nonlinearities in GHG transfer between ecosystem compartments such as photosynthesis. Nevertheless, many detailed climate models lack the integrity of atmospheric, oceanic and terrestrial systems which play a fundamental role in time delays and feedbacks. Many large scale atmospheric circulation models (Global Circulation Models: GCMs) focus on the details of spatial processes but ignore the possible effects of those highly uncertain feedback mechanisms (Claussen at al., 2002). Therefore, it is useful to explore these individual elements of dynamic complexity on a simpler integrated anthropogenic climate change simulator.

2. PROBLEM DESCRIPTION AND PURPOSE OF THE STUDY

Human induced climate change and related global warming is a serious problem requiring very urgent action. However, people prefer to apply 'wait and see' policies instead of taking prompt action. Most people believe that reducing GHG emissions can be delayed until there is greater evidence that climate change is dangerous and, until they begin to feel uncomfortable with existing climatic conditions. Governments also prefer 'wait and see' policies because they do not want to take costly actions to reduce emissions today for results that will occur decades after.

Wait and see policies, however, often do not work in systems with stocks and flows, long time delays (slow accumulations), multiple feedback processes and nonlinearities (Sterman, 1994).

The climate change problem, even when reduced to its simplest representation (as a stock of CO_2 gas accumulating the difference between emissions and absorptions), creates great difficulties for people trying to manage the emissions with respect to a target concentration level (Moxnes and Saysel, 2009). Adults' mental models of climate change violate even the most basic principle of physics: conservation of matter (Sterman & Sweeney, 2006). The main reason of these misperceptions is that, humans have big difficulties in perceiving and conceptualizing dynamic systems in general and complex dynamics of the climate system in particular. In addition to this, the climate system contains several uncertainties due to its chaotic dynamic structure. All these facts together, lead people to misinterpret the basic behavioral dynamics of the system and to make erroneous predictions about its behavior under different GHG emission scenarios. In this context, the need for adequately descriptive, yet simple and easily understandable models seems obvious.

Besides their contribution to climate science, simple system dynamics models of the climate system would also be helpful for people having no scientific background, to understand better the severity of climate change problem and the urgency of action.

The aim of this study is to build a coupled, simple, dynamic simulation model. The model is intended to comprise basic feedback structures like temperature-CO_2 circulation, temperature-methane emissions and, temperature-permafrost melting feedbacks, and to couple major elements of climate system, i.e. atmospheric, terrestrial and oceanic carbon as well as the heat transfer between Earth's surface layer and the deep ocean. Carbon cycle modules of climate-economy models, the system dynamics climate models and some GCMs are investigated and, an integrated model is constituted. STELLA software isee systems, v. 9.0.2) is used as the modeling platform. The model is validated with indirect structure tests (Barlas, 1996), with respect to the data created by large scale simulators reported in IPCC Technical Paper II (Houghton et. al., 1997) and with respect to several historical data provided by various IPCC reports, Carbon Dioxide Information Analysis Center (CDIAC) and NASA Goddard Institute for Space Studies (GISS).

The model also allows the user to observe the effects of some non-CO_2 gases on climate change and the effects of some variables such as bio-stimulation coefficient or temperature coefficient on major processes such as photosynthesis, respiration or wetland methane emissions.

3. MODEL DESCRIPTION

3.1. Overview of the Model

The model consists of seven sectors representing carbon circulations, atmospheric nitrous oxide, atmospheric methane, related radiative forcings and induced temperature change and, permafrost melting. The time horizon of the model is 1860-2100. The year 1860 is assumed as the beginning of industrial age. It consists of 23 stocks in 7 sectors. The material and information flows in between model sectors are depicted in Figure 1.

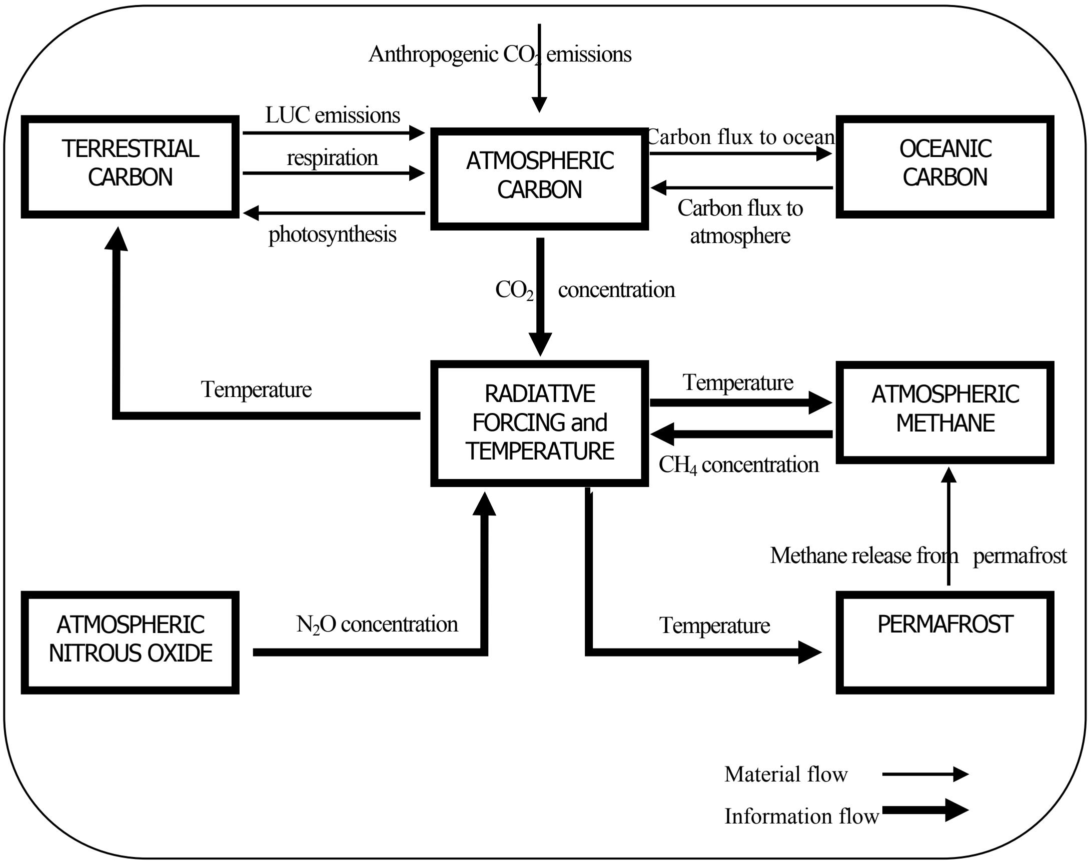

Figure 1. Model overview.

3.2. Sector Descriptions

3.2.1. Terrestrial Carbon Sector: For flow of carbon in terrestrial ecosystems the study of Emanuel et al. (1981) is adopted. The model consists of a globally aggregated terrestrial biosphere with five stocks, each representing carbon in different ecosystems with different turnover times. The flows between the stocks are represented with linear equations except respiration and photosynthesis. Some of the rate coefficients in Emanuel et al. (1981) are modified to calibrate the model. The temperature dependence of photosynthesis and respiration is also included in the model. Land use change (LUC) emissions are represented with time series and flows from terrestrial stocks to the atmosphere.

The ‘carbon in ground vegetation’ stock represents the carbon in all photosynthesizing vegetation types other than trees. Ground vegetation absorbs carbon from atmosphere through photosynthesis and releases carbon to the atmosphere through respiration and LUC emissions. Carbon is also transferred to the ‘detritus-decomposers’ reservoir by death of above ground parts of ground vegetation and to the ‘active soil carbon’ reservoir by death and initial decomposition of below-ground parts of ground vegetation.

The ‘carbon in non-woody tree parts’ stock represents the carbon in all photosynthesizing parts and non-woody parts like flowers, fruits of trees. Non-woody parts of trees absorb carbon from atmosphere through photosynthesis and release carbon to the atmosphere through respiration and LUC emissions. They also transfer carbon to the ‘detritus-decomposers’ pool by death of above ground parts and, to the ‘woody tree parts’ pool by aging of non-woody tree parts becoming woody tree parts.

The ‘carbon in woody tree parts’ stock represents the carbon in all non-photosynthesizing woody parts of trees and, in roots. Woody parts of trees accumulate carbon through aging of non-woody tree parts and becoming woody tree parts and, release carbon to the atmosphere through respiration and LUC emissions. They also transfer carbon to the detritus pool through death of their above ground parts and to the active soil carbon pool through death of their below ground parts.

The ‘carbon in detritus/decomposers’ stock represents the carbon contained in the litter and its decomposer organisms intermixed with soil, also known as humus altogether. This pool receives carbon from ground vegetation and trees through death of their above ground parts. It gives carbon to the atmosphere by respiration and through LUC emissions, and, to the active soil carbon reservoir by transport of decomposed material from the actively decaying litter layer.

The ‘active soil carbon’ stock represents the carbon in soils and its decomposers that undergo relatively rapid decomposition compared to fossil carbon. The accumulation of carbon to this pool occurs through death of below grounds parts of ground vegetation and woody tree parts and, transport of decomposed material from the actively decaying litter layer. The pool releases carbon to the atmosphere through respiration of the organisms decomposing it and through LUC emissions. Carbon release to the fossil carbon pool is represented in the model by a non-conserved flow with a value of zero since the turnover time of the fossil carbon pool is very long and is insignificant within the time horizon of this study.

All respiration, death and decomposition fluxes that outflow from the stocks are defined by the product of the stock with related rate coefficient. The general form of the linear equation for these outflows is:

Flux=Stock*rate coefficient (Eq. 1.)

where ‘Flux’ is the respiration, death or decomposition outflow from a stock and ‘rate coefficient’ is the empirical rate coefficient that represents the effect of all the micro processes contained in the related process.

LUC emissions flows from the terrestrial stocks are fractionated among the stocks according to the ratio of the carbon content of the related stock to the terrestrial sum.

For temperature dependence of photosynthesis and respiration, Q_{10} formulation of van’t Hoff (1898) is used.

$$M = M_0 Q_{10}^{(\frac{\Delta T}{10})} \qquad \text{(Eq. 2.)}$$

where;

M_0 is the initial rate of a process,

M is the rate of a process after a ΔT°C increase in temperature,

Q_{10} is the temperature coefficient, the fractional increase in M_0 when temperature increases by 10°C.

The carbon assimilation of the biosphere, the photosynthesis, is modeled with a nonlinear formulation. It is suggested in almost all modeling studies that carbon assimilation of plants is stimulated by increasing atmospheric CO_2 concentration and increasing temperature (Denman et. al., 2007). However, the dynamics of this stimulation are not well known. In this study, a formulation similar to the one given by Goudriaan & Ketner (1984) is proposed. But, gross primary production (GPP) is calculated instead of net primary production (NPP) since respirations are represented with separate functions.

The formula proposed for GPP is:

$$GPP_t = GPP_0 * \left(1 + \beta \ln \frac{C}{C_0}\right) * Q_{10}^{\left(\frac{\Delta T}{10}\right)} \qquad \text{(Eq. 3.)}$$

in which;

GPP_0 is the GPP at preindustrial times, the beginning of simulation

GPP_t is the GPP at time ‘t’

β is bio-stimulation coefficient, the coefficient for response of GPP to increasing CO_2

C_0 is the preindustrial atmospheric quantity of carbon

C is the current atmospheric quantity of carbon

$Q_{10}^{\left(\frac{\Delta T}{10}\right)}$ is the temperature effect described previously.

3.2.2. Oceanic Carbon Sector: The structure of the sector is based on the model of Oeschger et al. (1975). It is a box Eddy diffusion model with 11 stocks; one representing the carbon in mixed layer and ten representing carbon in deep ocean layers. Thickness of the mixed layer is 75 m. The deep ocean has upper five layers of 200 meter thickness and deeper five layers of 560 meter thickness.

The mixed layer exchanges carbon with the atmosphere and with the first deep ocean layer.

The gas flux between the atmosphere and the mixed layer is represented in the model through equilibrium carbon content of the mixed layer. The equation defining this flow is:

flux_atmosphere_to_ocean = (Equil_C_in_mixed_layer-C_in_mixed_layer)/Mixing_time (Eq. 4.)

'Equilibrium carbon in mixed layer' is the carbon in mixed layer when its partial pressure is equal to the partial pressure of atmospheric CO_2. Gas exchange occurs between atmosphere and mixed layer until this equilibrium is reached.

All other ten stocks representing deep ocean layers are designed with the same logic: Each layer receives an inflow, which is the outflow of its upper layer, and, discharges one outflow, which is the inflow of its lower layer.

The carbon concentration of layers is calculated by dividing the carbon content of the layer to its depth.

The Eddy diffusion flux from $layer_i$ to $layer_j$, F, is defined as:

$$F=-K(\partial c/\partial z) \qquad \text{(Eq.5.)}$$

where;

K is Eddy diffusion coefficient

$\partial c/\partial z$ is carbon concentration gradient with depth z.

3.2.3. Atmospheric Carbon Sector: The sector consists of only one stock, the 'carbon in atmosphere'. All the inflows/outflows of the stock, except the exogenous 'anthropogenic emissions' inflow, are outflows/inflows of the reservoirs in terrestrial carbon, oceanic carbon and permafrost sectors.

3.2.4. Atmospheric Methane Sector: The sector comprises one stock representing methane in the atmosphere. The stock is filled with exogenous inflows representing natural and anthropogenic methane emissions and, permafrost melting. It is drained with an outflow representing removal of methane by reaction with hydroxyl radical.

Since the carbon flows as methane are small compared to carbon fluxes and are not expected to create a significant change in carbon stocks, methane is not conserved in the model like carbon. The dynamics of the emissions are not considered in the study, except the wetland emissions. Emissions estimates available in the literature and scenarios of IPCC are used as time series instead. However, the temperature and organic matter availability dependence of methane production in wetlands are represented in the model since the change in methane production rate in wetlands creates a positive feedback in climate change. The model adapts the factors considered in Walter and Heimann (2000) and Walter et al. (2001) to a global scale and to the problem of longer term temperature change. For the substrate availability for methane production, annual change in global NPP is calculated. For the temperature dependence of methane production, a Q_{10} formulation is used as suggested by Walter and Heimann (2000). Methane oxidation, which takes place in the oxic zone of the soil above the water table, is assumed to be 40% of the total methane production.

The last inflow of the stock is CH_4 release from permafrost, which is connected to the Permafrost sector.

The main removal mechanism of methane in the atmosphere is its reaction with hydroxyl ion in the troposphere (Wuebbles and Hayhoe, 2002). Methane is oxidized in the troposphere in a series of reactions to form finally ozone (O_3). However, the hydroxyl ion is not only removed by methane but also by the products of its reaction with methane. Thus, increasing amount of methane in atmosphere decreases the amount of available hydroxyl ion thereby increasing the atmospheric lifetime of methane and creating a positive feedback for atmospheric methane (Lelieveld et al., 1998, Wuebbles and Hayhoe, 2002, Schimel et. al., 1995). On the other hand, OH is partly replaced as a by-product of CH_4 oxidation chain reactions and, formed by destruction of ozone by solar radiation (Lelieveld et al., 1998, Wuebbles and Hayhoe, 2002). The value, the rate and the pattern of change of the methane residence time is a subject including large uncertainties and needing further research. In this study, the following method is proposed for calculation of the residence time of methane:

$$\Delta CH_4 = \frac{CH_{4(t)} - CH_{4(t_0)}}{CH_{4(t_0)}} * 100 \qquad \text{(Eq.6.)}$$

$$\Delta CH_4 LF = \Delta CH_4 * sensitivity \qquad \text{(Eq.7.)}$$

$$RT_{(t)} - \frac{RT_{(t_0)}}{(100 - \Delta CH_4 LF)/100} \qquad \text{(Eq.8.)}$$

where;

ΔCH_4 is percent increase in atmospheric methane concentration

$CH_{4(t)}$ is atmospheric methane concentration at time ‘t’

$CH_{4(t0)}$ is atmospheric methane concentration at preindustrial times

ΔCH_4LF is percent decrease in CH_4 loss frequency

$RT_{(t)}$ is residence time of methane at time ‘t’

$RT_{(t0)}$ is residence time of methane at preindustrial times=reference methane residence time= 9 years,

CH_4LF is the loss frequency of methane

Sensitivity is the sensitivity of the CH_4 loss frequency to the increase in atmospheric CH_4 concentration (Schimel et. al., 1995).

3.2.5. Permafrost Sector: Permafrost is a large carbon reservoir. Yet, this carbon stock was not incorporated into global carbon budget studies and was not a matter of concern for global warming until recently because, all organic matter was trapped into a frozen environment that keeps it inactive. However there is strong evidence that permafrost is permanently thawing due to global temperature increase; forming new wetlands, causing methane flux and thus creating a strong positive feedback contributing to temperature increase.

The total carbon content of permafrost and its releasing mechanisms to the atmosphere are not well known currently. However, it is obvious that increasing global temperature may increase the depth of seasonally thawing soil and cause the carbon that was previously inactive to be released to the atmosphere (Zimov et al., 2006). In this study, it is intended to model permafrost melting process and related temperature increase.

The two stocks of the permafrost sector represent the permafrost area and the carbon in permafrost. The freezing inflow and the thawing outflow represent the seasonal increase and decrease in the area of permafrost respectively. When undisturbed, these flows are in dynamic equilibrium. When temperature increases, thawing begins to exceed freezing and carbon release to the atmosphere begins. The seasonal freezing fraction is assumed to be constant. However, actual thawing fraction (ATF) is assumed to change indirectly with temperature. The hypothesis suggested to represent this change and underlying assumptions are as follows:

Preindustrial thawing fraction (PTF)=Freezing fraction (Eq.9.)

Although it is not practically possible to calculate the average temperature of permafrost, for modeling purposes, the first one meter depth of it is assumed to be laid homogenously and to have an initial average temperature of -1°C.

It is assumed that all atmosphere, mixed layer and soil behave as a one dimensional homogeneous column. Then the heat capacity of permafrost (HCP) is equal to the heat capacity of atmosphere and mixed layer (HCAML).

HCP=HCAML (Eq.10.)

Since the melting temperature of ice is 0°C, the temperature change to start the devastating melting is calculated as:

$\Delta T=T_{final}-T_{initial}=0-(-1)=1°C$. (Eq.11.)

The heat required to start the severe melting process is calculated with the heat exchange formula of basic physics;

ΔQ=heat capacity*ΔT (Eq.12.)

The ratio of heat difference to critical heat, (HR), is calculated by dividing the 'Atmosphere and mixed layer heat difference' (AMLHD) to the heat required to start the severe melting process (HRSM).

HR=AMLHD/HRSM (Eq.13.)

A variable called 'thawing fraction multiplier', TFM, is defined as an exponentially growing function of the ratio of heat difference to critical heat.

TFM=f(HR) (Eq.14)

Then actual thawing fraction, ATF, is calculated as:

$$ATF=PTF*TFM \quad \text{(Eq.15.)}$$

The other stock of the sector, Carbon in permafrost, represents the carbon stored in upper one meter of permafrost. It has two outflows representing carbon release as CH_4 and carbon release as CO_2 from permafrost.

3.2.6. Atmospheric Nitrous Oxide Sector: Nitrous oxide (N_2O), the second important greenhouse gas after methane because of its long lifetime and its big global warming potential, has both natural and human-related sources. The main removal mechanism of N_2O from the atmosphere is photolysis (breakdown by sunlight) in the stratosphere.

The dynamics of atmospheric nitrous oxide are very simply represented in the model. The sector comprises one stock representing the quantity of nitrous oxide in the atmosphere. The stock has two inflows representing anthropogenic and natural emissions. Anthropogenic emissions are given as time series. The N_2O removal outflow is represented with a linear relationship.

3.2.7. Radiative Forcing & Temperature Change Sector: Radiative forcing is a measure of the influence of anthropogenic and natural factors causing climate change to the energy balance of the Earth-atmosphere system and is usually quantified as the 'rate of energy change per unit area of the globe as measured at the top of the atmosphere' (Forster et. al., 2007).

When unperturbed, the earth-atmosphere system is in an energy balance. However, increasing concentration of emitted greenhouse gases since the beginning of industrial era has disturbed and, is still continuing to disturb this energy balance. Higher amount of greenhouse gases in the atmosphere causes more infrared radiation to be absorbed, more heat storage and consequently a heat surplus in the balance of the system. Thus, this extra heat causes an increase in global average temperature while the system is striving to reach a new equilibrium state.

The structure of this sector of the model is built on the DICE model (Nordhaus, 1992). However, the temperature stocks used by Nordhaus (1992) and Fiddaman (1997) are converted to heat stocks and, temperature changes are calculated separately. The two stocks; 'atmosphere & mixed layer heat difference' and 'deep ocean heat difference' and, the temperature change variables represent the deviations from preindustrial conditions.

‘Atmosphere and mixed layer heat difference’ stock represents the heat accumulation per unit area in the system with disturbance of equilibrium conditions. The stock has one inflow, ‘Radiative forcing’ and, two outflows, ‘Feedback cooling’ and ‘Heat transfer to deep ocean’, which represent the mechanisms counteracting the disturbing effect of radiative forcing.

‘Deep ocean heat difference’ stock represents the heat accumulation per unit area in the deep ocean since preindustrial times. The only inflow of this stock is ‘heat transfer to deep ocean’, which is the outflow of the ‘Atmosphere and mixed layer heat difference’ stock.

4. MODEL REFERENCE BEHAVIOR

The model is run from 1860 to 2100. Historical GHG emissions, either measured or estimated, are obtained from (CDIAC). For future emissions, the A1, A2, B1 and B2 emission scenarios of MINICAM model from Special Reports on Emissions Scenarios (SRES) of IPCC are included in the model. However, the A1 MINICAM emission scenario is used in the reference run.

All GHG emissions, LUC emissions, temperature-photosynthesis, temperature-respiration and temperature-wetland emissions feedbacks are present in the reference run. Only the permafrost feedback is inactive.

When the model is run, the simulated atmospheric CO_2 concentration showed good correlation with historical data. In the reference run including also A1 MINICAM scenario for future emissions, the temperature increase attained the value of 2.76°C in year 2100 (See Figure 2 and 3).

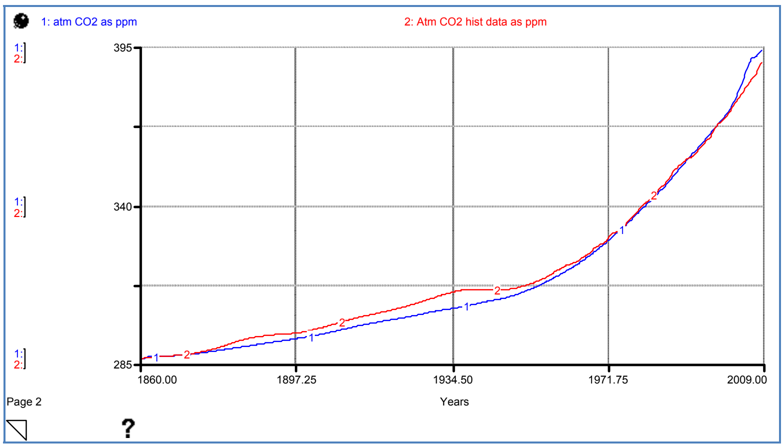

Figure 2 Atmospheric CO_2: simulation (curve 1) and historical data (curve 2)

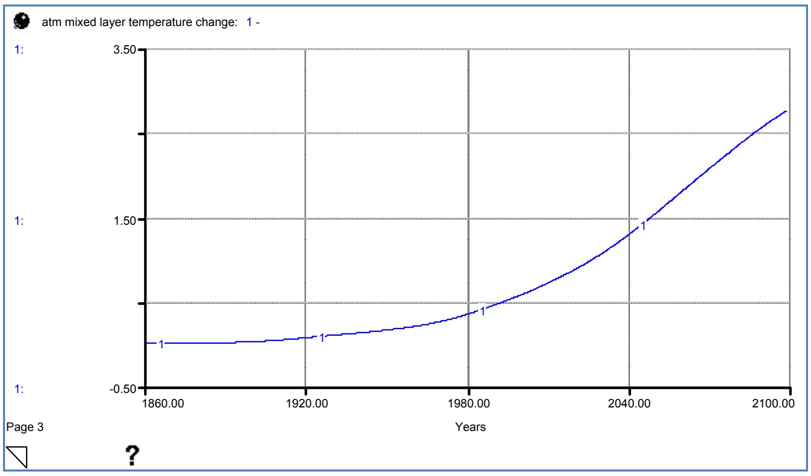

Figure 3 Reference behavior of the atmosphere-mixed layer temperature

5. MODEL VALIDATION

The structural validity of the model is assessed with direct structure tests and with indirect structure tests. Behavioral validation is also assessed with behavior pattern tests. Selected tests are presented below:

5.1. Extreme Condition Test: No Photosynthesis

For this test, the photosynthesis flows, the anthropogenic CO_2 emissions and the LUC emissions are set equal to zero and, the simulation is run. Since there is no photosynthesis, the carbon stocks of all the terrestrial reservoirs are used up due to respiration.

The atmospheric CO_2 concentration first increases significantly due to fast transfer of the terrestrial carbon to the atmosphere through respiration. Then, its increase slows down and it begins to decrease due to carbon flux to the ocean. The behavior of the system with and without photosynthesis is shown in Figure 4:

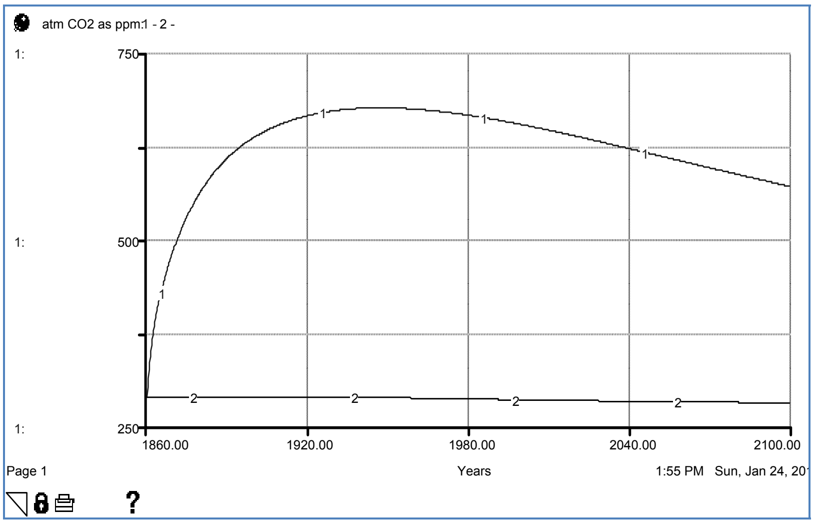

Figure 4 Atmospheric CO_2 without (curve 1) and with (curve 2) photosynthesis

5.2. Parameter Sensitivity Test: Sensitivity of the Atmospheric Carbon to the Bio-stimulation Coefficient

The bio-stimulation coefficient β (the coefficient determining the response of GPP to increasing atmospheric CO_2) is the major uncertain parameter of the photosynthesis formulation. The uncertainty range is given as 0 to 0.7 in Goudriaan & Ketner (1984).

A sensitivity analysis is performed with the values 0, 0.2, 0.4, 0.6 and 0.8 of β. The results are depicted in Figure 5 with curves 1 to 5, each representing the behavior of the atmospheric CO_2 for β values of 0, 0.2, 0.4, 0.6 and 0.8 respectively.

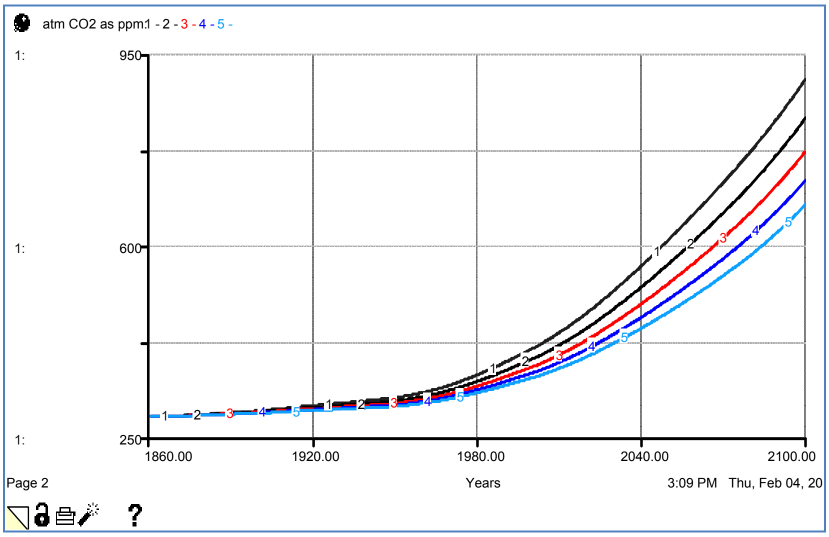

Figure 5 Sensitivity analysis for β (change of atmospheric carbon level

When β=0, the GPP becomes independent of atmospheric CO_2 concentration and only depends on temperature effect on the initial value of GPP. When β increases, GPP increases, which means the terrestrial system absorbs more carbon, causing the atmospheric carbon level and the temperature to increase less. However, since the relationship is logarithmic, as β increases, its effect to the atmospheric CO_2 level decreases.

5.3. Behavioral Validation with Behavior Pattern Test: Comparison of Model Produced Temperature Change with Historical Data

For historical temperature record, the data from Hansen et al. (2006) are used. The 1951-1980 interval is taken as base period and the temperature deviations from the average of this period are calculated. Since the year-by-year data have a very fluctuating pattern, a 5 year mean graph is also plotted to smooth the trend. Then the temperature deviations from the base period are calculated by the model and plotted. For 1930-1950 interval, the values calculated by the model are a little below of the data of Hansen. However, the curves exhibit a relatively better fit after 1950s.

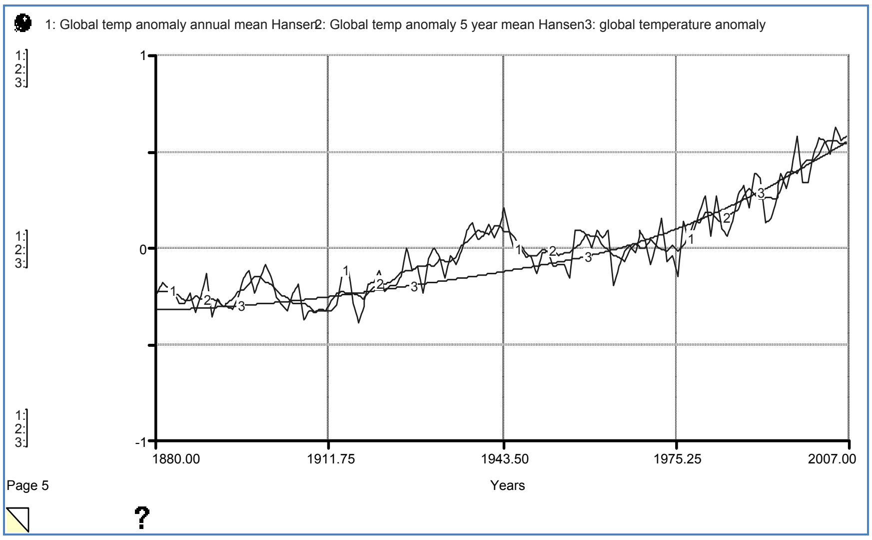

Figure 6 Temperature deviations from 1951-1980 base period (simulation: curve3, historical data & scenario: curve 1 & curve 2)

6. MODEL BEHAVIOR SENSITIVITY AND SCENARIO ANALYSIS

6.1. Analysis of Temperature-Photosynthesis, Temperature-Respiration and Temperature-Wetland Emissions Feedbacks

Increasing temperature affects both photosynthesis and respiration of land biota and, wetland methane emissions. It creates three feedback loops shown in Figure 7. The reinforcing respiration and methane emissions loops increase the temperature while the counteracting photosynthesis loop decreases.

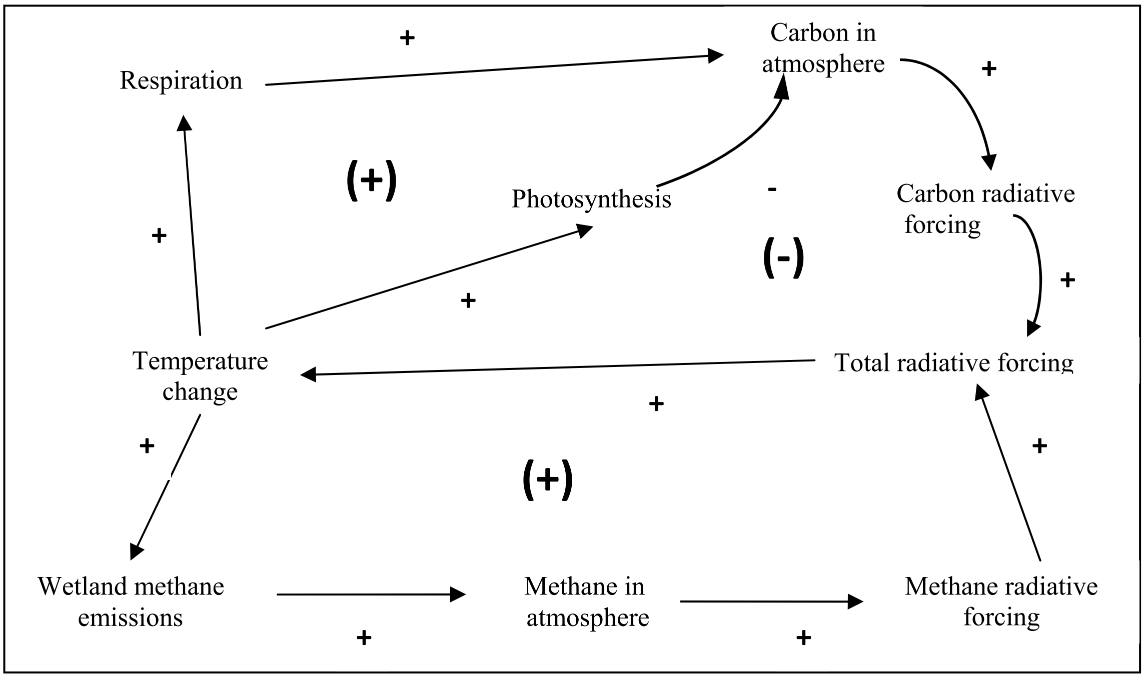

Figure 7 Photosynthesis, respiration and wetland emissions feedback loops

When all three feedbacks shown in Figure 7 are active, the cumulative temperature increase is 2.76°C in year 2100 while it is 2.48°C in the same year when all three are inactive. It can be concluded from this analysis that although the temperature increases photosynthetic activity, it also stimulates respiration and wetland emissions. However, the increase in the latter two dominates the effect of photosynthesis. Thus a temperature difference of 0.28°C occurs in the end of two simulations (Figure 8).

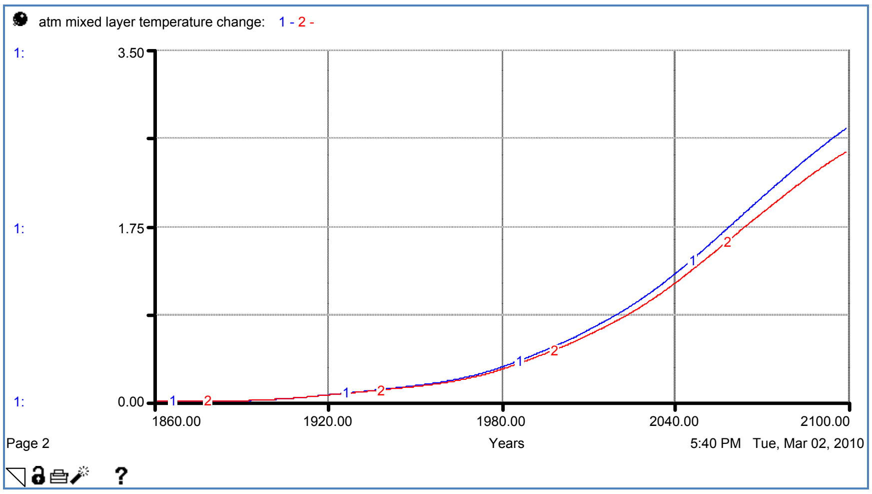

Figure 8 Global temperature change with (curve 1) and without (curve 2) the effect of temperature on terrestrial processes

6.2. Analysis of Permafrost Feedback

Methane release from permanently thawing permafrost, which is not represented much in simple climate models, is a subject of big concern recently for its potential effect to global warming. The permafrost module constructed in this study aims to represents the permafrost feedback depicted in Figure 9 and, to allow to observe its effect on global temperature increase. Note that this feedback loop is not influencing the reference behavior.

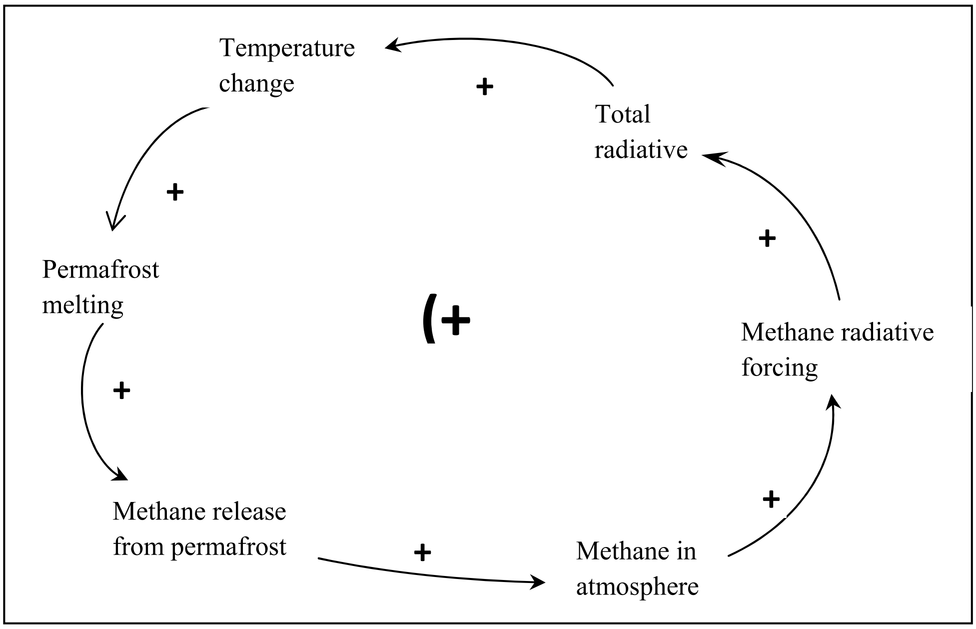

Figure 9 Permafrost feedback.

The permafrost feedback has three main uncertainties:

- thawing pattern of permafrost,
- carbon content of permafrost,
- percentages of CO_2 and CH_4 released from permafrost depending on whether the post-melting organic activity is aerobic or anaerobic.

A thawing pattern is described in the model as a graphical function. A sensitivity analysis comprising 100 runs is performed. The changes of two variables are analyzed: 'Carbon in permafrost' and 'CH_4 release fraction'. A normal distribution pattern is chosen. For 'carbon in permafrost' the mean value is 375 GtC and the standard deviation is 150. For 'CH_4 release fraction' the mean value is 0.5 and the standard deviation is 0.2. The simulation is run 100 times with randomly changing values of these two variables. The results are illustrated in Figure 10:

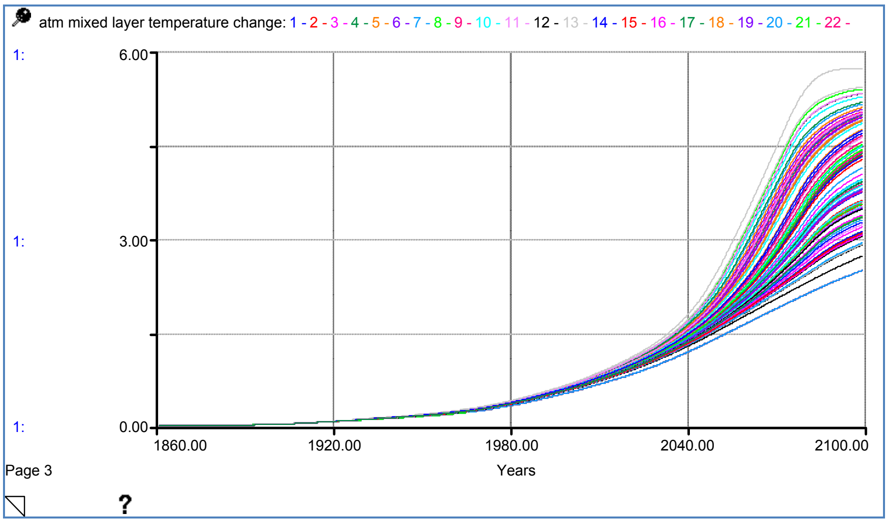

Figure 10 Sensitivity of the temperature to 'carbon in permafrost' and to 'CH_4 release fraction'

The minimum temperature increase is observed as 2.89°C with initial carbon content of permafrost of 106 Gt and CH_4 release fraction of 0.141 while the maximum temperature increase is observed as 5.71°C with initial carbon content of permafrost of 682 Gt and CH_4 release fraction of 0.910.

The analysis of permafrost feedback reveals that when the GHG release from permafrost is considered, even modest estimations for system variables result in higher temperature increases than the permafrost feedback-free behavior. The temperature increase reaches disastrous values with higher permafrost carbon stock and higher anaerobic activity rate estimations. Therefore, the permafrost feedback should seriously be considered as a subject of further research.

6.3. Scenario Analysis

In this section, several emission scenarios are applied to the model and the resulting behavior is observed.

The simulated temperature increase with A1, A2, B1 and B2 emission scenarios of MINICAM model are depicted in Figure 11:

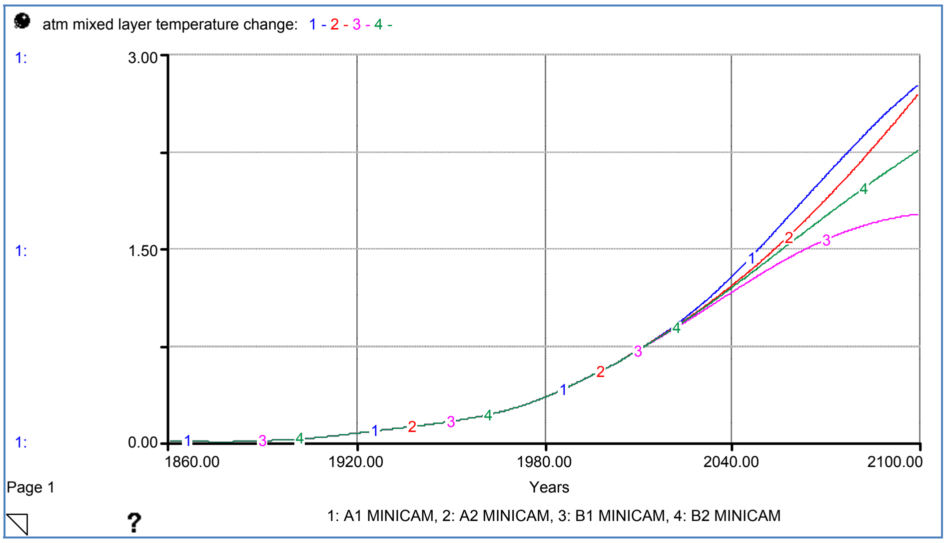

Figure 11 Temperature change with four different SRES scenarios

6.3.1. Scenario 01: Abrupt Anthropogenic CO_2 Emissions Cut in 2010

For this hypothetical extreme scenario, all anthropogenic CO_2 and LUC emissions are cut to zero in year 2010. The permafrost feedback is deactivated and, the radiative forcings of CH_4 and N_2O are turned off in order to observe the sole effect of CO_2 on temperature. When the simulation is run, it is observed that the atmospheric CO_2 concentration begins to decrease from year 2010 on. However, the temperature continues to increase until year 2033.5, then begins to decrease. But its rate of decrease after 2033.5 is smaller than its rate of increase until 2033.5. The temperature increase comes down to its 2010 level in year 2080 (Figure 12).

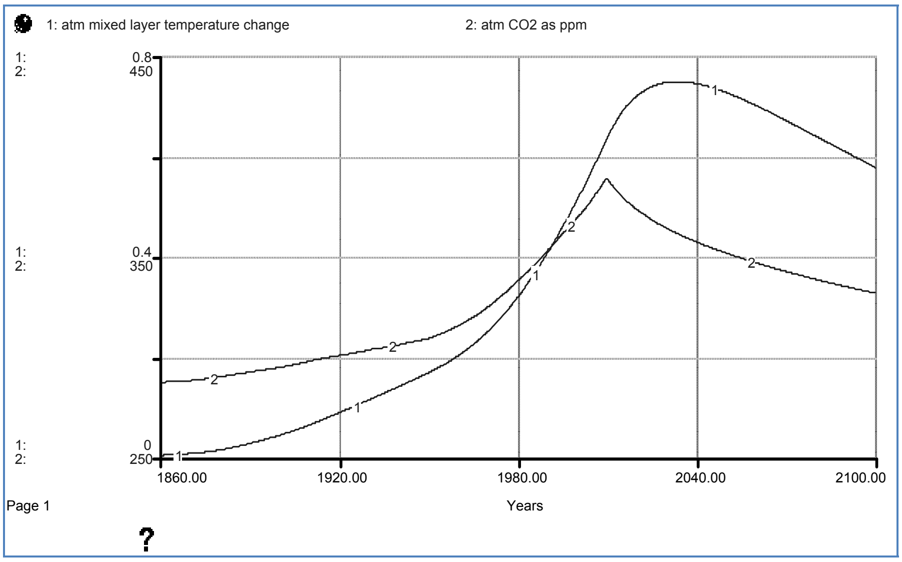

Figure 12 CO_2 and LUC emissions cut to zero in 2010. Behavior of the temperature and the atmospheric CO_2 concentration

6.3.2. Scenario 02: Obtaining Target CO_2 Levels

The critical 350 ppm atmospheric CO_2 level proposed by Hansen et al. (2008) is targeted in this scenario. The permafrost feedback is deactivated. The radiative forcings of CH_4 and N_2O are turned on to observe the full response of the climate system to the decrease in CO_2 emissions. The fossil fuel CO_2 emission estimate with coal phase-out by 2030 of Hansen et al. (2008) that is based on IPCC estimated fossil fuel reserves (Figure 13) is applied to the model. The CH_4 and N_2O emissions are kept constant at their estimated 2010 levels. The model is run until year 2250 to observe longtime behavior of atmospheric CO_2. The resulting behavior of the model is illustrated in Figure 14.

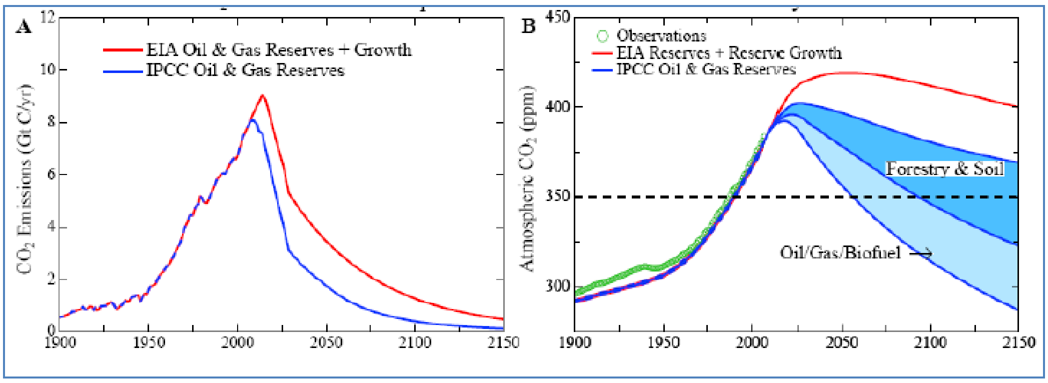

Figure 13 Emission estimates with coal phase-out by 2030 and resulting atmospheric CO_2 (taken from Hansen et al. 2008)

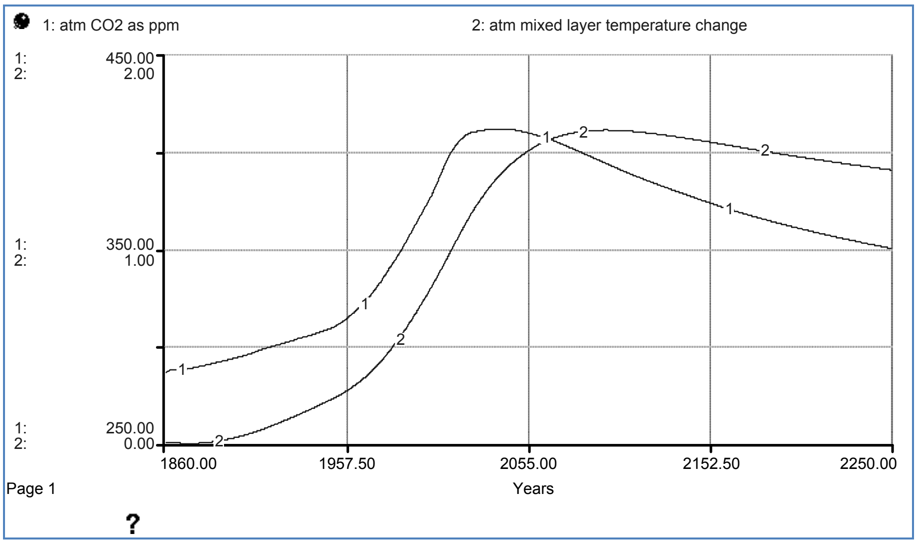

Figure 14 '350 ppm target' scenario. Behavior of the temperature and atmospheric CO_2 concentration

As can be seen from above graphs, although the fossil fuel emissions begin to decrease sharply in 2010, atmospheric CO_2 concentration keeps increasing until year 2041, takes the maximum value of 411 ppm, and then, begins to decrease slowly. It attains the target 350 ppm level in year 2249. In other words, it takes more than two centuries for atmospheric CO_2 level to reach the critical 350 ppm level. This result is in well agreement with Hansen et al. (2008). The corresponding temperature to this emission scenario barely stops increasing after attaining its maximum level of 1.61°C in year 2100, then begins to decrease very slowly down to 1.41°C in 2250. Even the application of this harsh scenario proves the inertia of the climate system and, the seriousness of the global warming problem and the urgency of action.

7. CONCLUSION

This modeling study was intended to reveal the nonlinear feedback dynamics of the climate system and to enable the user to observe and assess the results of various emission scenarios.

A box model coupling the atmospheric, terrestrial and oceanic carbon is constructed. The atmospheric methane, nitrous oxide, and the heat stored in the system are also represented in the model.

The model parameters are identified from the relevant literature and adjusted when needed for model calibration purposes.

The structure of the model is validated with structure oriented behavior tests and the model behavior is validated with behavior pattern tests.

Several sensitivity analyses are performed and it is observed that the model structure is sensitive to the bio-stimulation coefficient, β, and to the temperature coefficients, Q_{10}s.

Some emission scenarios are applied to the model and the behavior is analyzed. It is observed that there exists a large time gap between emission decrease and the response of the system to this decrease due to the inertia of the system components like ocean.

The permafrost melting process and its probable serious effects to the climate system is also analyzed and, a hypothesis is proposed to represent related feedback. Since the variables used to describe the process has large uncertainties, sensitivity analyses are performed to observe the range of different results.

The model can be used to apply different emission decrease scenarios and to observe resulting behavior. It can also be used to observe effects of the parameters with high degree of uncertainty on model behavior by assigning them different values. The effects of the feedbacks included in the structure, and of the emissions and/or radiative forcings of different GHGs to the global temperature increase can be analyzed by turning on and off relevant control switches.

As a further study subject, the model can be transformed to an interactive learning environment (ILE). A user friendly interface not necessitating the user to fully understand the logic and formulations underlying the model structure but letting him to enter different emission scenarios and observe the results, and then, giving instructions about the dynamics causing those results can be developed. The model with such an interface can be used as a tool to improve the understanding of ordinary people about dynamics of climate change and to increase the awareness. By keeping the interface and the instructions simple enough, the ILE can be made easily usable by high school students and can help to improve their perceptions of climate change as decision makers of the future. The model can also be organized as a web based ILE or a gaming platform to let people with various educational backgrounds experiment and develop an idea about climate change.

As endeavors to improve the model structure, the 'carbon saturation of the vegetation' hypothesis can be included in the photosynthesis formulations. Also, the mixed layer of ocean can be divided into warm ocean and cold ocean mixed layers and, their carbon exchange with the atmosphere can be analyzed separately. The effect of different feedbacks like ice-albedo feedback or water vapor feedback and, radiative forcings of other GHGs and aerosols can be included into the model structure. The dynamics of methane and nitrous oxide can be analyzed in deeper detail.

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