

**MEDNARODNA PODIPLOMSKA ŠOLA JOŽEFA STEFANA
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**IMPACT ANALYSIS FOR INTEGRATED
ASSESSMENTS OF CLIMATE-ENERGY MODELS**

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Jožef Stefan International Postgraduate School
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Doctoral Dissertation

ANALIZA VPLIVOV ZA CELOVITO OCENO MODELOV KLIME IN ENERGIJE

Doktorska disertacija

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Abstract

It is evident that the worldwide average temperature is rising and climate is changing (WMO, 2003) and it is believed that there is sufficient evidence that this is due to human activities (IPCC 2001). Human activities are primarily responsible for the release of carbon dioxide and other global warming pollutants which are causing a change in the composition of the atmosphere and its properties.

We have developed the global energy-climate model (GEC model) for the purpose of investigating the dependence of the Earth's temperature on the concentration of carbon dioxide in atmosphere. Global energy-climate model (GEC model) was constructed in the STELLA program, which makes use of Systems Dynamics Modeling (SDM) as a methodology. GEC model connects interactions between Earth's temperature, CO₂ emissions from coal, petroleum and natural gas. GEC model consists of three main sectors: Climate sector, energy consumption sector and CO₂ emission sector. Together, the interacting climate, energy consumption and CO₂ emissions sectors provide predictions of both Earth's and atmosphere temperature as a function of time. After the running of the climate sector, in this case, we have to deal with the zero-energy balance model, for which constant temperatures are obtained for the temperature of the atmosphere $255\text{ K} = -18\text{ }^{\circ}\text{C}$ and $288\text{ K} = 15\text{ }^{\circ}\text{C}$ for the temperature of the Earth. After the execution of the GEC model a gradual increase in atmosphere's and Earth's temperatures is obtained. This increase is due to the connection between the sectors of energy consumption, CO₂ emission and climate system. In this case the GHG effect is taken into consideration. We obtain a predicted increase of mean temperature for the time interval of 100 years of about 5 K, which is in accordance with the data obtained from IPCC for the same time interval, which is approximately 7 K.

The response of the climate system to anthropogenic forcing includes the potential for 'rapid climate change'. Rapid climate changes with their impacts are investigated in this thesis. The results obtained in this work show that increasing the rate of rapid climate changes can be associated also with nonlinear responses of economic and ecological factors.

Reducing emissions a small percentage below 1990 levels over the next 5 to 25 years could be one way to react and prevent negative impacts from climate change. These negative impacts affect mainly economic and ecologic systems. From the analysis of the results obtained, we can conclude that a great impact on the factors discussed has the decreasing rate of pollution, but in long-term, of much more importance is the year of achieving the pollution reduction.

Keywords: Climate change, climate impacts, integrated assessment, global energy-climate model, rapid climate changes, pollution emission reduction scenarios.

Povzetek

Povprečna temperatura zemeljske površine očitno narašča in podnebje se spreminja (WMO, 2003). Medvladni panel o klimatskih spremembah verjame, da je dovolj dokazov, da se to dogaja zaradi človeške aktivnosti (IPCC 2001). Človek je predvsem odgovoren za izpuste ogljikovega dioksida in drugih toplogrednih plinov ter polutantov, ki spreminjajo sestavo atmosfere in njene lastnosti.

Razvil sem globalni energijsko klimatski model (model GEC) za študij odvisnosti povprečne temperature zemeljske površine od koncentracije ogljikovega dioksida v atmosferi. Model GEC sem zgradil s programom STELLA in povezuje temperaturo z emisijami CO₂ iz premoga, nafte in zemeljskega plina. GEC model sestoji iz treh glavnih sektorjev: Klimatski, raba energije in emisije CO₂. Model napove temperaturo Zemlje in atmosfere v odvisnosti od časa. Povprečna temperatura atmosfere je 255 K = -18 °C in Zemlje 288 K = 15 °C. Opazoval sem povečanje povprečne temperature v odvisnosti od rabe energije, emisij CO₂ in klimatskega sistema z upoštevanjem toplogrednega učinka. Model napove povečanje temperature za okoli 5 K v naslednjih 100 letih.

Odziv klimatskega sistema na človeške dejavnike vključuje potencial za »hitro spremembo klime«. Rezultati v tem delu kažejo, da je povečanje hitrosti klimatskih sprememb povezano tudi z nelinearnimi odzivi gospodarskih in okoljskih dejavnikov.

Zmanjšanje emisij polutantov pod nivo iz leta 1990 v naslednjih 5 do 25 letih bi lahko bil eden od načinov, kako preprečiti negativne učinke klimatskih sprememb. Analiza rezultatov modela je pokazala, da je bistven dejavnik zmanjšanje onesnaževanja, za dolgoročen učinek pa je pomembno, da do zmanjšanja pride čim prej.

Ključne besede: Klimatske spremembe, klimatski učinki, celovita ocena, globalni energijsko klimatski model, hitra sprememba klime, scenariji zmanjšanja onesnaževanja.

Abbreviations

The following abbreviations are used throughout the text:

AGMT	Annual global mean temperature
AOGCM	Coupled atmosphere-ocean general circulation model
BAU	Business-as-usual (case)
CFC	Chlorofluorocarbons
EA	Environmental assessment
GECM	Global energy-climate model
GCM	General circulation model
GHG	Greenhouse gas
GMT	Global mean temperature.
GWP	Global warming potential
IA	Integrated assessment
IAM	Integrated assessment model of climate change
IEA	International Energy Agency or Integrated Environmental Assessment
IERA	Integrated environmental risk assessment
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
LW	Long wave
PER	Pollution emission reduction
RCC	Rapid climate change
SCM	Simple climate model
STM	Systems Dynamics Modeling
SW	Short wave
THC	Thermohaline circulation
UNFCCC	United Nations Framework Convention on Climate Change

1 Introduction

One of a most complicated physical system is Earth's climate. 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. The balance between the incoming energy and the outgoing energy determines the Earth's state. Since 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. There are temporal and spatial changes in temperature that are very important; some are natural, while others may be due to anthropogenic modifications of the climate system. In reality, the Earth's climate is changing and human activities are contributing to this change. Human activity has been increasing the concentration of greenhouse gases in the atmosphere (mostly carbon dioxide from combustion of coal, oil, and gas plus a few other GH gases), thereby contributing to probable global warming.

The climate system has important links with the global carbon cycle and the energy produced; it also depends on the distribution of land masses and mountains and oceans over the surface of the Earth. Thus, a complete model of the climate system would have to include the dynamics of these other systems - the result would be an enormously complex system. Simplified mathematical representations of the Earth's climate system can be carried out by numerical methods. Model-based climate projections are used to produce climate scenarios for investigating the impacts of anthropogenic climate change. These models are particularly useful for sensitivity analyses and in integrated assessment frameworks that require the evaluation of many different emission scenarios. Depending on the information needs of the impact assessment and the availability of pertinent models and data, a variety of methods is used to construct such climate scenarios.

Therefore, research and results carried out in this work could be divided in three major groups:

1. Modeling of the energy-climate system, i.e., construction of the GEC model
2. Analysis of certain factors after the rapid climate changes
3. Analysis of certain factors after the reduction of pollution

Global energy-climate model (GEC model) designed for this thesis uses the program STELLA. In the GEC model, the climate sector is linked with energy consumption sector and CO₂ emission sector. In the climate sector, the Earth's reservoir is linked with atmosphere's reservoir describing thermal energy stored in the atmosphere and the Earth's surface (a combination of land and water). The reservoirs are linked by a number of flows that transfer energy from one reservoir to another as well as to and from outer space. Energy consumption sector in this model will have four reservoirs: energy consumption from petroleum, energy consumption from coal, energy consumption from natural gas and primary energy consumption. World carbon dioxide emissions from the consumption of fossil fuels, in this model, will have just four reservoirs: CO₂ emission from petroleum, CO₂ emission from coal, CO₂ emission from natural gas and CO₂ emission from fossil fuels.

Model designed for this thesis uses the program STELLA. In the climate sector, the Earth's reservoir is linked with atmosphere's reservoir describing thermal energy stored in the atmosphere and the Earth's surface (a combination of land and water). The reservoirs are linked by a number of flows that transfer energy from one reservoir to another as well as to and from outer space. In the global energy-climate model (GEC model), the climate sector is linked with energy consumption sector and CO₂ emission sector.

The logical flow of this model is as follows. Energy consumption leads to carbon emissions. Emissions increase the concentration of CO₂ in the atmosphere, causing temperature to rise. As the global temperature rises, climate changes with implications for the ecological and economic systems. These implications influence the energy consumption.

The response of the climate system to anthropogenic forcing includes the potential for 'rapid climate change'. These terms are used to describe rapid large-scale changes in the climate system in response to gradual changes in its forcing. Rapid climate changes (RCC) with major impacts have occurred repeatedly in the past (Broecker, 1997). It was suggested that abrupt climate change, potentially with large impacts on ecosystems and societies, was possible at any time. Rapid climate changes typically have detrimental effects on ecological and economic systems. Rapid climate changes with their impacts are investigated in

this thesis. The results obtained in this work show that increasing the rate of rapid climate changes can be associated also with nonlinear responses of economic and ecological factors.

One way to react to potential climate change is halting growth in global warming pollution by reducing emissions. Because these reductions must take place in the face of economic growth it is of interest to know how would certain factors respond on in mid-term and long-term pollution emission reduction. By modeling of medium and longer term emission reduction scenarios, we analyse responding of some factors of post-2012, that could establish a foundation for undertaking actions to mitigate climate change, taking into account both their environmental and economic consequences.

2 Physics of Climate and Climate Change Problem

2.1 Radiation Laws

Earth's climate is governed by a combination of the laws of fluid dynamics, thermodynamics, radiative and energy transfer. The climate system is composed of five major components of the Earth: the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere. Each of these subsystems is coupled to each of the other four, through the exchange of immense quantities of energy, momentum and matter (Peixoto & Oort 1984). The Earth's atmosphere has an important influence on the energy budget of the global climate system. This is determined by the thermodynamic processes involved in solar and terrestrial energy transfers.

The Earth's principal source of energy is the sun, which produces electromagnetic radiation from nuclear fusion reactions involving hydrogen in its core. The sun's surface has a temperature of approximately 5800 K. The solar radiation is emitted over a spectrum of wavelengths, with a specific quantity of energy for each wavelength, calculated using Planck's law formula. An object that absorbs all radiation incident on it is called a blackbody. Maximum radiation at a given temperature is called blackbody radiation.

2.1.1 Planck's Law

Planck's law describes the radiation of a blackbody as a function of temperature and frequency:

$$E(\lambda, T) = \frac{8\pi c}{\lambda^5} \left[\frac{1}{e^{hc/2\pi\lambda kT} - 1} \right] \quad (1)$$

where $E(\lambda, T)$ is the amount of energy emitted at wavelength λ by a body at temperature T , speed of light $c = 3 \cdot 10^8$ ms⁻¹, Boltzmann's constant $k = 1.37 \cdot 10^{-23}$ JK⁻¹ and Planck's constant $h = 6.624 \cdot 10^{-34}$ Js. From this law it follows that all substances radiate unless their temperature is at absolute zero (0 K). Gases radiate at specific frequencies, while solids radiate at many frequencies, producing a continuous spectrum.

2.1.2 Stefan-Boltzmann law

Stefan-Boltzmann law is the integral of the Planck function (1) over all frequencies. This law relates the temperature of a surface to the amount of heat that it radiates:

$$B(T) = \int B_\nu(T) D\nu = \sigma T^4 \quad (2)$$

The Stefan-Boltzmann constant, $\sigma = 5.67 \cdot 10^{-8}$ Js⁻¹m⁻²K⁻⁴. Thus the amount of energy emitted increases with temperature.

2.1.3 Wien's Law

Wien's law relates the wavelength of maximum radiant emission to the temperature of the body (Fig.1). When:

$$\frac{dB}{d\lambda} = 0$$

$$\lambda_{\max} T = z \quad \text{where } z = 2.898 \cdot 10^{-3} \text{ mK.} \quad (3)$$

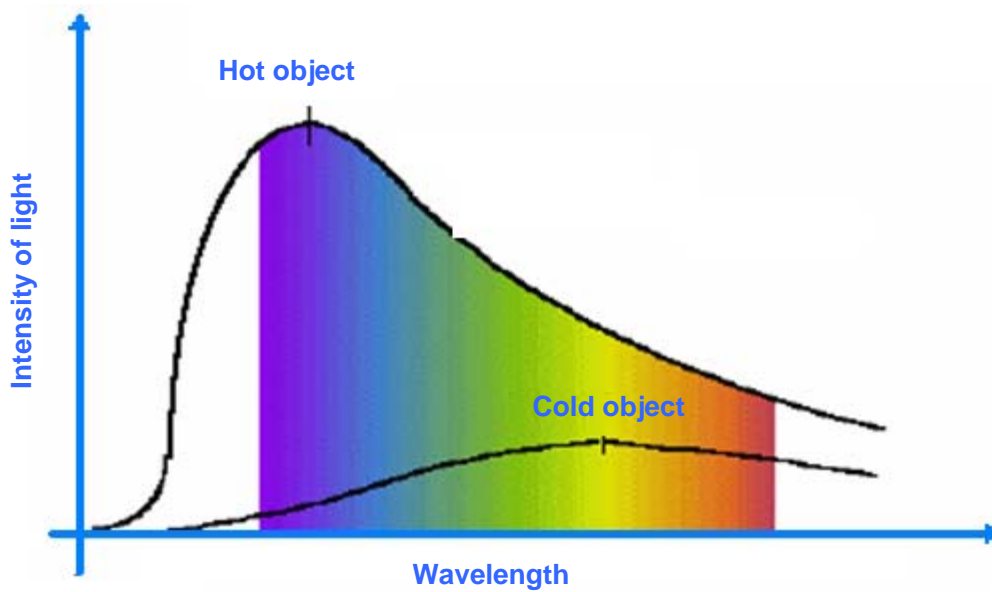


Figure 1: Wavelength of maximum radiant emission for a body to the temperature

It is possible to determine the wavelength of maximum radiation emission from the Sun. For $T = 5800$ K (the solar surface temperature) the wavelength of maximum energy is approximately $0.5 \mu\text{m}$. This represents radiation in the visible part of the spectrum, (for Earth is $11.4 \mu\text{m}$).

Emission of a substance is given by:

$$E_{\nu} = \varepsilon_{\nu} B_{\nu}(T) \quad (4)$$

where ε_{ν} - emissivity is a dimensionless number and ranges from 0 to 1; a perfect black body has an emissivity of 1 at all frequencies; grey bodies have a constant ε_{ν} but less than 1 at all frequencies while very shiny objects have an emissivity of close to 0.

2.1.4 Kirchhoff's Law

The previous laws deal essentially with the intensity emitted by a black body. However, in general, a medium will not only absorb but also reflect part of the incident radiation and transmit the remainder. Thus, in terms of the ratios of the absorbed, reflected, and transmitted radiation with respect to the monochromatic intensity of the radiation E_{λ} incident upon a layer, we may write

$$a_{\lambda} + r_{\lambda} + \tau_{\lambda} = 1 \quad (5)$$

These quantities are the coefficients of absorption, reflection (or albedo) and transmission at wavelength λ , respectively.

2.2 Solar Radiation

Radiation from the sun (photosphere) is essentially continuous – similar to a blackbody at ~ 5800 K. Most of the radiation from the sun (99%) is between the wavelengths of $0.15 \mu\text{m}$ and $4 \mu\text{m}$, and is called - shortwave radiation. Of this 9% is in the ultraviolet ($\lambda < 0.4 \mu\text{m}$), 45% is in the visible ($0.4\text{-}0.74 \mu\text{m}$), and 46% in the infrared ($\lambda > 0.74 \mu\text{m}$).

The solar radiation disperses uniformly in all directions. The flux of solar radiation received on a surface, held normal to the sun's direction, at the mean distance between the sun and the Earth is known as the solar constant (S_0).

The solar constant is the amount of incoming solar electromagnetic radiation per unit area, measured on the outer surface of Earth's atmosphere, in a plane perpendicular to the rays. The solar constant includes all types of solar radiation, not just the visible light. It is measured by satellite to be roughly $S_0 = 1366 \text{ Wm}^{-2}$ though it fluctuates by about 6.9% during a year - from $S_0 = 1412 \text{ W/m}^2$ in early January to $S_0 = 1321 \text{ Wm}^{-2}$ in early July, due to the Earth's varying distance from the sun, and by a few parts per thousand from day to day. Thus, for the whole Earth, with a cross section of $127.4 \cdot 10^6 \text{ km}^2$, the power is $1.740 \cdot 10^{17} \text{ W}$ (174 PW) plus or minus 3.5%.

The Earth receives a total amount of radiation determined by its cross section (πr^2), but as the planet rotates this energy is distributed across the entire surface area ($4 \pi r^2$). Hence, the average incoming solar radiation (called sometimes the solar irradiance), taking into account the half of the planet not receiving any solar radiation at all, is one fourth the solar constant or $\sim 342 \text{ W/m}^2$. At any given location and time, the amount received at the surface depends on the state of the atmosphere and the latitude.

Figure 2 is a combination of two graphs about electromagnetic radiation. The ideal solution from Planck's law (1) of the spectrum of energy arriving at the top of the Earth's atmosphere is shown in Figure 2a. The high point of the curve represents the wavelength of greatest energy flux ($0.5 \mu\text{m}$), as calculated by Wien's law (2). The wavelength at which it emits its maximum radiation is centered in the visible light portion of the spectrum. The area under the curve represents the total amount of energy received (1368 Wm^{-2} , calculated by the Stefan-Boltzmann law (3)). 8% of the energy flux is in the ultraviolet part of the spectrum, whilst 39% is visible radiation. Equations (1), (2) and (3) can be solved again for the Earth at a temperature of 255 K (-18°C), assuming the Earth to be a perfectly radiating (black) body, and Planck's law dictates that its wavelength of maximum radiation emission is in the invisible infrared part of the spectrum, centered at about $1 \mu\text{m}$. The stratosphere is partially cooler than earth's surface, and its Planck emission spectrum is shifted to slightly longer wavelengths.

In the Figure 2b, the absorption spectrum of earth's atmosphere is shown on the same wavelength scale as the Planck radiant emission graph. In Figure 2b, we also show, at each wavelength, the fraction of the light absorbed from the beam passing directly through the Earth's atmosphere. We can conclude that the atmosphere is moderately transparent to the visible so that much of the solar radiation can pass through the atmosphere without being absorbed. On the other hand, minor atmospheric constituents, of which the water vapor is the most important, absorb strongly in the infrared so the atmosphere is largely opaque to the planetary heat radiation.

Solar insolation received by the Earth drives climate. Changes in the amount of insolation as a function of time and location, and changes in the way insolation is changed into heat energy, all lead to climatic changes.

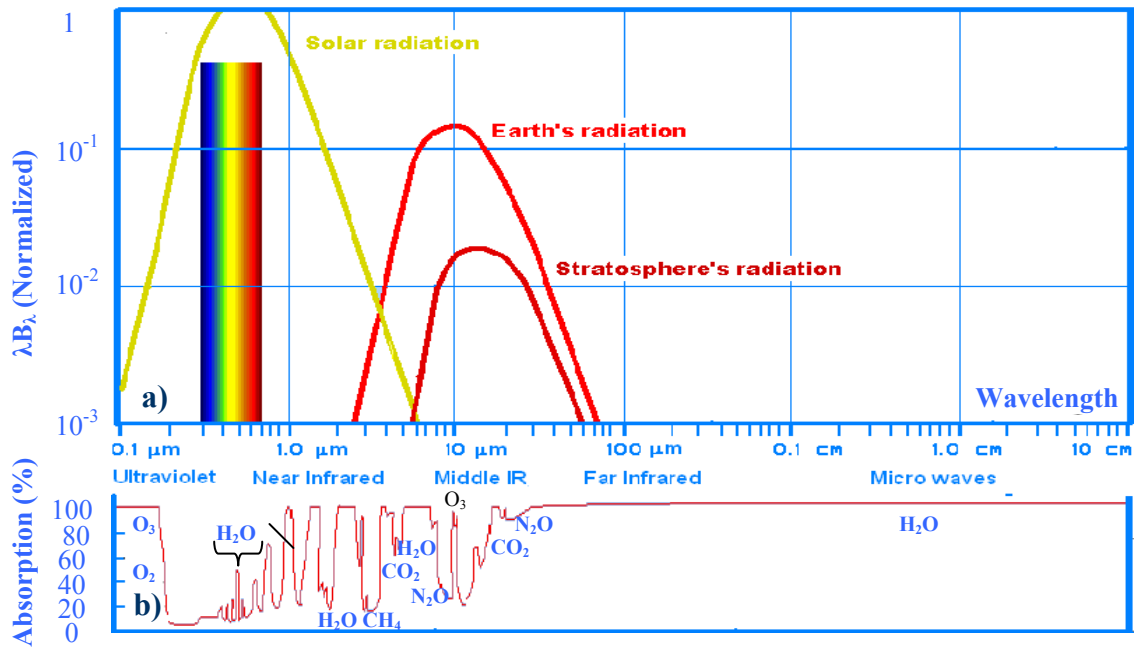


Figure 2: (a) The normalized blackbody emission spectra, Planck curves that show the proportional of energy radiated of each wavelength by the Earth (long-wave heat radiation) and the solar radiation incident on the Earth (short-wave solar radiation), (b) The fraction of radiation absorbed while passing from the ground to the top of the atmosphere as a function of wavelength

2.3 The Climate System

The climate system is the complex system comprised of five major components of the Earth: the atmosphere, the hydrosphere, the cryosphere (ice sheets), the land surface and the biosphere which are intimately interconnected. These interrelated and open sub-systems are linked through the fluxes of mass, energy, and momentum at different spatiotemporal scales.

The climate is defined as the mean physical state of the climatic system: the ensemble of all possible weather states, together with their frequencies. Therefore, the climate is determined by a set of time-averages of quantities that describe the structure and the behavior of the various parts of the climatic system, as well as by the correlations among them (Peixoto and Oort, 1992). A complete description of the climate system and the understanding of its characteristics and change require the study of the atmosphere, oceans, and land surface, and the measurements and study of physical, dynamical, chemical, and biological interactions. Climate is usually defined narrowly as the statistical description of weather in terms of the mean and variability of relevant quantities in a region over a certain period of time.

Weather, in turn, is the fluctuating state of the atmosphere, characterized by variables such as temperature, precipitation, cloud cover, and wind. The classical climate period, as defined by the World Meteorological Organization (WMO), is 30 years. However, longer periods are necessary to identify some important climate features such as the distribution of 'extreme' weather events.

Atmospheric climate is determined from its interactions with the large-scale ocean currents and the land with its features such as albedo, vegetation, and soil moisture.

Terrestrial climate varies spatially, depending on latitude, altitude, distance to the sea, land cover and other geographic features. A wider definition of climate thus refers to the state of the climate system as a whole not just near-surface atmospheric conditions.

The climate system evolves in time under the influence of its own internal dynamics and because of external forcings. These forcings may have natural causes - such as the Earth's changing position relative to the sun, the changing energy output of the sun, the variable amount of volcanic material in the atmosphere or anthropogenic causes - such as changing atmospheric composition and land-use change.

Any change in the components of the climate system or its interactions, or in the external forcing, may result in climate variations. This thesis is explicitly concerned with - anthropogenic climate change, which is defined as a statistically meaningful variation in either the mean state of the climate or its variability, persisting for an extended period of time, which is caused by anthropogenic influences on the climate system.

2.3.1 Global Earth-Atmosphere Energy Balance

For equilibrium, where the average temperature of the Earth neither rose nor fell the energy radiated from the sun to the Earth must, on average, equal the radiation energy the earth radiates back out to space. If at the location of the (mean) Earth orbit, the incoming solar energy flux is $S_0 = 1367 \text{ Wm}^{-2}$, then, given that the cross-sectional area of the Earth intercepting the solar energy flux is πr^2 where r is the radius of the Earth,

$$K = S_0 \pi r^2 = 1.74 \cdot 10^{17} \text{ W} \quad (6)$$

where K – solar power incident on Earth surface. Not all of this radiation is absorbed by the Earth; a significant fraction is reflected. The ratio of reflected to incident solar energy is called the albedo, Albedo depends on the nature of the reflecting surface and is large for clouds, light surfaces such as deserts and (especially) snow and ice. Under the present terrestrial conditions of cloudiness and snow and ice cover, on average a fraction $A \approx 0.30$ of the incoming solar radiation at the Earth is reflected back to space. Thus, solar radiation absorbed by Earth:

$$R_{inc} = (1 - A) S_0 \pi r^2 = 1.22 \cdot 10^{17} \text{ W} \quad (7)$$

In equilibrium, the total terrestrial flux radiated to space must balance the solar radiation absorbed by the Earth. If, in total, the spinning Earth radiates in all directions like a blackbody of uniform temperature T_e (known as the ‘emission temperature’ of the Earth) the Stefan-Boltzmann law gives:

$$F = \sigma T_e^4 \quad (8)$$

where F – emitted radiation per unit area and $\sigma = 5.67 \cdot 10^{-8} \text{ Wm}^{-2} \text{ K}^{-4}$ is the Stefan-Boltzmann constant, T_e – it is the temperature one would infer by looking back at Earth if a black body curve were fitted to the measured spectrum of outgoing radiation. So emitted terrestrial radiation:

$$R_{out} = 4\pi r^2 \sigma T_e^4 \quad (9)$$

Equating Eq.(7) with Eq.(9) gives:

$$\sigma T_e^4 4\pi r^2 = S_0 (1 - A) \pi r^2 \quad (10)$$

$$T_e = \left[\frac{S_0 (1 - A)}{4\sigma} \right]^{\frac{1}{4}} \quad (11)$$

Putting in numbers we find that the Earth has an emission temperature of $T_e = 255 \text{ K} = -18 \text{ }^\circ\text{C}$. Measured Earth's temperature (T_e) is actually 288 K. The difference is due to the natural greenhouse effect.

Whilst the single most important factor determining the global climate is the level of solar irradiance, the radiative properties of the atmosphere and the surface are also influential. The Earth's atmosphere contains a range of molecules that absorb light at many different wavelengths. Most of the ultraviolet in sunlight is absorbed by oxygen (O_2) and ozone (O_3) before it reaches the Earth's surface. In particular, a number of trace gases in the atmosphere, such as water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) affects the radiative balance by absorbing and emitting infrared radiation. In the remainder of this text, we use the term (well-mixed) greenhouse gases (GHGs) to denote all these gases with the exception of water vapor.

Greenhouse gases absorb thermal infrared radiation emitted by the Earth's surface and atmosphere. The atmosphere is warmed by this mechanism and, in turn, emits infrared radiation, with a significant portion of this energy acting to warm the surface and the lower atmosphere. As a consequence the average surface air temperature of the Earth is about 30°C higher than it would be without atmospheric absorption and re-radiation of infrared energy [Kellogg, 1996; Peixoto and Oort, 1992].

To calculate a corrected value we will consider a simple model in which the atmosphere is modeled by a shallow layer of uniform temperature T_a . The atmosphere is assumed to transmit a fraction τ_s of any incident solar (short-wave) radiation and a fraction τ_i of any incident thermal (infra-red or long-wave) radiation and to absorb the reminders. We assume that the Earth is at the temperature T_e . Taking account of albedo effects, the mean unreflected incoming solar flux at the top of the atmosphere is F_0 . Of this, a

proportion $\tau_s F_0$ reaches the ground, the remainder being absorbed by the atmosphere. The Earth is assumed to emit as a black body, and it therefore emits upwards the flux F_e , of which a proportion $\tau_l F_e$ reaches the top of the atmosphere. The atmosphere is not a black body, so that its emissivity (the ratio of the actual emitted flux to the flux that would be emitted by a black body at the same temperature), according to Kirchoff's law (5), equals to its absorptivity $1 - \tau_l$.

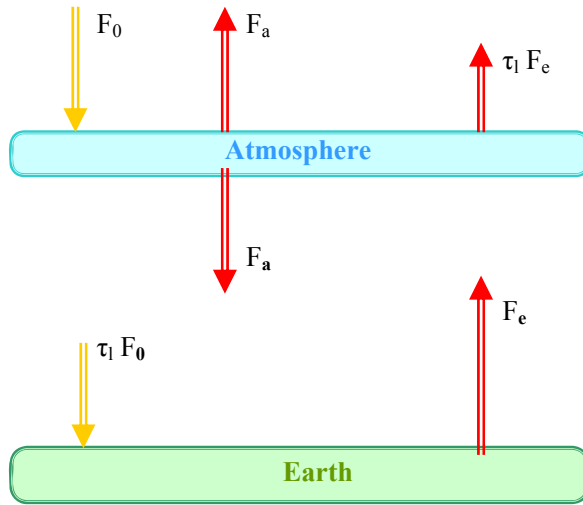


Figure 3: A simple model of greenhouse effect. Various solar and thermal fluxes are shown.

Therefore the atmosphere emits fluxes

$$F_a = 4\pi r^2 (1 - \tau_l) \sigma T_a^4$$

both upwards and downwards, as shown in Figure 3. We can now balance these fluxes assuming that the system is in equilibrium. At the top of the atmosphere we have

$$F_0 = F_a + \tau_l F_e \quad (12)$$

and at the ground

$$F_e = F_a + \tau_s F_0 \quad (13)$$

By eliminating F_a from equations (12) and (13), we obtain

$$F_e = 4\pi r^2 \sigma T_e^4 = F_0 \frac{1 + \tau_s}{1 + \tau_l}$$

In the absence of an absorbing atmosphere, we would have $\tau_s = \tau_l = 1$ so F_e would equal F_0 giving $T_e = 255$ K as in Eq. (11).

Absorptivity:

$$a = 1 - \tau$$

However, Rough values for the Earth's atmosphere are $\tau_s = 0.9$ (strong transmission and weak absorption of solar radiation) and $\tau_l = 0.2$ (weak transmission and strong absorption of thermal radiation), so that $F_e = 1.6 F_0$ leading to a surface temperature of

$$T_e \approx 286 \text{ K}$$

which is quite close to the observed mean value of 288 K.

This is a simple example of the greenhouse effect: the greater temperature depends on the fact that there is less absorption (greater transmission) for solar radiation than there is for thermal radiation. Thus, the atmosphere readily transmits solar radiation but tends to trap thermal radiation.

We can also find the atmospheric flux and the corresponding temperature from equation (12) and (13)

$$F_a = 4\pi r^2(1 - \tau_l) T_a^4 = F_0 \frac{1 - \tau_s \tau_l}{1 + \tau_l}$$

and this gives the temperature of the shallow atmosphere in the model $T_a \approx 245$ K.

These energy flows balance to maintain the temperature of the Earth's surface, the atmosphere, and the whole combination. This is the explanation why the temperature of the Earth has been moderately constant, but with variations such as ice ages, over millions of years.

2.3.2 Feedback processes in the climate system

Feedback concept in the climate system has the meaning that a perturbation of the climate system is either amplified or diminished by a feedback processes, such as: feedbacks on surface temperature, water vapor feedback, ice-snow albedo feedback, and many different cloud feedbacks, In particular, in observations of the variations of the real climate, many feedback processes act simultaneously so that their intrinsic magnitude cannot be estimated. The feedback mechanisms act as internal controls of the system and result from a special coupling or mutual adjustment among two or more subsystems. Part of the output returned to serve as an input again so that the net response of the system is altered; the feedback mechanisms may act either to amplify the final output (positive feedback) or to diminish it (negative feedback). There are a large number of such mechanisms operating within the various components of the climatic system or between the subsystems.

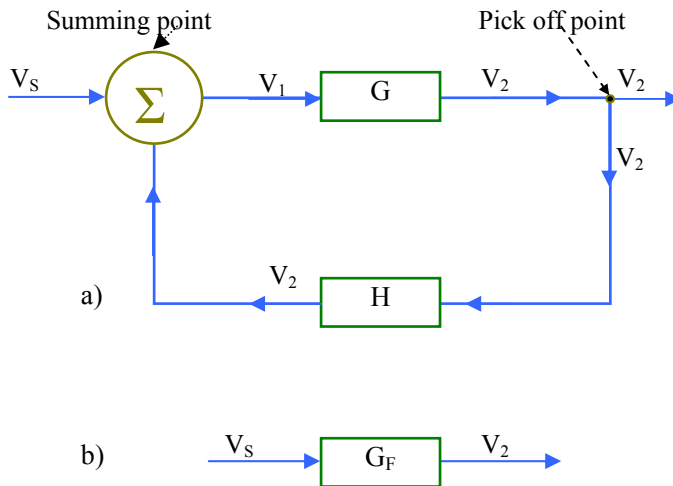


Figure 4: Feedback mechanism. At the output of the gain function G the signal V_2 is picked up and reintroduced into G by means of H .

A single feedback loop may be presented as in Figure 4a as a system in which the output is partially fed back to the input. A signal V_S entering the loop receives an extra input V_F which leads to:

$$V_1 = V_S + V_F \quad (14)$$

reinforced by the gain function (or transfer function) G as

$$V_2 = G V_1 \quad (15)$$

The signal is picked up by H and produces:

$$V_F = H V_2 \quad (16)$$

which was introduced in (14). All taken together, we have

$$V_2 = GV_1 = G(V_S + V_F) = G(V_S + HV_2) = GV_S + GHV_2 \quad (17)$$

or:

$$V_2 = \frac{G}{1-GH} V_S \quad (18)$$

which allows us to find an effective gain, which includes the feedback (see Figure 4b), so that

$$G_F = \frac{G}{1-GH} = \frac{G}{1-f} \quad (19)$$

where $f = GH$ is the feedback of the system

$$V_2 = \frac{G}{1-GH} V_S = G_F V_S = \frac{G}{1-f} V_S \quad (20)$$

In the case of zero feedback, $f = 0$ and $G_F = G$. For a negative feedback, $f < 0$ and $0 \leq G_F \leq G$. As f becomes larger and larger negative, G_F tends asymptotically to zero. For positive feedbacks with $0 \leq f \leq 1$, we find $G_F > G$.

When there are more loops, independent of each other, characterized by H , one could write:

$$V_F = \sum_i H_i V_2 \quad (21)$$

and obtain:

$$V_2 = \frac{G}{1 - \sum_i H_i G} V_S = \frac{G}{1 - \sum_i f_i}$$

To apply the previous concepts to the climate system let us take the simplest possible atmospheric model. The net radiation (solar minus terrestrial) flux F_{TA} at the top of the atmosphere will vanish under equilibrium conditions. Any external perturbations due, e.g. to changes in atmospheric carbon dioxide, water vapor, solar output, volcanic eruptions, etc, will induce an imbalance in the net radiation at the top of the atmosphere ΔF_{TA} . Assume, for example, a sudden doubling of effective CO_2 concentration. This would lead to an effective reduction in the Earth's long-wave radiation at the top of the atmosphere with a magnitude τ_1 and consequently would cause a decrease in the flux $\Delta F_{TA} = \Delta I$. The energy balance at the top of the atmosphere requires a constant (zero) flux F_{TA} . Therefore the Earth's surface temperature should rise by ΔT_{SFC} to compensate (this effect is called thermal forcing). Thus we will regard ΔF_{TA} as the signal input V_S for the climate system and ΔT_{SFC} as the output V_2 . We can then write

$$\Delta T_{SFC} = G_F \Delta F_{TA}$$

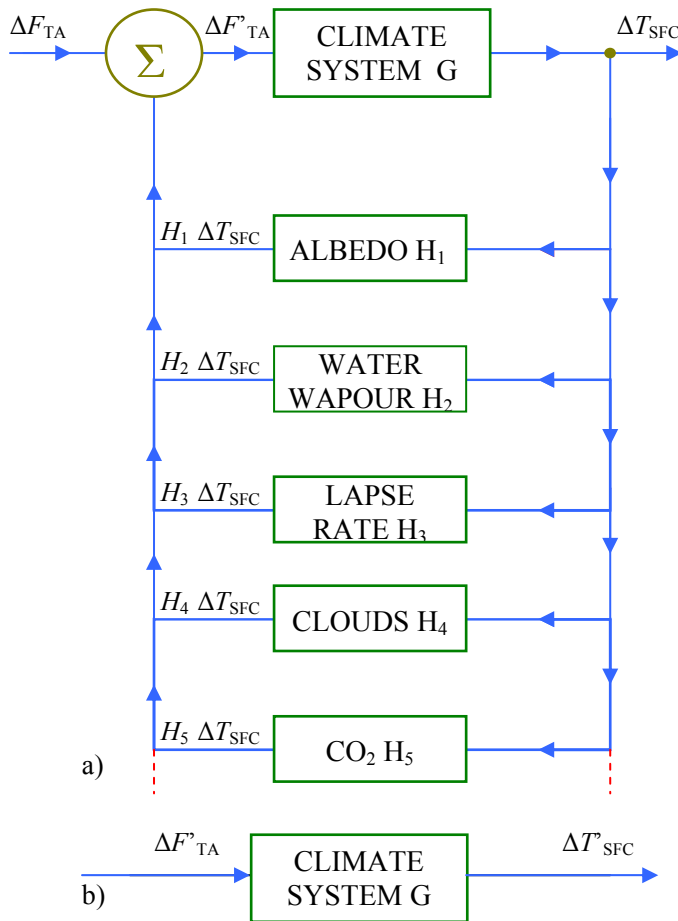


Figure 5: A set of possible feedback loops in the climate system. The symbols: F_{TA} , G , H_1 , H_2 , G_F represent the net radiation at the top of the atmosphere, the gain, feedback factors, and effective gain of the climate system respectively.

where G_F is the transfer function, so that the concepts outlined in the previous section can be applied to the climatic system. In the Figure 5, an example of the set of positive feedback loops in the climate system is presented. It should be noted that, clouds can lead to many different feedback processes since they are both excellent absorbers of thermal radiation (positive feedback) and effective reflectors of solar radiation (negative feedback).

Earlier we discussed that the increase of greenhouse gases in the atmosphere would lead to a warming of the surface of the Earth. There are however feedbacks reinforcing or mitigating the effect.

Effects reinforcing global warming:

- Melting of ice and snow due to an increase of surface temperature will lower the albedo A which will result in a further increase of the surface temperature T_e .
- More water vapor appearing in the air due to the enhanced evaporation processes will lead to smaller transmission τ_1 for the thermal radiation which will further increase the surface temperature.
- More CO_2 leads to an increased growth of plants which lowers the albedo.
- A higher sea water temperature gives less CO_2 absorption in sea water which will cause further increase in CO_2 .

Effects mitigating global warming:

- Increasing long-wave radiation from the atmosphere to space due to an increase of the atmospheric temperature will generally result in losing the energy by the atmosphere and thus reducing the temperature.
- Decreasing the so-called adiabatic lapse rate for humid air

The reinforcing and mitigating effects ascribed above may be described as a series of feedback mechanisms.

2.4 Energy for Human Use

Nonrenewable Energy - The most commonly used fossil fuels are petroleum, coal, and natural gas which are a nonrenewable source of energy. *Fossil fuels* are energy-rich substances that have formed from long-buried plants and microorganisms. Fossil fuels provide most of the energy that powers modern industrial society. Over 85% of our energy demands are met by the combustion of fossil fuels.

The fuels are burned to release the chemical energy that is stored within this resource. Chemically, fossil fuels consist largely of hydrocarbons, which are compounds composed of hydrogen and carbon. Some fossil fuels also contain smaller amounts of other compounds. Hydrocarbons form from ancient living organisms that were buried under layers of sediment millions of years ago. As accumulating sediment layers exerted increasing heat and pressure, the remains of the organisms gradually transformed into hydrocarbons. Fossil fuels are extracted from the earth's crust and, if necessary, refined into suitable fuel products, such as gasoline, heating oil, and kerosene.

The majority of fossil fuels are used in the transportation, manufacturing, residential heating, and electric-power generation industries. Crude petroleum is refined into gasoline, diesel fuel, and jet fuel, which power the world's transportation system. Coal is the fuel most commonly burned to generate electric power, and natural gas is used primarily in commercial and residential buildings for heating water and air, for air conditioning, and as fuel for stoves and other heating appliances.

Renewable Energy - Alternative energy sources, such as hydroelectric energy, solar energy, wind energy and geothermal energy are a renewable source of energy. These energy sources plus nuclear energy currently only account for a combined 14% of energy consumed worldwide. To date, alternative energy sources have been hindered by technological and environmental difficulties. For instance, the risk of nuclear accidents and the difficulty associated with safe disposal of radioactive waste have led to the decline of the nuclear power industry. Solar and wind power seem environmentally safe, but they are unreliable as steady sources of energy. As global energy consumption grows each year, development of certain alternative energy sources becomes increasingly important.

2.4.1 Formation of Fossil Fuels

Fossil fuels formed from plants and animals that lived up to 300 million years ago were buried under layers of accumulating sediment. As additional sediment layers built up over these organic deposits, the material was subjected to increasing temperatures and pressures. These physical conditions, and possibly other unknown factors, over millions of years, chemically transformed the organic material into hydrocarbons: chains of carbon and hydrogen ranging from simple configuration to complex compounds. Another affect of extreme pressure is that the oil and gas which are various mixtures of hydrocarbons, migrate upwards to the surface. Another affect of extreme pressure is that the oil and gas which are various mixtures of hydrocarbons, migrate upwards to the surface.

Petroleum Formation - Petroleum formed chiefly from ancient, microscopic plants and bacteria that lived in the ocean and saltwater seas. When these microorganisms died and settled to the seafloor, they mixed with sand and silt to form organic-rich mud. As layers of sediment accumulated over this organic ooze, the mud was gradually heated and slowly compressed into shale or mudstone, chemically transforming the organic material into petroleum and natural gas.

Natural Gas Formation - Most natural gas is formed from plankton—tiny water-dwelling organisms, including algae and protozoons—that accumulated on the ocean floor as they died. These organisms were slowly buried and compressed under layers of sediment. Over millions of years, the pressure and heat generated by overlying sediments converted this organic material into natural gas. Natural gas is composed primarily of methane and other light hydrocarbons. Natural gas is also found in independent deposits within the ground. Methane is a common gas found in swamps and is also the byproduct of animals' digestive system.

Oil and gas are found in the ground, not freely drifting up through the earth. This is because the hydrocarbons come across rock formations that they are unable to penetrate. Complex rock structures that effectively trap gas and oil are formed by tectonic plate activity.

Coal Formation - Coal is a solid fossil fuel formed from ancient plants—including trees, ferns, and mosses—that grew in swamps and bogs or along coastal shorelines. Coal is made of decomposed plant matter in conditions of high temperature and pressure, though it takes a relatively shorter amount of time to form. The successive stages of coal formation are peat, lignite, sub bituminous coal, bituminous coal, and anthracite.

2.4.2 Consumption of Fossil Fuels

Once fossil fuel has been extracted and processed, it can be burned. Fossil fuels are primarily burned to produce energy. This energy is used to power automobiles, trucks, airplanes, trains, and ships around the world; to fuel industrial manufacturing processes or it can be combusted for the generation of electrical power.

Combustion is the process of breaking atomic bonds to release energy in the form of light and heat. Fossil fuels have many hydrocarbons, each with numerous bonds. When they undergo combustion, they release a great deal of heat. This is the main reason why natural gas and heating oils are used extensively in the world today

Most of the world’s electric power is generated from combustion of fossil fuels. In 2003 fossil fuel-fired power plants produced 65% of the world’s electrical power, down from 71% in the late 1970s. In 2003 the world’s remaining electricity supply was generated primarily by hydroelectric power (17%) and nuclear fission (16%), with solar, geothermal, and other sources accounting for a relatively small amount.

To provide fuel for transportation, petroleum is refined into gasoline, diesel fuel, jet fuel, and other derivatives used in most of the world’s automobiles, trucks, trains, aircraft, and ships. Demand for natural gas, historically considered a waste by-product of petroleum and coal mining, and is growing in business and industry because it is a cleaner-burning fuel than petroleum or coal.

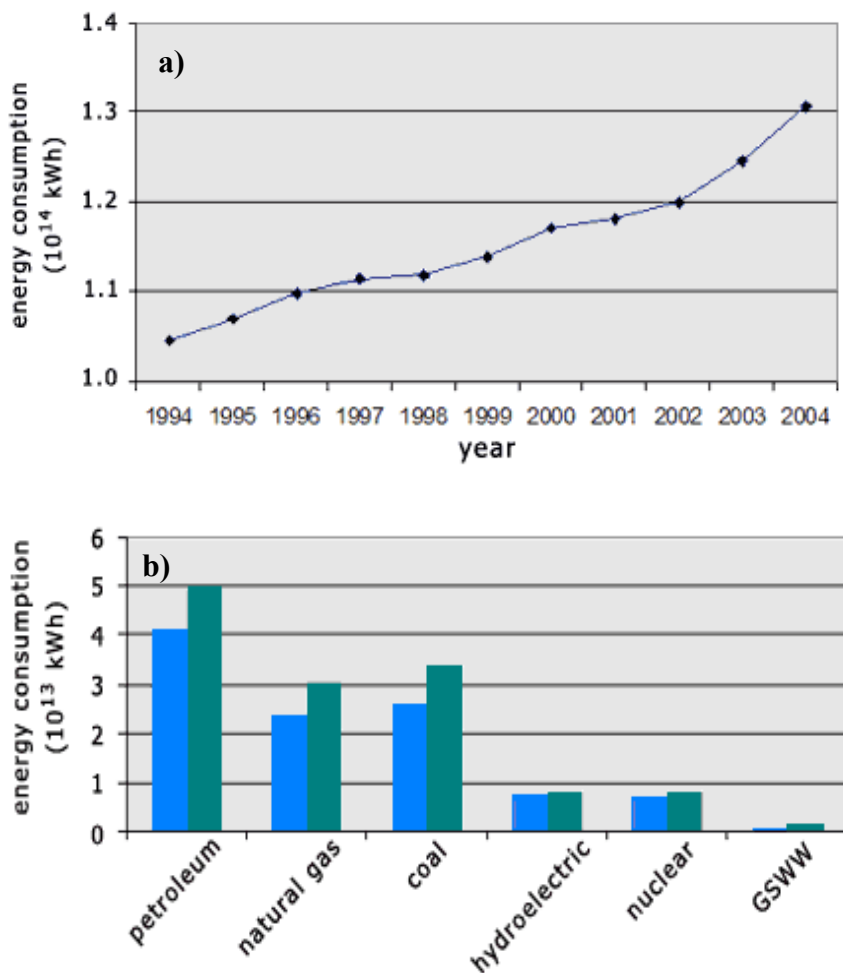


Figure 6: a) Total annual primary energy consumption and b) World consumption of primary energy by fuel type between 1994 (■) and 2004 (■) Key: GSWW: geothermal, solar, wind and wood/waste

2.4.3 World Fossil Fuel Supply

Because the global economy is powered by fossil fuels, it is critical to know how long world reserves will last. However, estimating the world's remaining fossil fuel reserves requires extensive information, including comprehensive geological maps of the world's sedimentary basins, models of energy consumption systems, and data showing world energy consumption patterns and trends. When estimating the world's fossil fuel supply, experts distinguish between reserves and resources. Reserves are proven fossil fuel deposits which are immediately available that can sold economically at today's prices. Resources are total amount fossil fuel deposits that geologists believe are located in certain sedimentary basins, but have not yet been discovered - and irrespective of whether the costs of extraction would make it uneconomic to exploit at today's prices. Both reserve and resource estimates are revised as data about new and existing deposits become available.

Worldwide deposits of fossil fuels are finite. Some experts use data on world energy deposits to estimate how many years world energy supplies will last at current and projected consumption rates.

The coal reserve is the largest. Known sources of coal could last 200-300 years more at today's rate of consumption. The global oil reserve will be exhausted within 40 years from the present. If a reasonable allowance is made for those resources not yet discovered, then oil might last another 60 years. There is some expectation that oil from sandy tars might provide an additional leeway (perhaps doubling the timescale). Natural gas reserves will also be exhausted in about 60 years

At the beginning of the 21st century, the world reserves of petroleum were estimated to be roughly $4.28 \cdot 10^{21}$ J (see table.1). By 2005, worldwide consumption of petroleum totaled 169.277 Quadrillion (10^{15}) Btu a year. The world's natural gas reserves were estimated to be roughly $3.67 \cdot 10^{21}$ J. Worldwide consumption of natural gas by 2005 totaled 105.331 Quad Btu/year. At the beginning of the 21st century the world coal reserves were estimated to be roughly $2.34 \cdot 10^{22}$ J, and by 2005 worldwide consumption of coal totaled 122.2 Quad Btu/year. Total worldwide energy consumption is expected to grow at about 2.2 percent per year until 2015.

Theoretical models can be developed to estimate how many years the world fossil fuel supply will last. However, these models are complicated by technological advances in the energy production industry, unexpected discoveries of new fossil fuel deposits, and political, social, and economic factors that influence energy production and consumption.

Because fossil fuels are being consumed at much faster rates than they are produced in the earth's crust, humankind will eventually deplete these nonrenewable resources. While it is unclear how far in the future this will happen, there is evidence that some regions are becoming depleted in certain types of fossil fuels.

Table 1. Energy potential of the world's fossil fuels

Reserves			
	Reliance	Conventional units	Joules
Oil	44%	$6.99 \cdot 10^{11}$ bbls	$4.28 \cdot 10^{21}$
Natural gas	29%	$3.40 \cdot 10^{15}$ ft ³	$3.67 \cdot 10^{21}$
Coal	27%	$9.87 \cdot 10^{11}$ tons	$2.34 \cdot 10^{22}$
Total			$3.14 \cdot 10^{22}$
Resources			
Oil		$1.42 \cdot 10^{12}$ bbls	$8.69 \cdot 10^{21}$
Natural gas		$1.60 \cdot 10^{16}$ ft ³	$1.73 \cdot 10^{22}$
Coal		$7.80 \cdot 10^{12}$ tons	$1.85 \cdot 10^{23}$
Total			$2.11 \cdot 10^{23}$

2.4.4 Environmental Effects of using Fossil Fuels

Fossil fuels (coal, oil, and natural gas) when burned emit greenhouse gases (GHG) and also other types of air pollution harmful to the environment. The principal greenhouse gases are: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons CFC-11 (CCl_3F) and CFC-12 (CCl_2F_2). Greenhouse gases absorb solar heat radiated from the Earth's surface and retain this heat, keeping the Earth warm and habitable for living organisms. Rapid industrialization through the 19th and 20th centuries, however, has resulted in increasing fossil fuel emissions, raising the percentage of GHG's in the atmosphere (Figures 7 and 8). Growth rates of GHG forcing (Figure 7), for specific time intervals are indicated, showing a particularly strong rate in 1850-1910 and 1955-1970. This increase in GHG's has led some scientists to predict a climate change scenario that could cause numerous environmental problems. Global climate change and acid rain are two of the most serious environmental issues related to large-scale fossil fuel combustion.

The contribution of non- CO_2 gases to total emissions can be estimated by expressing the emissions of all the gases in CO_2 -equivalent units. For a given gas, emissions expressed in mass are multiplied by its specific weighting factor, the Global Warming Potential (GWP), an estimate of the relative contribution of a kilogram of that gas to global radiative forcing, as compared to the same amount of CO_2 , integrated over a fixed period of time (e.g. 100 years). The UN Framework Convention on Climate Change (UNFCCC), following the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), uses the 100-year GWPs of 21 for CH_4 , 310 for N_2O and 23 900 for SF_6 . For the most common hydro fluorocarbons (HFC), GWPs vary between 140 and 3 000. The GWPs for perfluorocarbons (PFCs) vary between 6 500 (CF_4) to 9 200 (C_2F_6). These two PFCs, the ones most commonly used, are also significant sources of by-product emissions.

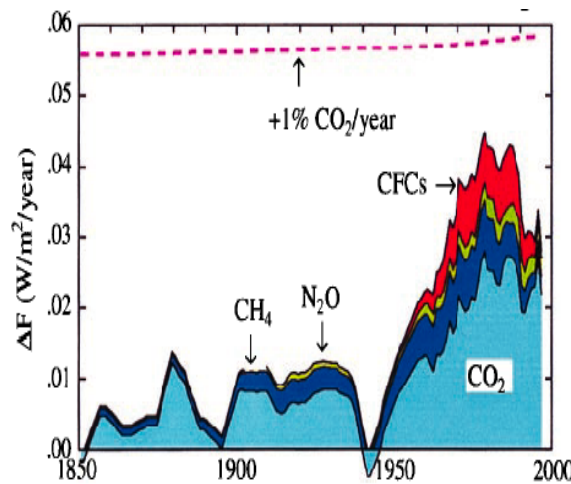


Figure 7: Fossil fuel CO_2 emissions. Mean annual growth rates are shown for four periods.

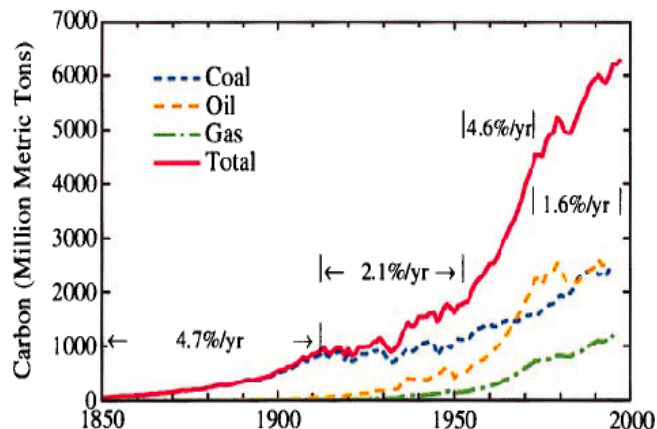


Figure 8: Growth rate of greenhouse climate forcing. Dashed line is forcing due to 1% CO_2 .

2.5 Anthropogenic influence on the climate system

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. The increase in GHG accumulation was fastest in the last decades. Through these activities humankind has significantly modified the composition of the Earth's atmosphere. Therefore, greenhouse gases are accumulating in Earth's atmosphere as a result of human activities, causing surface air temperatures and sub-surface ocean temperatures to rise. Temperatures are, in fact, rising. The changes observed over the last several decades are likely mostly due to human activities, but we cannot rule out that some significant part of these changes is also a reflection of natural variability.

Climate change may be due to natural external forces, such as changes in solar emissions or slow changes in the earth's orbital elements; natural internal processes of the climate system; or anthropogenic forces. The UNFCCC defines anthropogenic climate change as: "Climate change means a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere, and which is, in addition to natural climate variability, observed over comparable time periods". In general, climate change means all forms of climatic inconsistencies, over a longer period of time, which impact negatively on natural ecosystems and humankind. Climate change is a combination of deterministic response to forcing and chaotic fluctuations—the chaos being a consequence of the nonlinear equations governing the dynamics of the system [Lorenz, 1963].

The anthropogenic modification of atmospheric composition is associated with changes in the radiative energy budget of the Earth's climate system denoted as - radiative forcing. Radiative forcing means a change in the net downward flux of radiation, in W/m^2 , at the tropopause. (For details on the radiative forcing concept, see Ramaswamy et al., 2001).

2.5.1 Climate Change and Greenhouse Gases

Since the Industrial Revolution and especially during the past few decades, human activities have increased the atmospheric levels of greenhouse gases. Climate is defined as the average weather for a given area over a certain time period. Therefore any change in certain climatic variable that is statistically abnormal for a given area can be viewed as a change in climate. Thus, the rapid increase in concentrations of greenhouse gases has given rise to concern over potential resultant climate changes. The AGU Council approved a position statement on Climate Change and Greenhouse Gases in December 1998. The statement and a short summary of the procedures that were followed in its preparation, review, and adoption were published in the February 2, 1999, issue of *Eos* [AGU, 1999].

The principal greenhouse gas concentrations that have increased over the industrial period are: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons CFC-11 (CCl_3F) and CFC-12 (CCl_2F_2) [Hansen et al. 1998; Schimel et al. 1996]. The bulk of CO_2 emissions originate from fossil fuel burning. The rest is due to land-use change, especially deforestation, and cement production. CH_4 is emitted from natural gas activities, coal beds, landfills, and agriculture (rice paddies, ruminants). The main anthropogenic sources for N_2O are agriculture (nitrogen fertilizer, livestock), biomass burning, and industrial activities. Owing to their long atmospheric life-times (decades and longer), these GHGs are spatially well mixed. Aerosol precursors are emitted by fossil fuel and biomass burning.

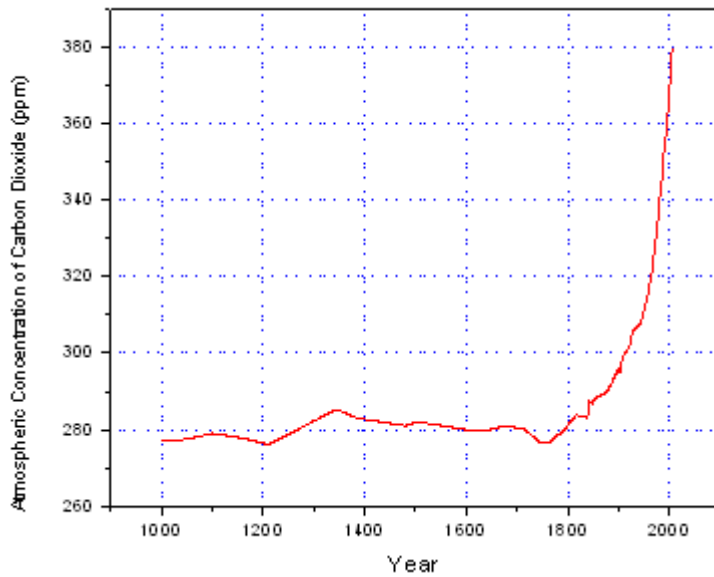


Figure 9: Increase in atmospheric concentrations of the carbon dioxide based on direct atmospheric measurements and on samples from ice cores and firn.

The observed increase of CO₂ in the atmosphere from about 280 ppm in the preindustrial era to about 390 ppm in 2007 [Friedli et al. 1986; Hansen et al. 1998; Keeling and Whorf, 1998] has come largely from fossil fuel combustion and cement production. Annual fossil CO₂ emissions increased from an average of 6.4 GtC/year (gigatonnes of carbon dioxide per year) in the 1990s, to 7.2 GtC per year in 2000-2005. In 2005, this exceeds by far the natural range over the last 650,000 years from 180 to 300 ppm, as determined from ice cores (Figure.9). These sources amounted to approximately 6.5 PgC/yr (1 Pg=10¹⁵ g) in 1996 [Marland et al., 1999]. Land use changes produce a non-negligible but more uncertain contribution of about 1.6 ± 1.0 Pg C/yr [Schimel et al. 1996]. These anthropogenic sources of CO₂ exceed the estimated uptake of CO₂ by the atmosphere and oceans, implying a significant but as yet unidentified terrestrial sink [Enting and Pearman, 1987].

Methane (CH₄) has increased from a pre-industrial value of about 715 ppb (parts per billion) to 1732 ppb in the early 1990s, [Houghton et al. 1996] and was 1774 ppb in 2005. (Figure.10). Fossil-fuel related sources of CH₄ amount to approximately 70-120 Tg CH₄/yr (1 Tg=10¹² g). Atmospheric increases in methane are largely caused by increasing emissions from man-made sources, such as landfills, agricultural activities, fossil fuel combustion, coal mining, the production and processing of natural gas and oil, and wastewater contribute about 200 - 350 Tg CH₄/yr [Schimel et al. 1996]. Methane causes about one third of the warming of CO₂ i.e. radiative forcing of around 0.5 W/m² (CH₄) and 1.5 W/m² (CO₂).

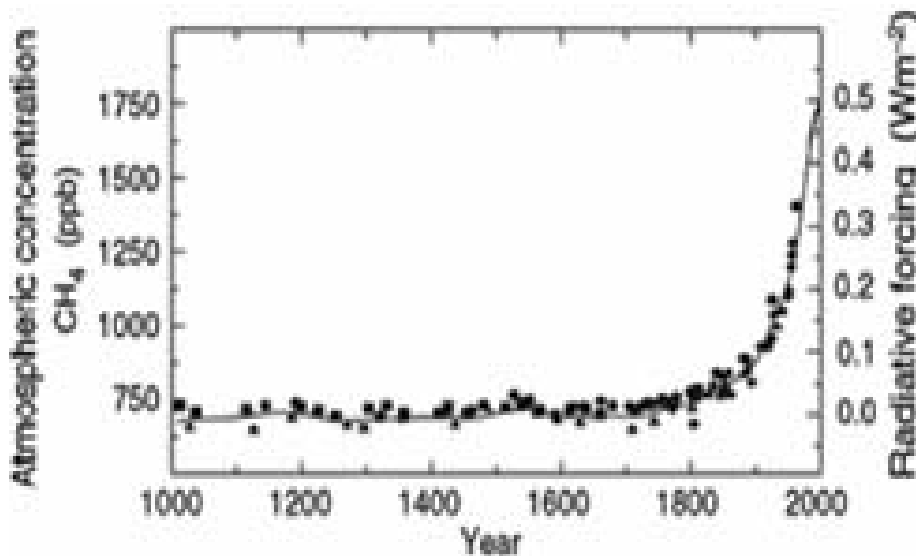


Figure 10: Increase in atmospheric concentrations of the methane based on direct atmospheric measurements and on samples from ice cores and firn.

Nitrous oxide (N_2O) is a potent, stable greenhouse gas with a long atmospheric lifetime, from 120 to 150 years. Nitrous oxide concentration increased from a pre-industrial value of about 270 ppb to 319 ppb in 2005 (Figure 11). The main anthropogenic sources are from agriculture and industrial sources including adipic acid and nitric acid production [Schimel et al.1996] while released naturally from oceans and by bacteria in soils. Estimated anthropogenic emissions of N_2O for the 1980's range from 3 to 8 TgN/yr [Houghton et al. 1996].

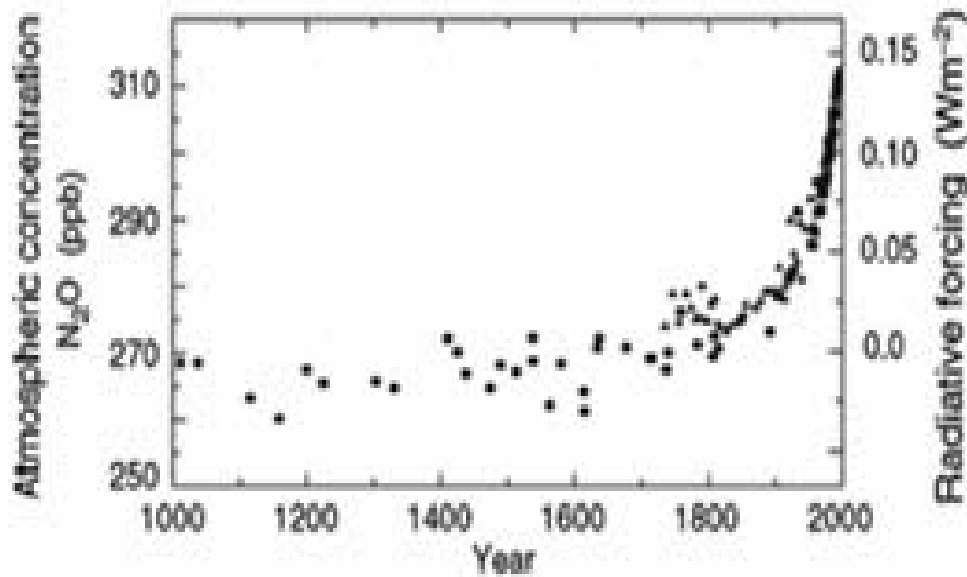


Figure 11: Increase in atmospheric concentrations of the nitrous oxide based on direct atmospheric measurements and on samples from ice cores and firn.

Chlorofluorocarbons CFC-12 and CFC-11 are manmade compounds which can be easily converted from gas to liquid or liquid to gas. Because of these properties, CFC's have been widely used as aerosol cans, refrigerants and in spray propellants and foam blowing. Studies in the 1970's showed that when CFC's are emitted into the atmosphere, they break down molecules in the Earth's ozone layer. Since then, the production of CFC's has significantly reduced in response to the Montreal Protocols and subsequent international agreements. Atmospheric concentrations of these compounds are expected to diminish substantially during the next century [Prather et al. 1996]. Contributions of anthropogenic emissions of GHGs to the enhanced greenhouse effect (measured in Wm^{-2}) are presented in Figure 12.

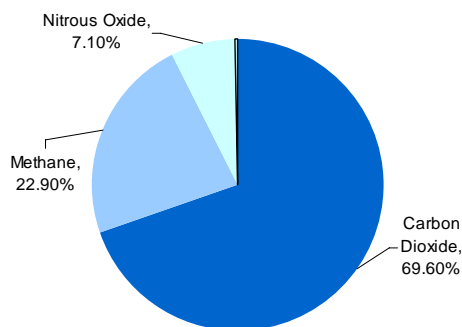


Figure 12: Contributions of anthropogenic emissions of GHGs

Climate model calculations indicate that to a good approximation the global warming influence of the several greenhouse gases is equal for equal forcing [Wang et al., 1991], lending support to the utility of the concept of climate forcing and response.

2.5.2 Observed response of the climate system

The proof that the climate system has already responded to the anthropogenic forcing requires two steps:

- the detection of climatic changes [see Folland et al. 2001], and
- their attribution to anthropogenic perturbations, as opposed to internal climate variability or natural forcing [Mitchell et al. 2001].

Climate was earlier defined as the statistical description of the whole climate system, or its atmospheric component. In practical terms, of course, only a limited amount of data about the climate system can be observed, processed, and thus be used for the detection of changes. Most statements about past and future climate change use the globally and annually averaged near-surface temperature (AGMT) as the primary proxy to describe the state of the global climate system.

Climatic changes observed during the 20th century that are consistent with model projections include a much stronger increase in night-time temperatures than in day-time temperatures, in winter and spring over summer and autumn temperatures, and in land surface over sea surface temperature. They also include significant precipitation changes that tend to increase the existing gradient between dry and wet regions, an accelerated rise in global average sea level, and wide-spread decreases in snow cover and ice extent. The noted changes in average climate characteristics are generally associated with substantial changes in the frequency and severity of »extreme« climate events represented by the tails of the respective distribution.

Concerning the attribution of the observed changes, it is concluded in [Mitchell et al. 2001] that 20th century climate was unusual, that the observed warming is inconsistent with estimates of internal climate variability, that the observed warming in the second half of the 20th century appears to be inconsistent with natural external forcing of the climate system, and that the vertical stratification of the observed warming is inconsistent with natural forcing whereas anthropogenic factors do provide an explanation of the 20th century temperature change. The knowledge is summarized as follows: “There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities.” [Houghton et al. 2001].

The most commonly considered indicator of climate change is the surface air temperature. Extensive efforts have been made to examine the trends in global and regional mean temperatures over time [Ghil and Vautard, 1991; Schlesinger and Ramankutty, 1994] and in the global patterns of temperature change Hegerl et al., 1996; Santer et al., 1995].

Global average temperature near the earth's surface have increased by 0.76 K in the past 100 years (1906–2005) and the linear trend for the past 50 years is 0.13 K (\pm 0.03 K) per decade [Trenberth, 2007]. Worldwide temperature measurements, carefully screened for instrumental and measurement artifacts, such as effects of urbanization, have been used to estimate that global mean annual surface temperatures have increased between 0.3 and 0.6 K during the last 150 years [Hansen and Lebedeff, 1987; Nicholls et al., 1996]. The variations of AGMT over the last 140 years are presented in Figure 13.a. AGMT has increased over both the last 140 years and 100 years by 0.6 ± 0.2 K, with an intermediate cooling period due to a masking of the GHG warming by ‘cooling’ aerosols

Land regions have warmed at a faster rate than the ocean, which is about 0.27 K after 1979. Observations since 1961 also show that the average temperature of the global ocean has increased to depths of at least 3000 m and that the ocean has been absorbing more than 80% of the heat added to the climate system. Such warming causes seawater to expand, contributing to sea level rise. It is also estimated that eleven of the last twelve years (1995-2006) rank among the 12 warmest years in the instrumental record of global surface temperature since 1850 [“Climate Change 2007 The Physical Science Basis”]. In this ranking, the year 2006 was the sixth warmest year on record, and December 2006 was the warmest December since global surface records were instituted [WMO, 2006].

However, it must be stressed that the increase has not been monotonic, with interannual fluctuations in the global annual mean temperature equal to an appreciable fraction of the overall rise over this time period. No single explanation can account for this variability.

Although temperature is usually the first variable considered in assessments of global climate change, it is important to consider other data that integrate the state of the climate system over space and time. These include temperature proxy data (such as tree ring records), borehole temperature measurements in soil, permafrost, and ice sheets, and measurements of the mass balance of valley glaciers and ice caps. Several recent proxy temperature reconstructions have suggested that the warming during the twentieth century is greater than any seen in the last 400 to 600 years [Mann et al., 1998] and perhaps the last 1200 to 1500

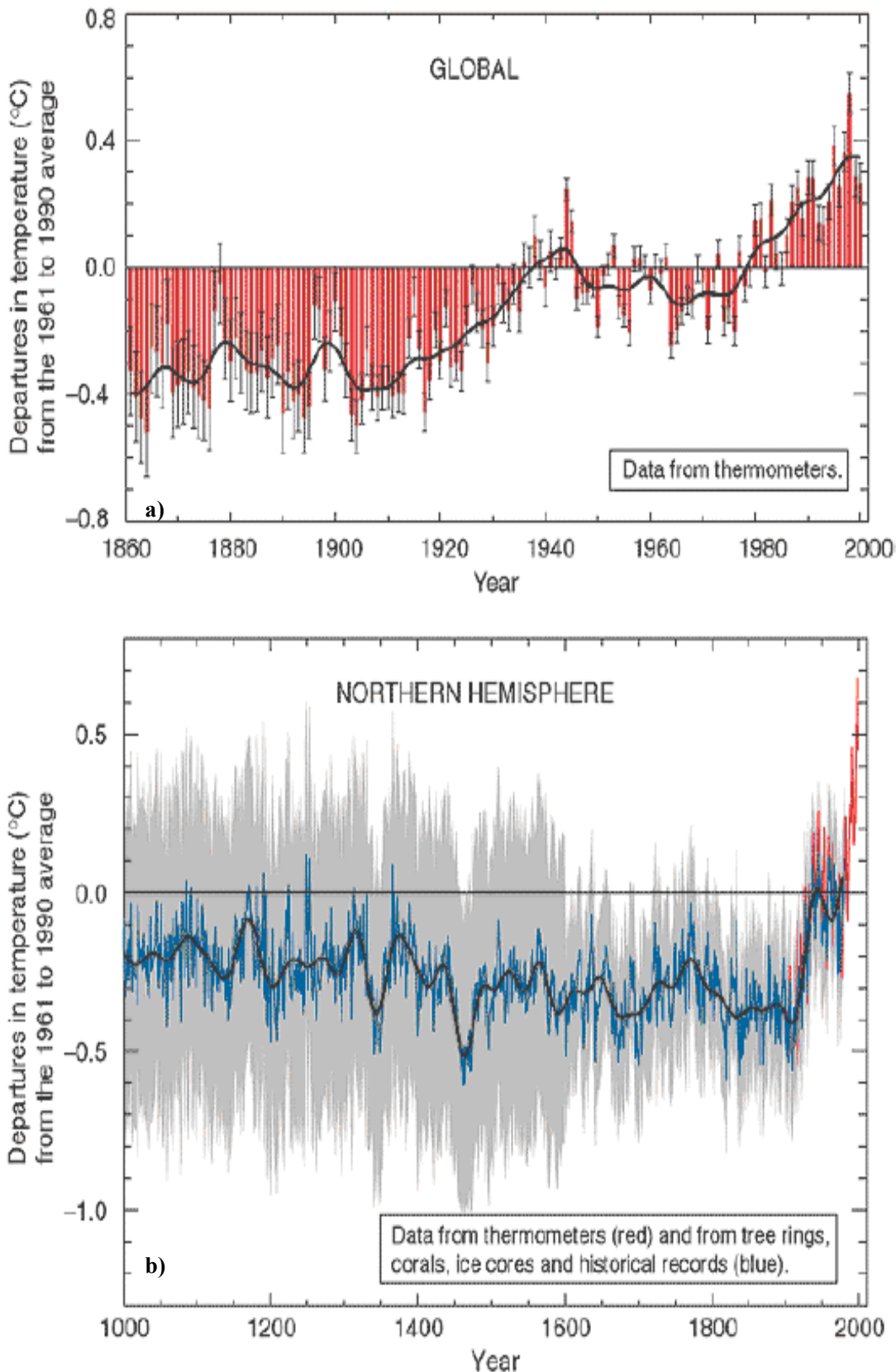


Figure 13: Variations of the Earth's surface temperature over the last 140 years and the last millennium. (a) The Earth's surface temperature is shown year by year (red bars) and approximately decade by decade (black line). Uncertainties in the annual data are represented by thin black whisker bars representing the 95% confidence range. (b) Additionally, the year by year (blue curve) and 50 year average (black curve) variations of the average surface temperature of the Northern Hemisphere for the past 1000 years have been reconstructed from 'proxy' data calibrated against thermometer data. The 95% confidence range in the annual data is represented by the grey region. Source: Houghton et al. (2001)

years [Overpeck, 1998]. A completely independent estimate [Pollack et al., 1998], based on analysis of subsurface temperature measurements, supports the unusual character of the recent global warming in the context of the last 5 centuries. Figure 13.b extends this time series to the last millennium whereby geographical coverage is restricted to the Northern hemisphere due to limited data availability. The text notes that “it is likely that the 1990s have been the warmest decade and 1998 the warmest year of the millennium” (Houghton et al., 2001).

There is evidence from the record of the past few thousand years that climatic conditions were sometimes warmer and sometimes cooler than at present [Dahl-Jensen et al., 1998; Feng and Epstein, 1994]. There is also evidence of large and abrupt climate changes that exceed recent experience [Denton and Karlen, 1973; Gasse and Vancampo, 1994; von Grafenstein et al., 1998]. These climatic variations occurred during a time when variations in atmospheric CO₂ were minimal [Barnola et al., 1995].

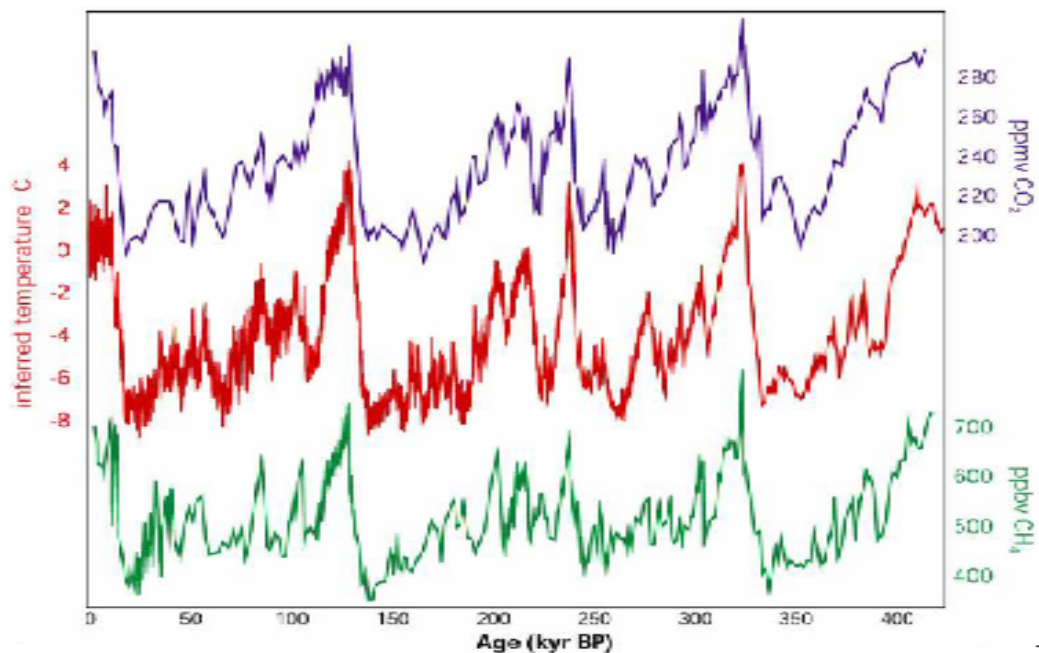


Figure 14: Four glacial cycles recorded in the Vostok ice core. Source J. R/ Petit et al. Nature, 399, 1999

To evaluate geologic evidence for the influence of greenhouse gases, one must focus on records from periods when changes in atmospheric CO₂ were much larger than those that occurred during the millennia immediately preceding the recent increase in anthropogenic CO₂ production.

Larger natural variations in atmospheric CO₂ have been inferred from the geologic record of the more distant past [for an overview, see Sundquist and Broecker, 1985]. Variations of 80-100 ppm, observed in analyses of gas bubbles trapped in glacier-ice cores (Fig.8a,b) [Barnola et al., 1987]. Ice core methane profiles show a similar correlation with climate [Chappellaz et al., 1990; Jouzel et al., 1993; Stauffer et al., 1988]. Figure 14 shows carbon dioxide concentration (top), proxy temperature (middle), and methane concentration (bottom) from analyses of ice cores from Vostok, Antarctica [Jouzel et al., 1993].

Paleoclimate model simulations (using models similar in many ways to the models used in modern climate projections) support the importance of CO₂ in explaining global mean temperatures in the geologic past [Berger et al., 1998; Kasting and Ackerman, 1986; Weaver et al., 1998]. Model simulations have also shown the importance of changes in other climate controls, for example the configuration of Earth's orbit [Berger and Loutre, 1997; Kutzbach et al., 1988].

Thus current interpretation of the geologic record suggests that greenhouse gases both respond and contribute to climate change. Atmospheric CO₂ is viewed as one of many components of the climate system that interact in complex ways over a wide range of timescales. A change in one of these interactive components is likely to affect other aspects of the global climate system. This interactive relationship between CO₂ and climate implies that the geologic record is not likely to reveal analogs of simple climate forcing by anthropogenic CO₂ emissions [Sundquist, 1986]. There is no known geologic precedent for large increases of atmospheric CO₂ without simultaneous changes in other components of the carbon cycle and climate system.

2.6 Projections of future climate change

This section briefly summarizes the available knowledge about future climate change. For a more detailed review see [Cubasch et al. 2001; Giorgi et al. 2001].

It is now established that human activities have increased GHG concentrations in the atmosphere. Prediction of the future persistence of anthropogenic greenhouse gases in the atmosphere is based on mathematical models that simulate future additions and removals. The greenhouse gas concentrations predicted by these models are subject to large uncertainties in the effects of both natural processes and human activities. Climate model calculations indicate that to a good approximation the global warming influence of the several greenhouse gases is equal for equal forcing [Wang et al., 1991], lending support to the utility of the concept of climate forcing and response.

2.6.1 Current and projected greenhouse-gas emissions

Global concentration of CO₂ has increased from a pre-industrial value of about 280 ppm (parts per million) to 379 ppm in 2005 (see Figure 9). In 2005, this exceeds by far the natural range over the last 650,000 years from 180 to 300 ppm, as determined from ice cores (see Figure 4). The annual CO₂ growth-rate was larger during the last 10 years (1995–2005 average: 1.9 ppm per year), than it has been since the beginning of continuous direct atmospheric measurements (1960–2005 average: 1.4 ppm per year). Annual fossil CO₂ emissions increased from an average of 6.4 gigatonnes of carbon dioxide (GtC) per year in the 1990s, to 7.2 GtC per year in 2000–2005.

Methane has increased from a pre-industrial value of about 715 ppb (parts per billion) to 1732 ppb in the early 1990s, and was 1774 ppb in 2005 (see Figure 10). The atmospheric concentration of methane in 2005 exceeded by far the natural range of the last 650,000 years (320 to 790 ppb. Figure 4). Growth rates have declined since the early 1990s, consistent with total emissions (sum of anthropogenic and natural sources) being nearly constant during this period.

Nitrous oxide concentration increased from a pre-industrial value of about 270 ppb to 319 ppb in 2005 (see Figure 11). The growth rate has been approximately constant since 1980. More than a third of all nitrous oxide emissions are anthropogenic and are primarily due to agriculture

Without action to combat climate change, atmospheric concentrations of greenhouse gases will continue to rise. In a ‘business as usual’ scenario, they will reach 550 ppm CO₂e by 2035, then increase at 4.5 ppm/year and continue accelerating.

As a result of this increase in GHG emission, there is a projected value of 0.2°C increase in global warming in the next two decades, even if the concentration for the GHG remains constant at the 2000 level. Even if annual greenhouse-gas (GHG) emissions remained at the current level of 42 GtCO₂e/year, the world would experience major climate change. That rate of emissions would be sufficient to take greenhouse-gas concentrations to over 650 ppm CO₂ equivalent (CO₂e) by the end of this century, likely to result eventually in a rise in the global mean temperature of at least 3 °C from its pre-industrial level.

Total greenhouse-gas emissions were 42 GtCO₂e in 2000, of which 77% were CO₂, 14% methane, 8% nitrous oxide and 1% perfluorocarbon and sulphur hexafluoride. In 2003, 65% of emissions come from burning fossil fuels in -, electricity, transport, buildings and industry. Agriculture and changes in land use (particularly deforestation) produce 35% of emissions (Figure 15).

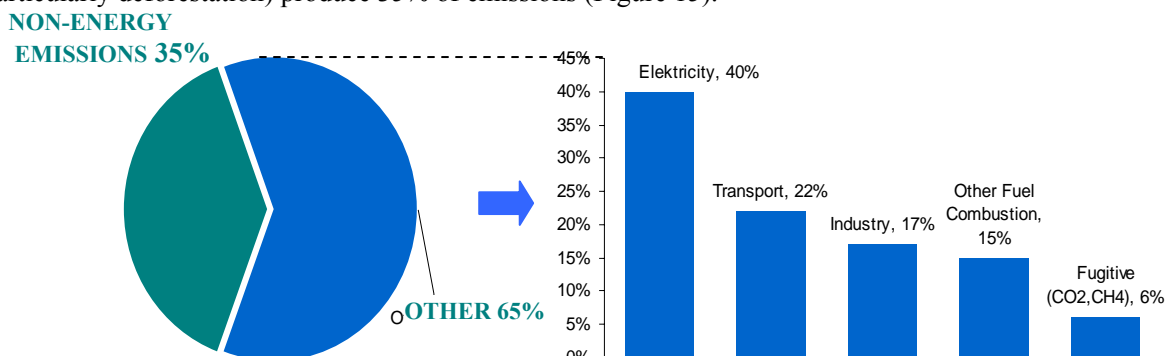


Figure 15: Greenhouse gases by energy sectors in 2003. Source World Resources Institute

Sources of greenhouse-gas emissions comprise:

- Fossil-fuel combustion for energy purposes in the power, transport, buildings and industry sectors amounted to 26.1 GtCO₂ in 2004. Combustion of coal, oil and gas in electricity and heat plants accounted for most of these emissions, followed by transport (of which three quarters is road transport), manufacturing and construction and buildings. World Energy Council reported that global carbon dioxide emissions from burning fossil fuels rose 12% between 1990 and 1995. Industrial processes such as the production of cement and chemicals involve a chemical reaction that releases CO₂ and non-CO₂ emissions. Also, the process of extracting fossil fuels and making them ready for use generates CO₂ and non-CO₂ emissions (so-called fugitive emissions).
- Land-use changes alter the albedo (reflectivity) of the surface and modify evapotranspiration and surface roughness. One large effect of altered vegetation occurs via the impact of snow on albedo. The albedo of a cultivated field, e.g., is affected more by a given snowfall than is the albedo of an evergreen forest. Land-use change such as deforestation releases stores of CO₂ into the atmosphere. Changes in land use account for 18% of global emissions. This is driven almost entirely by emissions from deforestation, desertification, and cultivation. Land-use emissions are projected to fall by 2050, because it is assumed that countries stop deforestation after 85% of forest has been cleared.
- Agriculture; methane, nitrous oxide and F-gases are produced by agriculture, waste and industrial processes. F-gases (hydro fluorocarbons or HFCs, perfluorocarbons or PFCs and sulphur hexafluoride or SF₆) are widely used in refrigeration and air conditioning but have a high global warming potential and can sometimes stay in the atmosphere for thousands of years.

Electricity - A quarter of all global greenhouse-gas emissions come from the generation of electricity and heat (Figure 16), which is mostly used in domestic and commercial buildings, and by industry. This was the fastest growing source of emissions worldwide between 1990 and 2002, growing at a rate of 2.2% per year. Emissions from this source are likely to increase over four-fold between now and 2050 because of increased synfuel production from gas and coal, according to the IEA. Total power-sector emissions are likely to rise more than three-fold over this period.

Transport - Transport accounts for 13.5% of global greenhouse-gas emissions (Figure 16), making it the third largest source of emissions jointly with agriculture and industry. Total CO₂ emissions from transport are expected to more than double in the period to 2050, making it the second-fastest growing sector after electricity.

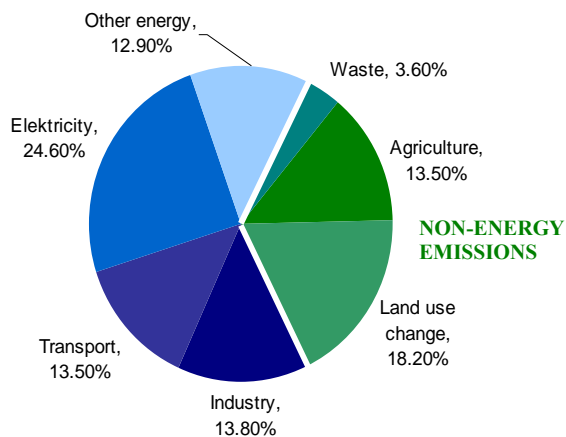


Figure 16: Greenhouse gases by sectors in 2003. Source World Resources Institute

The fastest growing sectors are driven by growth in demand for transport. Fugitive emissions are expected to increase over four-fold in the period to 2050, because of an increase in production of synfuels from gas and coal, mostly for use in the transport sector. Other 'business as usual' (BAU) projections show similar patterns. The US Energy Information Administration is currently projecting an increase from 25 GtCO₂ in 2003 to 43.7 GtCO₂ by 2030, at an annual average rate of increase of 2.1%, as does the POLES model.

Industry - Industry accounts for 14% (Figure 16) of total direct emissions of GHG (of which 10% are CO₂ emissions from combustion of fossil fuels in manufacturing and construction and 3% are CO₂ and non-CO₂ emissions from industrial processes such as production of cement and chemicals). A further 8% of emissions are accounted for by direct combustion of fossil fuels and biomass in commercial and residential buildings, mostly for heating and cooking. Direct emissions from both industry and buildings are both expected to increase by around two thirds between 2000 and 2050 under BAU conditions.

Formal projections suggest that the situation in the absence of climate-change policies is worse than in this simple example. International Energy Agency (IEA, 2006) projects an increase of over 50% in annual global fossil fuel CO₂ emissions between 2004 and 2030, from 26 GtCO₂ to 40 GtCO₂, an annual average rate of increase of 1.7%, IEA envisages emissions of 58 GtCO₂ by 2050.

Land use - Changes in land use account for 18% of global emissions (Figure 16). This is driven almost entirely by emissions from deforestation, desertification, and cultivation. Land-use changes alter the albedo (reflectivity) of the surface and modify evapotranspiration and surface roughness. Land-use emissions are projected to fall by 2050, because it is assumed that countries stop deforestation after 85% of forest has been cleared.

Global emissions of greenhouse gases increased by 75% between 1970 and 2004 to about 45,000 GtCO₂e. Global carbon dioxide emissions rose by approximately 90% during the same period, methane by some 40% and nitrous oxide by 50%. This can be explained by the increase of methane emissions from the use of fossil energy use (+85%), and particularly gas consumption, and from waste generation (+75%) (landfill sites and waste water). Emissions from agriculture have remained the same on balance. The increase in nitrous oxide emissions is the result of an increase in the use of synthetic fertilisers and manure and of an increase in livestock and arable farming.

In the overall growth in GHG, the main contributing factor was the energy supply sector, with an increase of 145% from 1970 to 2004. The growth in direct emissions in this period from transport was 120%, industry 65%, and land use, land use change, and forestry was 40%, the agriculture sector by 27%, and from buildings by 26%. However, the buildings sector has a high level of electricity use and hence the total of direct and indirect emissions in this sector is much higher (75%) than direct emissions.

2.6.2 Projecting the Growth of Greenhouse-Gas Emissions

Projections of future emissions from land-use changes remain uncertain. At the current rate of deforestation, most of the top ten deforesting nations would clear their forests before 2100. Based on rates of deforestation over the past two decades, and assuming that countries stop deforestation when 85% of the forests they had in 2000 have been cut down, annual emissions will remain at around 7.5 GtCO₂/yr until 2012, falling to 5 GtCO₂/yr by 2050 and 2 GtCO₂/yr by 2100. Non-CO₂ emissions from agriculture amount to 14% of total GHG emissions. Of this, fertilizer use and livestock each account for one third of emissions; other sources include rice and manure management. Though agriculture is highly dependent on climate, it is also highly adaptive. Weather extremes, pests, and weeds will likely present challenges in a changing climate. Total non-CO₂ emissions are expected to double in the period to 2050.

The US Environmental Protection Agency (EPA) projects an increase in agricultural emissions from 5.7 to 7.3 GtCO₂e between 2000 and 2020 with business as usual. Increases in emissions from other sources, including waste and industrial processes, are also expected.

Less is known about historical trends in emissions from agriculture and changes in land use, but emissions due to land-use changes and deforestation are thought to have risen on average by around 1.5% annually between 1950 and 2000, according to the World Resources Institute. In total, between 1990 and 2000 (the period for which comprehensive data are available), the average annual rate of growth of non-CO₂ greenhouse gases, in CO₂e terms, was 0.5% and of all GHGs together 1.2%.

Global emissions are projected to continue to rise in the absence of climate-change policies; 'business as usual' will entail continuing increases in global temperatures well beyond levels previously experienced by humankind.

Some simple arithmetic can illustrate this. The concentration of greenhouse gases in the atmosphere is currently at around 430 ppm CO₂e, adding 2-3 ppm a year. Emissions are rising. But suppose they continue to add to GHG concentrations by 3 ppm a year. That will be sufficient to take the world to 550 ppm in 40 years and well over 700 ppm by the end of the century. Yet a stable global climate requires that the stock of greenhouse gases is constant and therefore that emissions are brought down to the level that the Earth system can naturally absorb from the atmosphere annually in the long run.

Looking at emissions from all sources together, the IPCC Special Report on Emissions Scenarios, (SRES) published in 2000, considered a wide range of possible future scenarios. Although they differ considerably, all entail substantial increases in emissions for at least the next 25 years and increases in greenhouse-gas concentrations at least until the end of the century. All but one SRES storyline envisage a concentration level well in excess of 650 ppm CO₂e by then. Academic studies also envisage steady increases. The MIT EPPA model reference projection, for example, envisages an average annual increase in CO₂ emissions of 1.26% between 1997 and 2100 (faster in the earlier years). In the rest of this review, for the purposes of illustrating the size of the emission abatement required to achieve various CO₂e

concentration levels, a BAU trajectory based on IEA, EPA, IPCC and Houghton projections has been used. This is broadly representative of BAU projections in the literature and results in emissions reaching 84 GtCO₂e per year, and a greenhouse-gas level of around 630 ppm CO₂e, by 2050. Despite the differences across the emissions scenarios in the literature and the unavoidable uncertainty in making long-run projections, any plausible BAU scenario entails continuing increases in global temperatures, well beyond levels previously experienced by humankind, with the profound physical, social and economic consequences described in Part II of the Review. If, for instance, the average annual increase in greenhouse-gas emissions is 1.5%, concentrations will reach 550 ppm CO₂e by around 2035.

The uncertainty in the emissions of most sources is large, except for CO₂ from combustion where the uncertainty will be about 5% or less. For other sources, e.g. CO₂ from the use of oil and gas as chemical feedstock, CO₂ from deforestation, CH₄ from fossil fuel production and rice cultivation and from waste and wastewater, N₂O from agricultural activities and emissions from the use of fluorinated substances, the uncertainty can be much larger, in particular when making estimates at country level.

The emissions of the greenhouse gases carbon dioxide, methane, nitrous oxide and of the fluorine-containing gases HFCs, PFCs and SF₆ are covered by the UN Climate Convention (UNFCCC) and the Kyoto protocol. The objective is the reduction, between 2008 and 2012, of emissions of greenhouse gases by the industrialized countries that have signed the Kyoto Protocol, including countries in Eastern Europe and the former Soviet Union, to an average level of 5% below the 1990 level. Some countries are working together to lower emissions of carbon dioxide from fossil fuels. One proposal is to establish a system requiring companies to pay to emit carbon dioxide above a specified level. This payment could take several forms, including:

- (1) purchasing the rights to pollute from a company whose carbon dioxide emissions fall below the specified level,
- (2) purchasing and then preserving forests, which absorb carbon dioxide; and
- (3) paying to upgrade a carbon dioxide emitting plant in a lesser-developed country, lowering the upgraded plant's carbon dioxide emissions.

Of the several anthropogenic greenhouse gases, CO₂ is the most important agent of potential future climate warming because of its large current greenhouse forcing, its substantial projected future forcing [Houghton et al., 1996], and its long persistence in the atmosphere.

2.6.3 Predicted Climate Change from Increased Greenhouse Gases

Predictions of future climate changes resulting from increased greenhouse gas concentrations must be deduced from our understanding of atmospheric physics. Projections of future climate change are based on simulations with numerical models, which are simplified mathematical representations of the Earth's climate system. At one end of the complexity spectrum, zero-dimensional energy-balance models are used to explore global temperature change in response to GHG emissions. These models are particularly useful for sensitivity analyses and in integrated assessment frameworks that require the evaluation of many different emission scenarios. Other types of models are applied to estimate specific features of future climates. For instance, Earth system models of intermediate complexity, may be used to understand important processes within the climate system, including their interactions and feedbacks, and to use this knowledge for simulations of future changes. Uncertainty in our understanding of complex "feedback" mechanics is the primary reason models cannot be trusted to accurately forecast future climates. Clouds are a good example of this feedback problem. They tend to form over warm, wet areas; but, depending on the immediate situation, they may provide either a positive feedback by acting as a greenhouse gas or a negative one by blocking solar radiation and cooling the surface.

All climate models are simplified representations of the actual climate system, which limit the accuracy and reliability of their projections. Furthermore, even with models that take several years to run (Hansen et al., 1988), the full reality cannot be simulated. On the other hand, models can be used to ensure that simulations of the evolution of climate resulting from realistic assumptions are accurate mathematical progressions, according to basic physical laws.

The precise consequences of global warming are more difficult to predict. This is due to a degree of uncertainty in the current climate models, which is inevitable when considering such complex systems. Some of the predicted responses to increases in greenhouse gases include:

- **increases in mean surface air temperature** - Recent model simulations have indicated that a gradual increase in the atmospheric concentration of a GHG gas will lead to an increase in the average surface air temperature of the Earth [Kattenberg et al., 1996]. Gradual increase until the CO₂ concentration is doubled results in a temperature increase of 3°C ± 2°C.

- increases in global mean rates of precipitation and evaporation** - An increase in surface air temperature would cause an increase in evaporation and generally higher levels of atmospheric water vapor. The positive feedback associated with this leads to the expectation that an increase in surface air temperatures would lead to a more intense hydrological cycle, with more frequent heavy precipitation events [Houghton et al., 1992; Kattenberg et al., 1996]. However, simulations of the regional and seasonal distribution of precipitation are poor [Kattenberg et al., 1996]. The models also indicate that warming will be greatest at the higher latitudes during the winter season and in the atmosphere layer closest to the surface. Other atmospheric processes, like rainfall patterns, are related to the energy budget and, therefore, should also change. Worldwide, the rainfall might increase by about 5% to 7% (Weatherald and Manabe, 1981) with most of this occurring at high latitudes. In the long run, however, the middle latitude continents will most likely become dryer in the summer
- rising sea level** - The main factors that contribute to sea level rise are thermal expansion of ocean water and the melting of glaciers, both of which are in response to higher air temperatures. It has been well established that melt water from the world's small glaciers has contributed to sea level rise during the last century [Meier, 1984]. However, recent measurements indicate that between 1993 and 1998 the southeastern part of the Greenland ice sheet thinned overall, with a thickening at a rate of 0.5 ± 0.7 cm/yr at elevations above 2000 m and a thinning at the low elevations at rates up to 1 m/yr [Krabill et al., 1999].

Worldwide measurements from tidal gauges during the last 100 years indicate that mean sea level has risen between 10 and 25 cm (18 cm mean) [Douglas, 1991; Gornitz, 1995; Warrick et al., 1996]. Most modeling studies, predict that the trend in rising sea level will continue in the future [Warrick and Oerlemans, 1990; Warrick et al., 1996; Wigley and Raper, 1993].

The IPCC (2001c) has predicted numerous potential effects, including: increased coastal erosion, inhibition of primary production processes (i.e. reduced agriculture), higher storm-surge flooding, changes in surface water quality and groundwater characteristics, increased disease risk, loss of renewable and subsistence resources, impacts on agriculture and aquaculture through decline in soil and water quality.
- Agricultural changes** - Ecosystems all over the world will change as a result of many of the effects brought on by global warming. Higher temperatures and changes in rainfall patterns will lead to shifts in plant species i.e. some plants will not grow so well in areas that they have grown in for centuries. Obviously this has massive implications for agriculture. If it becomes more difficult to grow major crop plants in their traditional areas this could lead to food shortages and famine. Food prices will increase, causing knock-on effects in the world's economies.

In the long run, the climatic changes could affect agriculture in several ways: productivity (in terms of quantity and quality of crops), agricultural practices (through changes of water use (irrigation) and agricultural inputs such as herbicides, insecticides and fertilisers), environmental effects (in particular in relation of frequency and intensity of soil drainage, soil erosion, reduction of crop diversity), rural space (through the loss of previously cultivated lands, land renunciation, and water amenities).
- Extreme weather** - There is already some evidence for increasing storm intensity. Worldwide, the proportion of hurricanes reaching categories 4 or 5 has risen from 20% in the 1970s to 35% in the 1990s. This trend is predicted to continue. Precipitation hitting the US from hurricanes also increased by 7% during the 20th century

Figure 17 shows global climate projections over the next century under a range of scenarios (IPCC). In all of the scenarios studied, atmospheric CO₂ concentration will increase and so will average global temperature. For instance, in the A2 scenario average land temperatures (which increase by 2.7-7.0°C) are predicted to increase by more than sea temperatures (which increase by 2.0-3.8°C) by the year 2100.

Figure 17a depicts the anthropogenic emissions of CO₂, the single most important GHG, for the six "equally plausible" illustrative SRES emission scenarios. The other panels show the associated CO₂ emissions, CO₂ concentrations, global mean temperature increase, and global mean sea level rise, respectively, as computed by a simple climate model tuned to various AOGCMs. The range of projected AGMT change between 1990 and 2100 for all SRES scenarios and all emulated AOGCMs is from 1.4°C to 5.8°C. For comparison, the AGMT difference between the last glacial maximum (20,000 years before present) and the present climate is around 5°C [Folland et al., 2001]. The uncertainty about future AGMT change is caused equally by differences between forcing scenarios and between climate models. The relative importance of scientific uncertainties is larger for most other climate parameters, such as regional climate changes, changes in precipitation and sea level, and changes in climate variability and extremes.

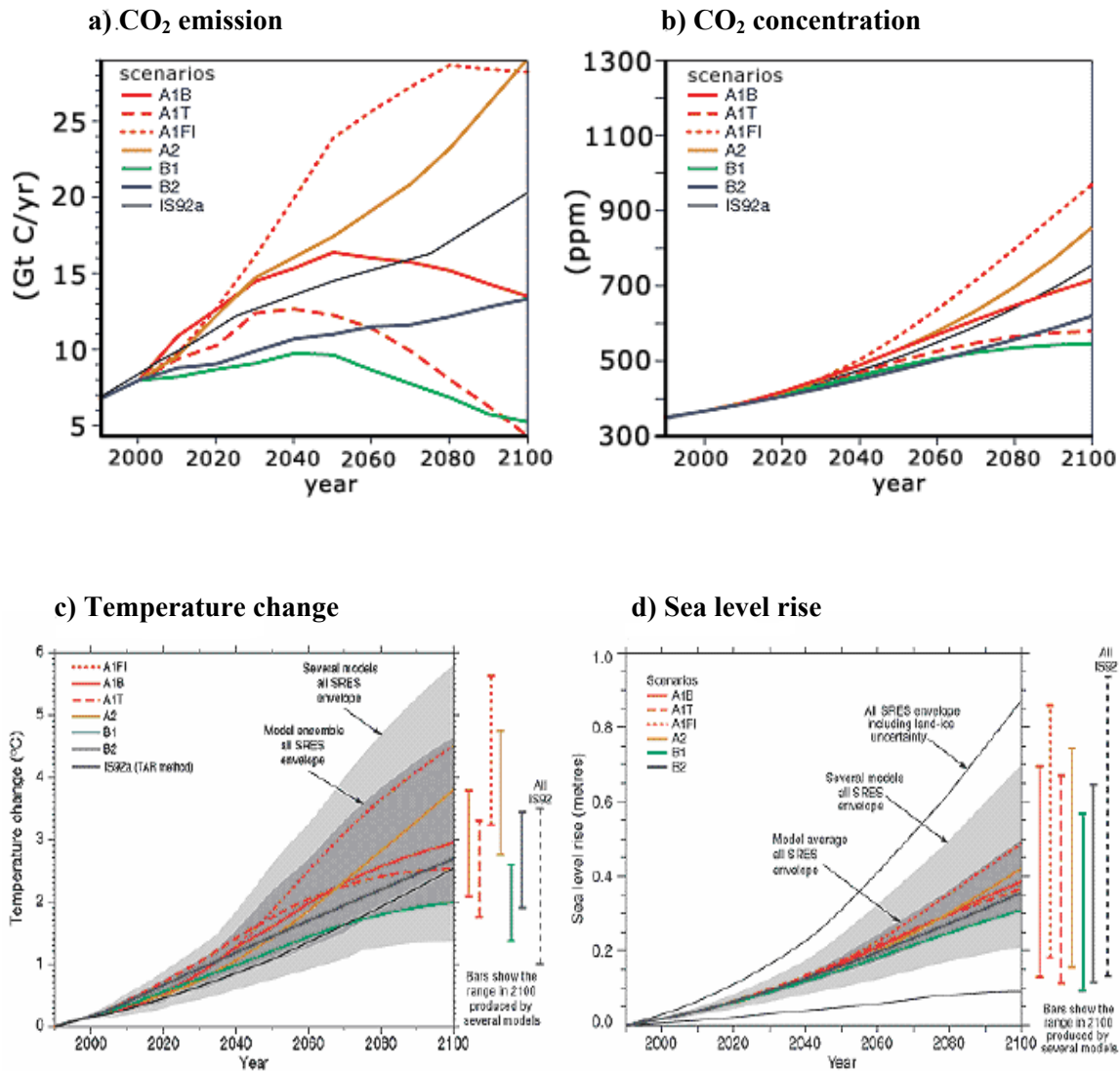


Figure 17: Global climate projections over the next century under a range of scenarios (a) CO₂ emissions; (b) CO₂ concentrations; (c) temperature increase; (d) sea level rise; (not allowing for uncertainty relating to ice dynamical changes in the West Antarctic ice sheet). The bars in (c) and (d) depict the range of results in 2100 for each of the six scenarios when the simple model is tuned to seven complex climate models (AOGCMs) with a range of climate sensitivities. The various shaded envelopes in (c) and (d) refer to the range of results for the full range of 35 SRES scenarios rather than the six ‘illustrative’ scenarios. In (d), the former case is further split up according to the inclusion or not of land-ice uncertainty. Source: Houghton et al. (2001)

2.6.4 Predictive Capabilities and Uncertainties

Projections of future climate change are always uncertain. The respective sources of uncertainty are:

- 1) The freedom of human choice is the primary source of uncertainty about future GHG emissions in particular and about socioeconomic development in general. Many future scenarios indicate the plausible range of future GHG emissions in the absence of an internationally coordinated climate policy.
- 2) Climate models are imperfect representations of the climate system.
- 3) The long-term evolution of complex nonlinear systems, such as the climate system, is fundamentally unpredictable, even if the governing equations are perfectly deterministic.

A principal source of uncertainty in modeling climate change during the industrial period arises from uncertainties in the representation of the influence of anthropogenic aerosols. Recent climate modeling studies which include the effects of aerosols [Hasselmann, 1997; Hegerl et al., 1997; Houghton et al., 1995; Kattenberg et al., 1996; Mitchell et al., 1995;] show improved comparisons between the simulated and observed global temperature trends during the industrial period. Additional uncertain contribution to

radiative forcing of climate change during the industrial period arises from possible changes in solar irradiance. It is estimated that solar forcing may have contributed about half of the observed surface warming since 1900 [Lean and Rind, 1998].

The response of the climate system to anthropogenic forcing includes the potential for ‘rapid climate change’, or ‘large-scale climate singularities’. These terms are used to describe rapid large-scale changes in the climate system in response to gradual changes in its forcing. Singularities may result from a combination of the nonlinearity in functional relationships (e.g., the melting point of ice as a physical threshold in the climate system) and the complexity in the climate system, which gives rise to the possibility of positive feedback loops. Long-term observations as well as experimental studies indicate that smooth, or ‘regular’, behaviour is an exception rather than a rule in the dynamics of complex systems. Dansgaard-Oeschger oscillations [Dansgaard et al., 1993] as well as Heinrich events [Bond et al., 1992] are obvious examples of irregular behaviour of the climate system as a result of weak external forcing. Recently some important aspects of irregular climate change were successfully simulated with CLIMBER-2, a three-dimensional statistical-dynamical Earth system model of intermediate complexity [see, e.g., Claussen et al., 1999; Petoukhov et al., 2000].

Assessments of future changes in climate variability and extremes have been made possible only recently, primarily due to the increasing availability of comparable integrations with different GCMs and of ensemble integrations from single GCMs [see Kharin and Zwiers 2000; Raisanen and Palmer 2001; Milly et al. 2002].

Model-based climate projections can be used to produce climate scenarios for investigating the impacts of anthropogenic climate change. Depending on the information needs of the impact assessment and the availability of pertinent models and data, a variety of methods is used to construct such climate scenarios. [see Mearns et al., 2001 for a review]. Some scenarios are restricted to deterministic projections of AGMT change from simple climate models, others focus on possible changes in current modes of inter annual climate variability such as the El Niño-Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), and still others use sophisticated downscaling methods to produce probabilistic projections of changes in several

Many ecological and social systems are sensitive to the climatic variations associated with anthropogenic climate change. The most comprehensive review of the scientific knowledge on climate impacts is provided in the second volume of the IPCC Third Assessment Report [McCarthy et al., 2001]. On the basis of hundreds of scientific studies, the IPCC concludes: “The overall processes and patterns of observations reveal a widespread and coherent impact of 20th-century climate changes on many physical and biological systems” [Smith et al., 2001, p. 927]. Assessments of climate impacts are a crucial source of information for the development of adequate societal response strategies. To facilitate the evaluation and aggregation of projected impacts, and the formulation of suitable responses, various classification schemes for categorizing climate impacts have been developed [Rothman et al., 2003]. Many studies classify impacts according to the (economic) sector affected (such as agriculture, forestry, energy, water resources, health, tourism, etc.); a physical standpoint focuses on the affected system (atmosphere, aquatic systems, geologic systems, biological systems including humans, and built infrastructure); a productivity standpoint emphasizes the affected capital type (manufactured, human, social, and natural); and recent approaches emphasize the different (interlinked) constituents of human well-being (such as material welfare, health, social relations, security, freedom, and peace of mind).

The IPCC has taken into account a wide range of factors to produce a summary pattern of the risks and potential impacts of global warming, scored against the increase in global average temperature. In all scenarios modeled:

- risks to unique and already threatened systems will increase,
- the frequency and severity of extreme weather events will increase,
- the impacts will be negative for at least some regions, although which regions is so far unclear,
- economic and ecological impacts will be felt for most people, though some may (initially) be perceived as positive,
- risk of large scale, irreversible, abrupt change.

2.7 Integrated Assessment and Integrated Models

The climate change problem is large, complex and multifarious, and the aim is to tackle the whole problem (or a wide aspect of it). Therefore, a need for a technique for managing the climate change impacts of human actions is immediate – and this is - the Integrated Assessment (IA)

A scientific study of some problems of practical importance, with the purpose of enabling (or at least helping) someone make a decision about what actions should be taken to achieve the best effects - means assessment.

The concept of integrated assessment as a discipline is relatively new, and some of the ideas involved are quite novel. Although the name has quickly become well-established, there is still widespread uncertainty about this discipline. Useful overview papers have been written [Parson and Fisher-Vanden 1995], [Parson 1995], [Hordijk 1995], [Dowlatabadi 1995].

In the climate change literature, integrated assessment models have a relatively short history of less than a decade. One of the first IAM is introduced by [Nordhaus 1991]. Computer models in climate change fall into two categories.

- Global Circulation Models (GCMs) are the main underlying research tools that attempt to predict the consequences of increases in atmospheric carbon dioxide and other greenhouse gases. They are essentially unidisciplinary and focus on one specific part of the problem, namely the response of the environment to the pressures of greenhouse gases.
- Many researchers combine the scientific and economic aspects of climate change in order to assess policy options for climate change. These models are known as integrated assessment models (IAMs). Examples include:[Edmonds, 1993] [Dowlatabadi 1995], [Dowlatabadi and Morgan 1993, 1995], [Kelly and Kolstad 1997], [Parson and Fisher-Vanden 1995], [Kolstad 1996], [Lempert, Schlesinger, and Banks 1996], [Manne, Mendelsohn, and Richels 1993, 1997], [MIT 1994], [Morita, et. al. 1994], [Nordhaus 1994], and [Peck and Teisberg 1992]. These IAMs attempt to simulate the whole IA problem using simplified sub-models (much, much simpler than the GCMs). Some are essentially just simulation models, with the ability to vary ranges of policy options; others are designed to calculate optimal abatement strategies. IAMs are receiving increasing attention of late. The Intergovernmental Panel on Climate Change (IPCC), which in the past has focused primarily on the physics of climate change, has released a report on the socio-economic dimensions of climate change. The report includes a chapter which reviews IAMs [Weyant, et. al. 1996].

An integrated assessment model is defined more broadly as any model which combines scientific and socio-economic aspects of climate change primarily for the purpose of assessing policy options for climate change control. Other authors have similar definitions; for example [Weyant, et. al. 1996] defines integrated assessment even more broadly as any model which draws on knowledge from research in multiple disciplines. [Weyant, et. al. 1996] give three purposes for integrated assessment:

- assess climate change control policies, An example is the assessment of an Intergovernmental Panel on Climate Change [IPCC, 1990, 1992] control policy on sea level rise and the resulting effects on coastal ecology or tourism. Another example is the computation of the optimal climate control policy
- constructively force multiple dimensions of the climate change problem into the same framework,. For example identifying the driving forces behind climate change by identifying to which sectors climate change is most sensitive. and quantify the relative importance of climate change in the context of other environmental and non-environmental problems facing mankind.. Another example is ranking the importance of the temperature change from a doubling of CO₂ (the climate sensitivity parameter) and the discount rate parameter, which can only be done within an interdisciplinary framework.

Integrated assessment is a particularly powerful and general tool for conducting integrated assessment but is not identical to integrated modeling, though the two are often confused or the terms used interchangeably. It is possible to perform an IA without using any computer models. First of all, the initial aim of the process of assessment is to gain understanding of the way the system functions; models are an excellent method of both encapsulating (summarising) and disseminating this understanding. Once available, they enable quantitative experimentation into the effects of various proposed responses, for example scenario analysis. They may also allow quantification of the uncertainty of the assessment

A particular merit in using IA to model the whole of a system is that it is better at handling cycles, feedbacks and responses. Delayed feedbacks - and most feedbacks in environmental systems will be delayed - often lead to unexpected and unpredictable behaviours, instability and even chaos [Pippard 1985].

2.7.1 Integrated Climate Change Assessment

About twenty integrated assessment models have been developed, tackling the problem from different approaches with different emphases. A number of models cover the drivers that lead to greenhouse emissions (economic, demographic, social and technological processes), the effects of emissions on the state of the environment (using much simpler models than the full blown Global Circulation Models) and the impact of changes of state.

Climate change Modeling demands integrated assessment because it is necessary to make predictions about the future in several different areas:

- the future socioeconomic state (including population growth, level of industrialization among different populations, social and economic demand for and availability of polluting lifestyles, development of abatement technologies),
- the rate at which greenhouse gases are emitted and fixed (these are functions of the socioeconomic state of the world),
- the effects of the resulting levels of greenhouse gases on the climate,
- the effects of climate changes on humans (for example agriculture, water supply, land loss from rises in sea-levels, extreme weather events, spread of diseases, damage to ecosystems);
- ways to change any or all of the above (global actions and local actions).

All these factors will change in the future and so have to be predicted by some sort of assessment models. Because they are inter-related, the assessment must be integrated to account for these links; even within each of the main areas, an integrated view is necessary. The very large scale of the climate change problem means that there are a number of unusual features to work in this field:

- The global scale of the underlying causes demands international negotiations before individuals are prepared to accept mitigating actions. There is no single individual or organisation capable of introducing mitigating actions (with or without public support).
- The problem is very long term. Climate change is being caused, and remedial actions are required, now, but the effects will not be felt until some time in the future.

Questions of inter-generational equity are important. This is alternatively expressed as:

- Mitigating actions are a cost now whereas benefits will only be felt in the future [Dowlatabadi and Morgan 1993; Dowlatabadi 1995] or as:
- Polluting lifestyles are a benefit now whereas the costs of climate change will be paid in the future.

A feature of the uncertainty about changes to the climate is the possible existence of unprecedented, low-probability, high-consequence events (such as abrupt changes to the pattern of ocean current patterns). It is very hard, by their nature, to anticipate such events, or to predict the whole range of their consequences if they occur.

2.7.2 Integrated Environmental Assessment

Environmental Assessment (EA) is the process of collecting information about the current and future state of environmental quality and resources, analysing it, and deciding on actions to optimise the future environmental state and avoid, diminish or remedy environmental harm. The ultimate purpose of Environmental Assessment is to optimize the quality of the environment. EA's are performed by the following procedure [DOE 1995]:

- Examine the current environmental character of the area under study (the "baseline").
- Identify natural and artificial processes which may already be changing the character of the study area.
- Consider the possible interactions between anticipated environmental pressures and both existing and future site conditions.
- Predict the possible effects, both beneficial and adverse, of the pressures on the environment.
- Introduce measures to avoid, minimise or mitigate adverse effects and enhance positive effects.

Integrated Environmental Assessment (IEA) is increasingly recognised as an important technique for managing the environmental impacts of human actions. IEA may be defined as the interdisciplinary process of identification, analysis and appraisal of all the relevant natural and human processes which affect the quality of the environment and environmental resources.

2.7.3 Integrated Environmental Risk Assessment (IERA)

A type of environmental assessment that may form part of an integrated assessment is Environmental Risk Assessment (IERA). IERA focuses on discrete, occasional and usually accidental events, rather than routine, continuous conditions. IERAs are usually performed on the operation of industrial plant which pose environmental hazards. "Risk" is made up of the combination of two distinct elements:

- what is the probability (or frequency) that an event (usually an accident) will occur
- what are the consequences if it does occur

Assessment of the consequence side is, in principle, similar to any other environmental assessment, although since it deals in general with events that have never happened, there is a much greater requirement for predictive computer models.

The new element is the question of how often the event occurs, and this requires the assessor to examine the industrial process in question to determine and quantify possible accident scenarios and their root causes. Moreover, since different accident scenarios have both different probabilities and different consequences, it is necessary to couch the assessment in probabilistic terms. Whereas most models are deterministic (calculating the consequences of a single, specified accident of probability one), models developed with IERA in mind normally run additionally in probabilistic mode (calculating the consequences of an ensemble of possible accidents, with different probabilities). Probabilistic runs are used to calculate, for example, how often accidents will occur at an industrial plant which lead to a certain environmental pollutant concentration threshold being exceeded.

2.7.4 Uncertainty in Integrated Assessment

One of the dominant issues of climate change is the role of uncertainty. [Manne and Richels 1992], IA models generally have so many variables and dependencies that there are huge numbers of permutations, making uncertainty analysis very difficult. Efficient algorithms and heuristics are needed to solve such problems [Dowlatabadi 1995]. It is important, when using a computer model to make decisions, to have some idea about the level of uncertainty in the model's outputs, and what the main sources of this uncertainty are. Nordhaus [Nordhaus 1994] devotes considerable space to the implications of uncertainty for forming control policies. Other papers that have considered these issues include [Hammitt et al. 1992], [Kolstad 1993], and [Peck et al. 1989]. The uncertainty problem has two dimensions:

- parametric (the quantitative data used in the model) and structural. Parametric uncertainty analysis can be a large task, requiring a large number of model runs followed by a statistical analysis. For a large model with a large number of parameters and a substantial run time, this may only be done once for a typical scenario. We are uncertain about particular parameters of the climate change problem, but it is expected that uncertainty will diminish with time and/or effort (e.g., R&D). A close relative of parametric uncertainty is stochasticity. Stochasticity arises from phenomena that affect the economic or physical processes, but are not modeled. For example, volcanoes, sunspots, and hundreds of other phenomena affect the global mean temperature in a way that is approximated by a parametric uncertainty process [see Kelly et al. 1998]. Secondly, one cannot know the future values of many economic and technology processes because if the future were known, consumers would act on that knowledge in ways which change the future. These two elements--parametric uncertainty and stochasticity - generate significant uncertainty in trying to formulate policy for controlling greenhouse gases (GHGs).
- Structural (the assumptions and simplifications that constitute the model itself). is even harder, requiring a model comparison exercise, which in turn requires a set of models which are similar enough in their functionality to be comparable. These are usually done as one of exercises where groups of modellers predict results for a suitable scenario, and the various predictions compared. They involve a great deal of work, co-ordinating model developers, finding a suitable scenario with the requisite data, performing the model runs and assessing and comparing the results.

Code comparison exercises are, however, extremely useful for finding the strengths and weaknesses of models. The same is true of structural uncertainty analysis. Because of the complexity, most IAMs treat uncertainty more simply via sensitivity analysis in various forms. The most common treatment is a type of Monte Carlo analysis known as *stochastic simulation* [Weyant, et. al. 1995].

2.7.5 Comparison of impacts

Assessing impacts is often one of the most difficult parts of an IA. It is often necessary to make trade-offs and compromises between different impacts. The problem is that many impacts cannot be directly compared, because they cannot be measured in the same way or on the same scale. The European Commission's ExternE project is a major effort to establish a coherent and consistent framework for costing the diverse impacts of energy use. This is expected to prove an important step forward in the assessment of environmental impacts.

2.7.6 Optimization

When faced with an environmental problem, there are generally a number of possible remedial actions. Each course of action will have different results and will be more or less effective at solving the problem. Each course of action will also entail different costs and drawbacks. In these situations, the following sorts of questions arise:

- How can we achieve a specified reduction in environmental harm while minimising the cost?
- How should we spend our fixed budget to achieve the greatest reduction in environmental harm?

Answering these questions is called optimisation. A simple method for this is trial-and-error scenario testing, which is effective when there are only a small number of possibilities. More sophisticated methods include the simple method of linear programming and generic algorithms. Depending on the nature of the problem, optimisation can be straightforward and fast or difficult and time-consuming. Since it is often the output of a computer model that is to be optimised, it is natural to get a computer to perform the optimisation as well. In fact, optimisation is a feature of a larger program rather than a stand-alone tool in its own right.

3 Results

3.1 Global Energy-Climate Model (GEC Model)

Our understanding of the climate system has been revolutionized recently, by the development of sophisticated computer models. The predictions of such models are used to mitigate the severity of global warming and its impacts. Yet, these models are not perfect representations of reality, because they remove from explicit consideration many physical processes which are known to be key aspects of the climate system

Global energy-climate model (GEC model) was constructed in the STELLA program, which makes use of Systems Dynamics Modeling (SDM) as a methodology. Dynamic systems are coordinated or related sets of processes and reservoirs (places where things can reside or forms in which matter or energy exists) through which material or energy flows. System Dynamics attempts to model the basic structure of a system so as to be able to capture the behavior that the system produces (Sterman, 2000). Interactions between objects are accomplished by feedback loops that exist between objects within the system. In feedback loops a change in one variable affects other variables in the system over time (often including delays), which in turn affects the original variable. GEC model connects interactions between Earth's temperature, CO₂ emissions from coal, petroleum, natural gas and energy production from coal, petroleum, natural gas

GEC model consists of three main sectors:

- Climate sector
- Energy consumption sector
- CO₂ emission sector

The logical flow of the energy-climate model is as follows. The energy consumption sector and climate sector interact through the CO₂ emissions sector. Increase in energy consumption is associated with carbon emissions. Emissions increase the concentration of CO₂ in the atmosphere, causing temperature to rise. Much of the macro behavior of the model arises from the feedback structures. The climate sector includes surface-atmosphere reservoirs. Together, the interacting climate, energy consumption and CO₂ emissions sectors provide predictions of both Earth's and atmosphere temperature as a function of time.

3.2 Modeling Energy Consumption

There are two types of energy sources: nonrenewable fossil fuels, and renewables. Nonrenewables are disaggregated into coal (and other solid fuels) and an oil/gas composite. Energy consumption in this model will have four reservoirs: energy consumption from petroleum, energy consumption from coal, energy consumption from natural gas and primary energy consumption (Figure 18). Primary energy consumption refers to the direct use at the source, or supply to users without transformation, of crude energy, that is, energy that has not been subjected to any conversion or transformation process. The total primary energy covers the major energy sources such as fossil fuels (petroleum, natural gas, coal), as well as nuclear and hydroelectric. Type of fuel used is an important factor in emissions because fuels have significantly different ratios of CO₂ emissions per unit of energy consumed. Coal produces 21% more CO₂ than oil and 76% more CO₂ than natural gas per unit of energy consumption. Nuclear, solar, wind, hydroelectric, and biomass energy sources do not result in significant CO₂ emissions. Consequently, CO₂ emissions per unit of energy used are directly related to fuels and technologies in use, and assumptions about fuels and the rate of technological change play a significant role in emissions forecasts

World energy consumption from coal, natural gas, petroleum, fossil fuels and primary energy obtained from GEC model are represented in the Figure 19. Data for the energy consumption are taken from Energy Information Administration, International Energy Annual 2005, table 1.

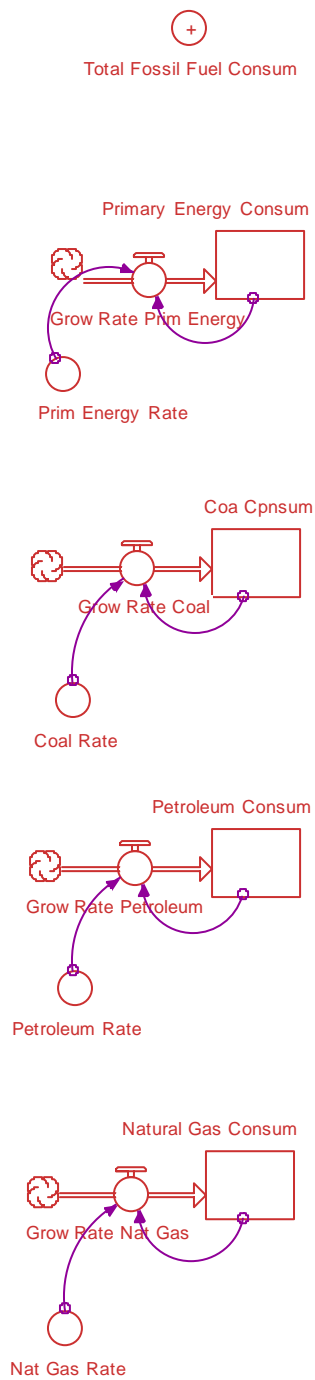


Figure 18: Representation of the energy consumption model.

Algorithm 1: Stella Equations of the Energy Consumption Sector

$$\text{Coal_Consum}(t) = \text{Coal_Consum}(t - dt) + (\text{Grow_Rate_Coal}) * dt$$

$$\text{INIT Coal_Consum} = 89.2$$

INFLOWS:

$$\text{Grow_Rate_Coal} = \text{Coal_Consum} * \text{Coal_Rate}$$

$$\text{Natural_Gas_Consum}(t) = \text{Natural_Gas_Consum}(t - dt) + (\text{Grow_Rate_Nat_Gas}) * dt$$

$$\text{INIT Natural_Gas_Consum} = 73.4$$

INFLOWS:

$$\text{Grow_Rate_Nat_Gas} = \text{Natural_Gas_Consum} * \text{Nat_Gas_Rate}$$

$$\text{Petroleum_Consum}(t) = \text{Petroleum_Consum}(t - dt) + (\text{Grow_Rate_Petroleum}) * dt$$

$$\text{INIT Petroleum_Consum} = 136.4$$

INFLOWS:

$$\text{Grow_Rate_Petroleum} = \text{Petroleum_Consum} * \text{Petroleum_Rate}$$

$$\text{Primary_Energy_Consum}(t) = \text{Primary_Energy_Consum}(t - dt) + (\text{Grow_Rate_Prim_Energy}) * dt$$

$$\text{INIT Primary_Energy_Consum} = 347.4$$

INFLOWS:

$$\text{Grow_Rate_Prim_Energy} = \text{Primary_Energy_Consum} * \text{Prim_Energy_Rate}$$

$$\text{Coal_Rate} = 0.0065$$

$$\text{Nat_Gas_Rate} = 0.0065$$

$$\text{Petroleum_Rate} = 0.004$$

$$\text{Prim_Energy_Rate} = 0.0054$$

$$\text{Total_Fossil_Fuel_Consum} = \text{Coal_Consum} + \text{Natural_Gas_Consum} + \text{Petroleum_Consum}$$

Table 2: World energy consumption (10^{15} BTU) from coal, natural gas, petroleum and total primary energy.

History	Year	Coal Consum	Petroleum Consum	Nat Gas Consum	Tot Fossil Fuel Consum	Primary Energy Consum
	1990	89.20	66.60	73.40	229.20	347.40
	2000	107.93	77.26	86.98	272.17	404.72
	2005	122.5	169.4	103.7	395.6	462.2
Projections	2010	178.32	209.98	146.74	535.04	619.55
	2020	189.92	218.38	156.28	564.57	653.01
	2030	202.26	227.12	166.43	595.81	688.27
	2040	215.41	236.2	177.25	628.86	725.43
	2050	229.41	245.65	188.77	663.83	764.61
	2060	244.32	255.47	201.04	700.84	805.90
	2070	260.20	265.69	214.11	740.01	849.42
	2080	277.11	276.32	228.03	781.46	895.28
	2090	295.13	287.37	242.85	825.35	943.63
	2100	314.31	298.87	258.64	871.81	994.59

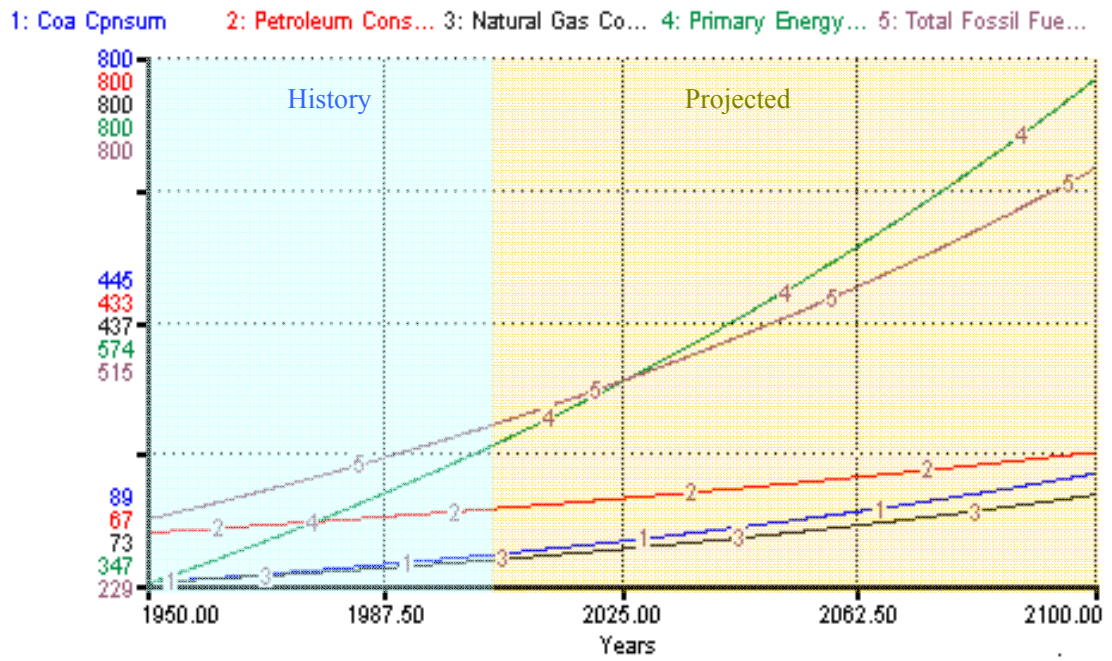


Figure 19: World energy consumption from coal (blue line+1), petroleum (red line+2) natural gas (black line-3), primary energy (green line-4), and fossil fuels (brown line-5) obtained from GEC model.

3.3 Modeling CO₂ Emissions

The problem with greenhouse warming is that certain trace gases with high absorption coefficients are being introduced into the atmosphere through anthropogenic activities. This will cause a greenhouse warming of some magnitude over the next several decades. Since the concentration of most of these gases is highest in the troposphere, most warming will be in the lower atmosphere and on the surface. From all the GHGs, carbon dioxide contributes about 55% of the effect and is produced by fossil fuel burning (67%) and deforestation and other forms of land clearing and burning. The release of CO₂ to the atmosphere by fossil fuel burning and deforestation is increasing the amount of CO₂ in the atmosphere by approximately 0.4% per year.

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. That share is projected to stabilize at between 20% and 21% from 2005 to 2030.

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.

Emissions from coal, petroleum and gas equal the rate of energy consumption multiplied by the carbon content of the fuel.

CO₂ emissions in this model will have just four reservoirs: CO₂ emission from petroleum, CO₂ emission from coal, CO₂ emission from natural gas and CO₂ emission from fossil fuels (Figure 20). CO₂ emissions from fossil fuels obtained from GEC model are represented in the Figure 21. These data are in agreement with IEA data (table. 2).

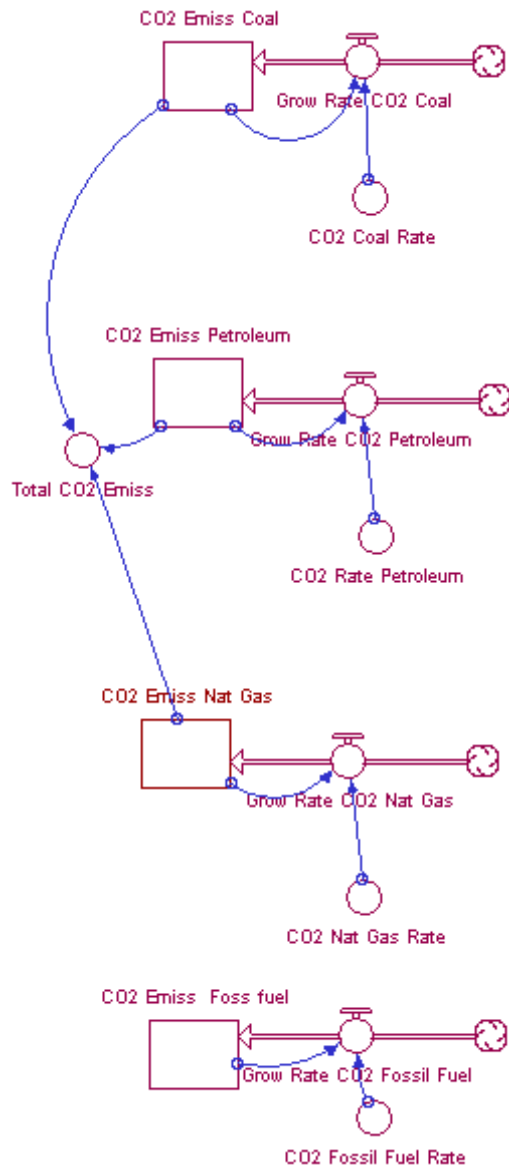


Figure 20: Representation of the CO₂ emission sector.

Algorithm 2: Stella Equations of the CO₂ Emissions Sector

```

Coal_Productl(t) = Coal_Productl(t - dt) + (Grow_Rate_Coal) * dt
CO2_Emiss_Coal(t) = CO2_Emiss_Coal(t - dt) + (Grow_Rate_CO2_Coal) * dt
INIT CO2_Emiss_Coal = 6.489
INFLOWS:
Grow_Rate_CO2_Coal = CO2_Emiss_Coal*CO2_Coal_Rate
CO2_Emiss_Nat_Gas(t) = CO2_Emiss_Nat_Gas(t - dt) + (Grow_Rate_CO2_Nat_Gas) * dt
INIT CO2_Emiss_Nat_Gas = 3.090
INFLOWS:
Grow_Rate_CO2_Nat_Gas = CO2_Emiss_Nat_Gas*CO2_Nat_Gas_Rate
CO2_Emiss_Petroleum(t) = CO2_Emiss_Petroleum(t - dt) + (Grow_Rate_CO2_Petroleum) * dt
INIT CO2_Emiss_Petroleum = 8.750
INFLOWS:
Grow_Rate_CO2_Petroleum = CO2_Emiss_Petroleum*CO2_Rate_Petroleum
CO2_Emiss_Foss_fuel(t) = CO2_Emiss_Foss_fuel(t - dt) + (Grow_Rate_CO2_Fossil_Fuel) * dt
INIT CO2_Emiss_Foss_fuel = 18.33068
INFLOWS:
Grow_Rate_CO2_Fossil_Fuel = CO2_Emiss_Foss_fuel*CO2_Fossil_Fuel_Rate
CO2_Coal_Rate = 0.0374
CO2_Fossil_Fuel_Rate = 0.0287
CO2_Increase = CO2_Abs_Calibration *
(CO2_Emiss_Foss_fuel- 1)
CO2_Nat_Gas_Rate = 0.0425
CO2_Rate_Petroleum = 0.0152
Total_CO2_Emiss = CO2_Emiss_Coal+CO2_Emiss_Nat_Gas+CO2_Emiss_Petroleum

```

Table 3: World carbon dioxide emissions by fuel type, (Milion Metric Tons Carbon Dioxide

	Year	Coal	Petroleum	Natural Gas	Total
History	1990	8253	9009	3954	21226
	2000	8673	10091	4985	23751
	2005	11,378	10995	5666	28,051
Projected	2010	11,921.68	11,399.26	5,608.82	28,929.76
	2020	12,672.74	11,855.23	5,945.35	30,473.33
	2030	13,471.13	12,329.44	6,302.08	32,102.64
	2040	14,319.81	12,822.62	6,680.20	33,822.62
	2050	15,221.95	13,335.52	7,081.01	35,638.49
	2060	16,180.94	13,868.94	7,505.87	37,555.75
	2070	17,200.34	14,423.70	7,956.22	39,580.26
	2080	18,283.96	15,000.65	8,433.60	41,718.20
	2090	19,435.85	15,600.67	8,939.61	43,976.13
	2100	20,660.30	16,224.70	9,475.99	46,361.00

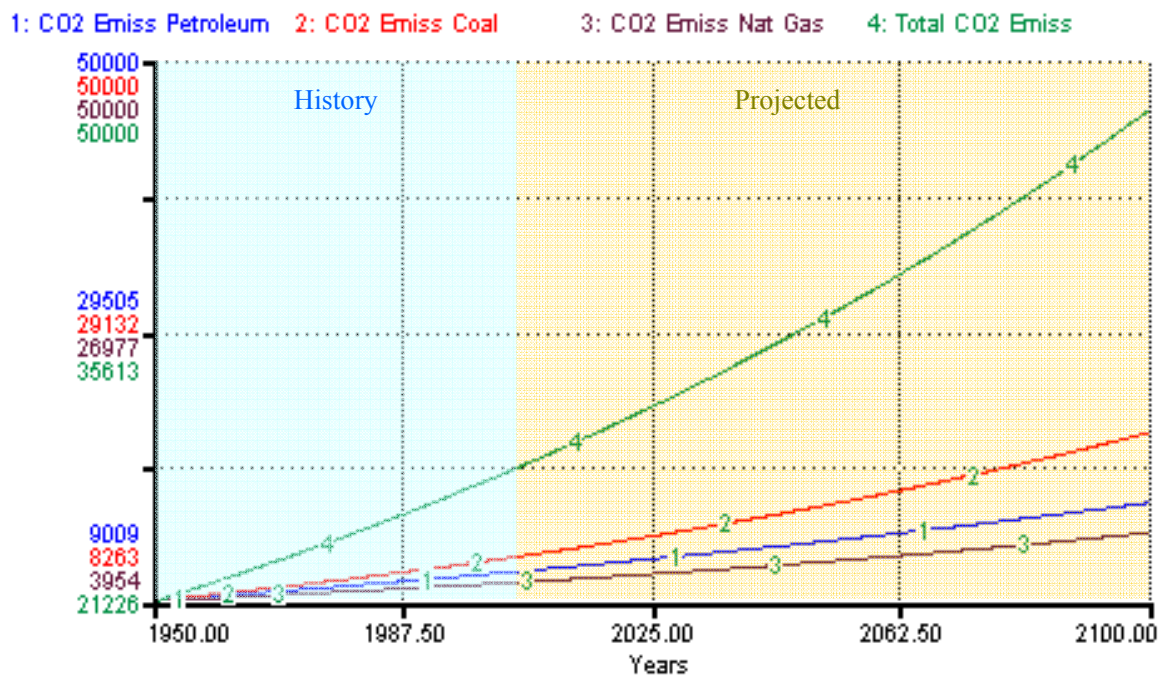


Figure 21: World carbon dioxide emissions of fossil fuels from petroleum (blue line-1), coal (red line-2), natural gas (brown line-3), and total (green line-4), obtained from GEC model.

3.4 Modeling Climate System

The global climate system is a consequence of and a link between the atmosphere, oceans, the ice sheets (cryosphere), living organisms (biosphere) and the soils, sediments and rocks (geosphere). Only by consideration of the climate system in these terms is possible to understand the flows and cycles of energy and matter in the atmosphere. The Earth's global energy balance is shown in Figure 22. The determination of the Earth's radiation budget is essential to atmospheric modeling and climate studies. Radiation budget experiments have used satellites to measure the fundamental radiation parameters -- the amount of solar energy received by the planet, the planetary albedo (the portion of incoming solar radiation that is reflected back to space), the emitted terrestrial radiation (also referred to as the long-wave radiation – LW radiation), and the net planetary energy balance (the difference between the absorbed solar energy and the LW radiation). Of the total sunlight falling on Earth (100%), 31% is reflected back to space and 69% is absorbed. This part is used by the climate and serves for keeping the temperature. The absorbed radiation is then emitted as infrared radiation. About half the light reaching Earth's atmosphere passes through the air and clouds to the surface, where it is absorbed and then radiated upward in the form of infrared heat. Because Earth is shaped like a sphere, not all locations face the sun directly, so tropical regions receive more sunlight than polar regions. Earth's daily rotation also decreases the time for receiving sunlight. Thus, the average of the total amount of solar energy received by the Earth is $55.6 \cdot 10^{24}$ Joules/year [Barry and Chorley, 1992]. Almost all of the reflected sunlight (24% out of 31%) is reflected by clouds, which cover 3/5 of Earth. In cloud-free areas the remaining 7% of the sunlight is reflected by the atmosphere (4%) and by the surface (3%). If clouds covered the whole Earth they would reflect 38% of the sunlight, more than twice what would be reflected by a completely cloud-free Earth (17%). Atmospheric gases, mostly water vapor with a little help from ozone and carbon dioxide, also absorb 19% of the sunlight, providing one third of the heating of the atmosphere. Because clouds and the atmosphere prevent some of the sunlight from reaching the surface and prevent some of the sunlight reflected from the surface from going back to space, the total amount of reflected sunlight going back into space from the surface is only 3%. The surface is heated by absorbing 50% of the sunlight, almost 3/4 of the total absorbed by the whole Earth. Most of this energy is absorbed by the oceans. The near-equator zone is heated more because the amount of absorbed sunlight is larger than the emitted infrared. The poles are cooled because the infrared radiation is larger than the absorbed. This pattern of heating and cooling drives atmospheric winds (the weather) and ocean currents.

The "greenhouse effect" is the warming of climate that results from the atmosphere trapping heat radiating from Earth's surface. Certain gases in the atmosphere resemble glass in a greenhouse, allowing sunlight to pass into the "greenhouse," but blocking Earth's heat from escaping into space. Land surface temperatures respond very quickly to changes in sunlight so that nighttime is cooler than daytime. At middle latitudes, land surface temperatures are larger than ocean temperatures in summer and smaller in winter. The warm surface cools by emitting infrared ("heat") radiation. Earth's surface also cools because of direct contact between the atmosphere and surface (6%, more important over land) and because of evaporating water (30%, more important over oceans). Earth's surface absorbs 50% of the sunlight, but its temperature is so high that it emits an amount of energy (116%), greater than the total from the sun (100%). This is possible because most of the infrared radiation is absorbed by water vapor and carbon dioxide in the atmosphere, then the heated atmosphere emits infrared radiation (102% of incident sunlight) downward towards the surface, so that the total heat loss by radiation is only 14%. This is the greenhouse effect. Without it, Earth's surface temperature would be 35°C colder, well below the freezing point of water. Since the energy received is approximately equal to the energy radiated from the Earth, in energetic aspect the Earth is in a stable state (Schneider, 1992).

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 model is to determine the Earth's temperature at which the incoming and outgoing flows are balanced.

The differential equations governing the climate system are well known. In a common approach to solving these equations, errors arise owing to the replacement of the exact derivative terms with finite differences.

It is predicted that over the next several decades the Earth will warm through greenhouse effects by a few degrees Celsius. This may lead to profound changes of climate and biomass.

Climate system in this model will have just two reservoirs where energy is stored -- the atmosphere and

the Earth's surface linked by six flows (Figure 23). Some of the main features of this model are briefly described below.

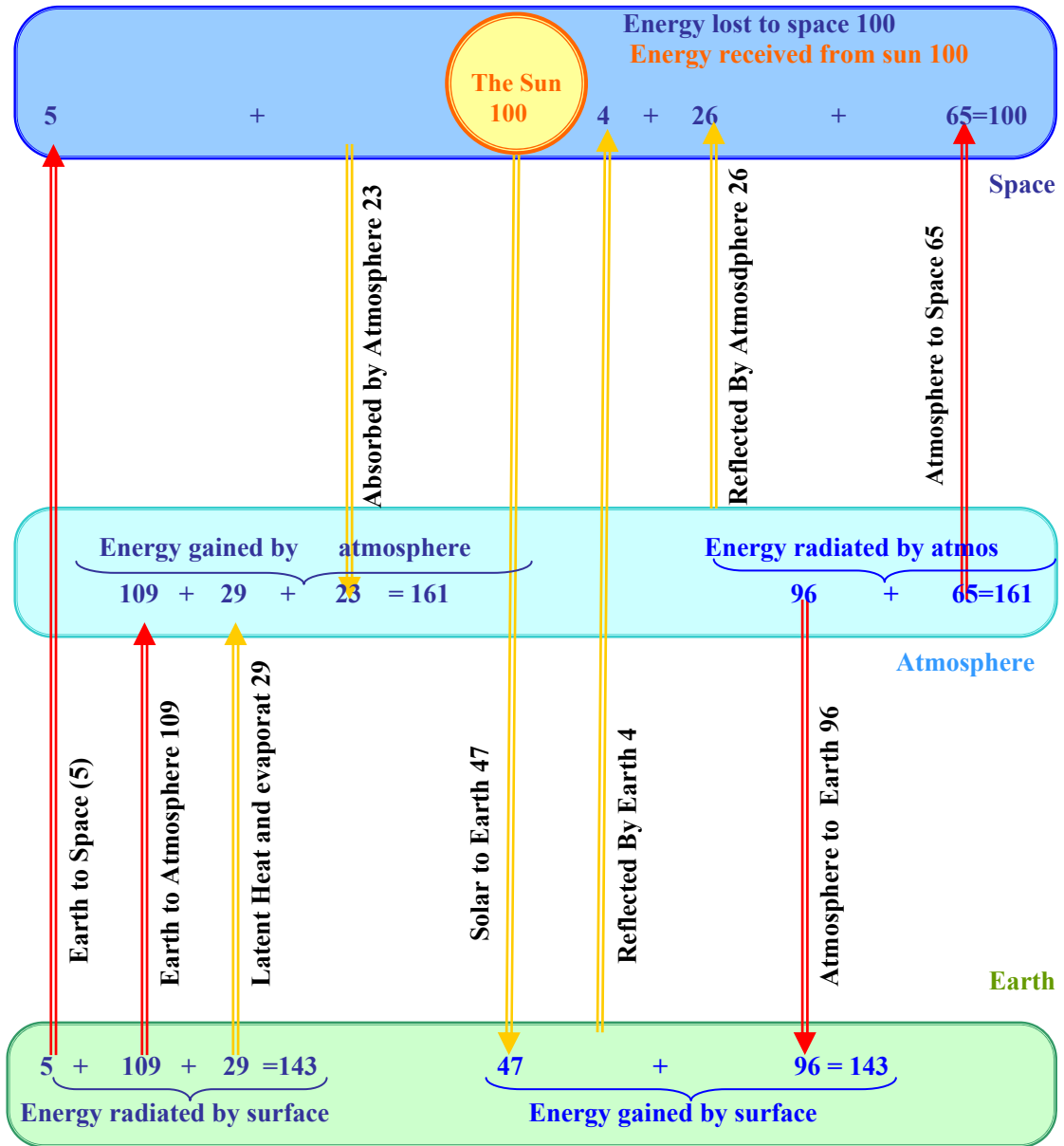


Figure 22: The Earth’s global energy balance. Source, [Baede et als]

I've assumed that the oceans cover 70% of the surface S (an area of about $3.57 \cdot 10^{14} \text{ m}^2$) 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:

$$m = \rho h S = 1000 \frac{\text{kg}}{\text{m}^3} 100\text{m} \cdot 3.57 \cdot 10^{14} \text{ m}^2 = 0.357 \cdot 10^{20} \text{ kg} \tag{22}$$

where ρ - density of water. The water heat capacity:

$$H = \pi d^2 h \rho c \tag{23}$$

where c – specific heat capacity of water.
The Earth's average temperature:

$$T_e = \frac{Q}{H} \quad (24)$$

where Q – total energy stored in the oceanic part of the reservoir is:

$$Q = mc\Delta t = 0.125 \cdot 10^{20} \text{ kg} \cdot 4.186 \cdot 10^3 \frac{\text{J}}{\text{kgK}} \cdot 288\text{K} = 1.50 \cdot 10^{25} \text{ J} \quad (25)$$

Obtained result is about 2.7 times greater than the total amount of energy received by the Earth from the sun in one year. By analogous calculations we find the amount of energy received by the Earth. If the land area is $1.53 \cdot 10^{14} \text{ m}^2$, 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 6.610^{22} J . The same calculations are carried out for the atmosphere, assuming a mass of $5.14 \cdot 10^{18} \text{ kg}$, an average temperature of -18°C , and a heat capacity of 700 J/kg K , which results in $9.17 \cdot 10^{23} \text{ J}$. Below, I 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:

$$R_{SE} = S_0 - I_C - I_S - I_A \quad (26)$$

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

$$I_A = S_0 (1 - \alpha) \quad (27)$$

where $\alpha = 0.82$ – atmospheric absorption coefficient, and insolation reflected by surface:

$$I_S = A_e (S_0 - I_C - I_A) \quad (28)$$

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:

$$I_C = S_0 P A_c \quad (29)$$

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:

$$R_{SA} = (1 - \alpha) S_0 \quad (30)$$

Radiation emitted from surface lost to space (Earth to space - R_{ESp}) - Some portion of the infrared radiation emitted from the surface escapes, passing through the atmosphere without being absorbed -- this is energy lost from the system. The magnitude of this flow is currently estimated to be 8 units of energy, but it is also a function of the temperature (specifically the fourth power of the temperature) of the surface since the temperature determines the overall amount of infrared energy emitted. A simple way of expressing this is:

$$R_{ESp} = (1 - \alpha) F_e \quad (31)$$

F_e – Stefan Boltzman law applied for the case of Earth

$$F_e = k S \sigma T_e^4 = 5.1 \cdot 10^{14} \cdot 5.67 \cdot 10^{-8} \cdot 3.155 \cdot 10^7 \frac{S}{yr} T_e^4 F_e$$

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.

$$k = 31557600 \frac{S}{yr} = 3.155 \cdot 10^7 \frac{S}{yr}$$

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:

$$R_{ASp} = F_A \quad (32)$$

F_A – Stefan Boltzman law applied for the case of atmosphere,

$$F_A = k S \sigma T_A^4 \quad (33)$$

Here, $\sigma = 5.67 \cdot 10^{-8} \text{ Js}^{-1} \text{ m}^{-2} \text{ K}^{-4}$ 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}) - This flow consists of several different processes -- heat transfer through evaporation and condensation, and convective motion of air that is warmed at the surface. A full mathematical formulation of these processes would be far too complex for a model of this sort, so we will instead apply the simple assumption that all of these processes will depend on the temperature of the Earth surface in a relatively simple fashion:

$$R_{EA} = \alpha k S \sigma T_e^4 \quad (34)$$

Long wave radiation emitted from atmosphere to surface (Atmosphere LW to Earth - R_{AR}) - This flow represents the emission of infrared energy from the atmosphere back to the surface -- the greenhouse effect. The magnitude of this flow is really just a function of the temperature of the atmosphere, and so we define the flow with a nonlinear temperature dependence like the other flows that represent radiative heat transport:

$$R_{AE} = k S \sigma T_A^4 \quad (35)$$

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.

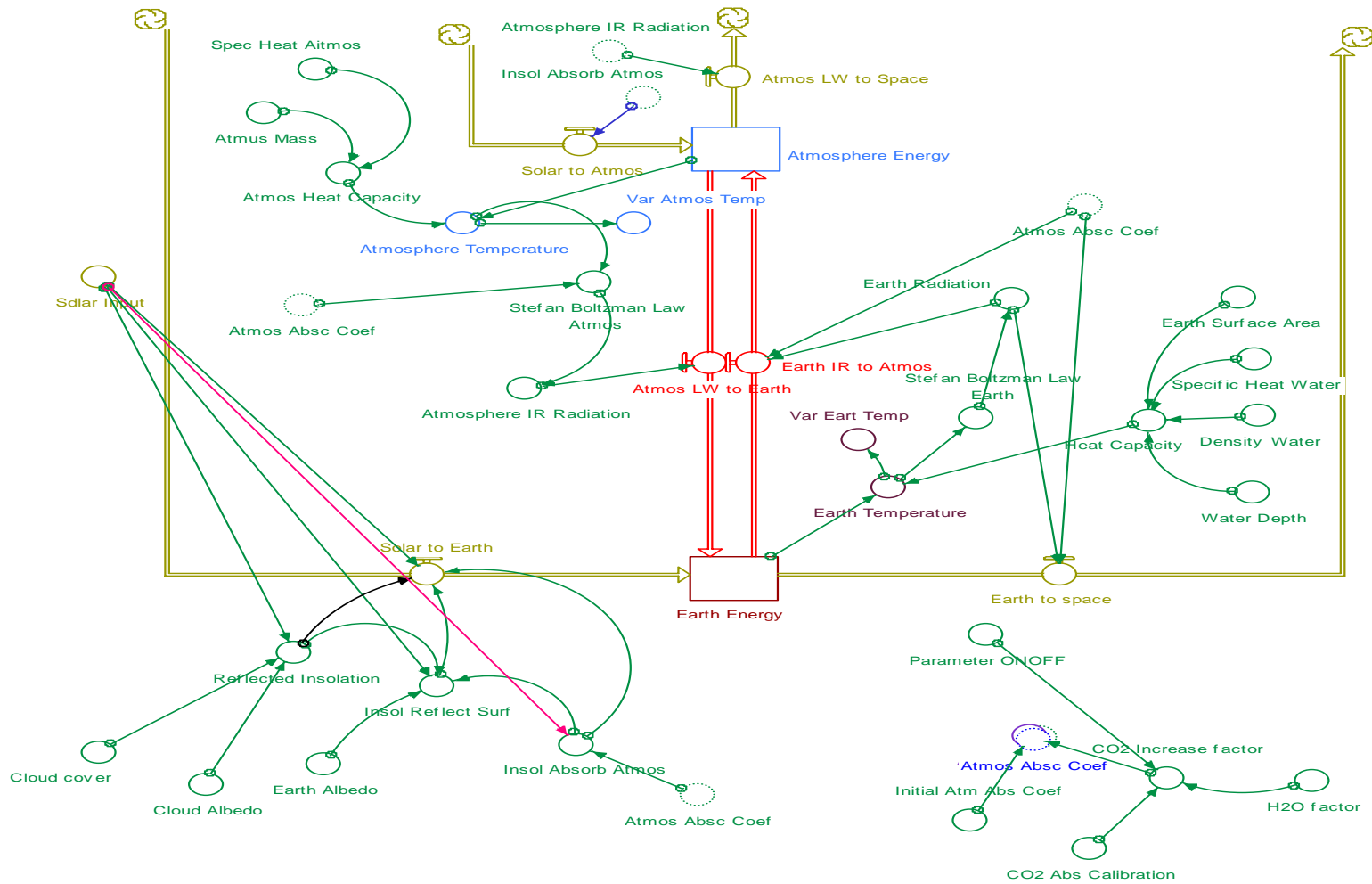


Figure 23: Representation of the climate sector.

Algorithm 2: Stella Equations of the Climate Sector

$\text{Atmosphere_Energy}(t - dt) + (\text{Surface_to_Atmosphere} + \text{Solar_to_atmos} - \text{Atmos_LW_to_Surface} - \text{Atmos_LW_to_Space}) * dt$
 INIT Atmosphere_Energy = 0.165*5.56E24
 INFLOWS: Surface_to_Atmosphere = Atmos_Absc_Coef*Surface_radiation
 Solar_to_atmos = (1-Atmos_Absc_Coef)*(Sdlar_input-Reflected_insolation)
 OUTFLOWS:
 Atmos_LW_to_Surface = Atmosphere_rIR_radiation*Atmos_Absc_Coef
 Atmos_LW_to_Space = Atmosphere_rIR_radiation
 $\text{Surface_Energy}(t) = \text{Surface_Energy}(t - dt) + (\text{Atmos_LW_to_Surface} + \text{Solar_to_Surface} - \text{Surface_to_Atmosphere} - \text{Surface_to_Space}) * dt$
 INIT Surface_Energy = 2.712*5.56E24
 INFLOWS:
 Atmos_LW_to_Surface = Atmosphere_rIR_radiation*Atmos_Absc_Coef
 Solar_to_Surface = (Sdlar_input-Reflected_insolation-Insol_reflect_surf)*Insol_absorb_atmos
 OUTFLOWS:
 Surface_to_Atmosphere = Atmos_Absc_Coef*Surface_radiation
 Surface_to_Space = (1 - Atmos_Absc_Coef) *Surface_radiation {J/yr}
 a = 1
 Atmosphere_rIR_radiation = Stefan_Boltzma_Law
 Atmosphere_Temperature = Atmosphere_Energy/Atm_Heat_Capc+246
 Atmos_Absc_Coef = Atm_Abs_Coef_now+CO2_Increase
 Atm_Abs_Coef_now = 0.8
 Atm_Heat_Capc = 5.16E21
 b = 2E-3
 Cloud_albedo = 0.5*Parameter_1
 Cloud_cover = 0.6
 CO2_Abs_Calibration = 0.00008
 CO2_Increase = CO2_Abs_Calibration *
 (CO2_Emiss_Foss_fuel- 1)
 Earth_Albedo = a-b*Surface_Temperature
 Global_mean_temperature = (Surface_Temperature+Atmosphere_Temperature)/2
 Heat_Capacity = 2.15E23
 Insol_absorb_atmos = Atmos_Absc_Coef
 Insol_reflect_surf = Earth_Albedo*(Sdlar_input-Reflected_insolation-Insol_absorb_atmos-
 Inso_absorb_surfacel)
 Inso_absorb_surfacel = 0.51*5.56E24
 Parameter_1 = 0.6
 Reflected_insolation = Sdlar_input*Cloud_cover*Cloud_albedo
 Sdlar_input = 5.56E24
 Stefan_Boltzman_Law = 5.1E14*5.67E-8 {J/m2 s K4} * 3.15576E7 {s/yr} *
 Surface_Temperature^4 {K4}
 Stefan_Boltzma_Law = 5.1E14*5.67E-8 {J/m2 s K4} * 3.15576E7 {s/yr} *
 Atmosphere_Temperature^4 {K4}
 Surface_radiation = Stefan_Boltzman_Law
 Surface_Temperature = Surface_Energy/Heat_Capacity
 Var_Atm_Temp = 249+Atmosphere_Temperature
 Var_Eart_Temp = 288+Surface_Temperatur

Global Energy-Climate Model (GEC Model)

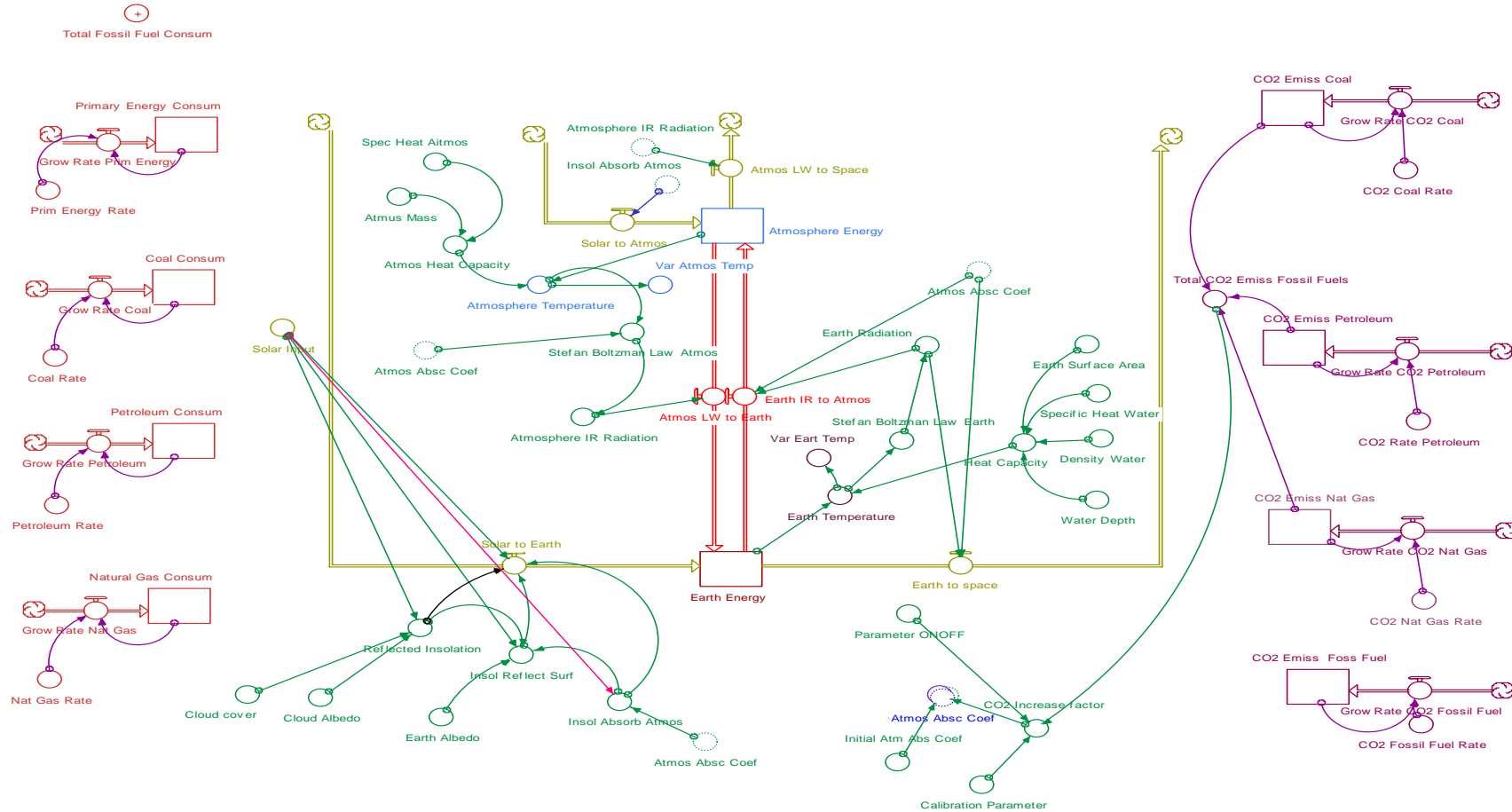


Figure 24: Representation of the Global Energy-Climate Model (GEC Model).

Algorithm 3: Stella Equations of the Global Energy-Climate Model (GEC Model)

$$\text{Atmosphere_Energy}(t) = \text{Atmosphere_Energy}(t - dt) + (\text{Surface_to_Atmosphere} + \text{Solar_to_atmos} - \text{Atmos_LW_to_Surface} - \text{Atmos_LW_to_Space}) * dt$$

$$\text{INIT Atmosphere_Energy} = 0.165 * 5.56E24$$

INFLOWS:

$$\text{Surface_to_Atmosphere} = \text{Atmos_Absc_Coef} * \text{Surface_radiation}$$

$$\text{Solar_to_atmos} = (1 - \text{Atmos_Absc_Coef}) * (\text{Sdlar_input} - \text{Reflected_insolation})$$

OUTFLOWS:

$$\text{Atmos_LW_to_Surface} = \text{Atmosphere_rIR_radiation} * \text{Atmos_Absc_Coef}$$

$$\text{Atmos_LW_to_Space} = \text{Atmosphere_rIR_radiation}$$

$$\text{CO2_Emiss_Coal}(t) = \text{CO2_Emiss_Coal}(t - dt) + (\text{Grow_Rate_CO2_Coal}) * dt$$

$$\text{INIT CO2_Emiss_Coal} = 6.489$$

INFLOWS:

$$\text{Grow_Rate_CO2_Coal} = \text{CO2_Emiss_Coal} * \text{CO2_Coal_Rate}$$

$$\text{CO2_Emiss_Nat_Gas}(t) = \text{CO2_Emiss_Nat_Gas}(t - dt) + (\text{Grow_Rate_CO2_Nat_Gas}) * dt$$

$$\text{INIT CO2_Emiss_Nat_Gas} = 3.090$$

INFLOWS:

$$\text{Grow_Rate_CO2_Nat_Gas} = \text{CO2_Emiss_Nat_Gas} * \text{CO2_Nat_Gas_Rate}$$

$$\text{CO2_Emiss_Petroleum}(t) = \text{CO2_Emiss_Petroleum}(t - dt) + (\text{Grow_Rate_CO2_Petroleum}) * dt$$

$$\text{INIT CO2_Emiss_Petroleum} = 8.750$$

INFLOWS:

$$\text{Grow_Rate_CO2_Petroleum} = \text{CO2_Emiss_Petroleum} * \text{CO2_Rate_Petroleum}$$

$$\text{CO2_Emiss_Foss_fuel}(t) = \text{CO2_Emiss_Foss_fuel}(t - dt) + (\text{Grow_Rate_CO2_Fossil_Fuel}) * dt$$

$$\text{INIT CO2_Emiss_Foss_fuel} = 18.33068$$

INFLOWS:

$$\text{Grow_Rate_CO2_Fossil_Fuel} = \text{CO2_Emiss_Foss_fuel} * \text{CO2_Fossil_Fuel_Rate}$$

$$\text{Coa_Productl}(t) = \text{Coa_Productl}(t - dt) + (\text{Grow_Rate_Coal}) * dt$$

$$\text{INIT Coa_Productl} = 91.023$$

INFLOWS:

$$\text{Grow_Rate_Coal} = \text{Coa_Productl} * \text{Coal_Rate}$$

$$\text{Natural_Gas_Product}(t) = \text{Natural_Gas_Product}(t - dt) + (\text{Grow_Rate_Nat_Gas}) * dt$$

$$\text{INIT Natural_Gas_Product} = 75.901$$

INFLOWS:

$$\text{Grow_Rate_Nat_Gas} = \text{Natural_Gas_Product} * \text{Nat_Gas_Rate}$$

$$\text{Petroleum_Product}(t) = \text{Petroleum_Product}(t - dt) + (\text{Grow_Rate_Petroleum}) * dt$$

$$\text{INIT Petroleum_Product} = 136.216$$

INFLOWS:

$$\text{Grow_Rate_Petroleum} = \text{Petroleum_Product} * \text{Petroleum_Rate}$$

$$\text{Primary_Energy_Product}(t) = \text{Primary_Energy_Product}(t - dt) + (\text{Grow_Rate_Prim_Energy}) * dt$$

$$\text{INIT Primary_Energy_Product} = 349.833$$

INFLOWS:

$$\text{Grow_Rate_Prim_Energy} = \text{Primary_Energy_Product} * \text{Prim_Energy_Rate}$$

$$\text{Surface_Energy}(t) = \text{Surface_Energy}(t - dt) + (\text{Atmos_LW_to_Surface} + \text{Solar_to_Surface} - \text{Surface_to_Atmosphere} - \text{Surface_to_Space}) * dt$$

$$\text{INIT Surface_Energy} = 2.712 * 5.56E24$$

INFLOWS:

$$\text{Atmos_LW_to_Surface} = \text{Atmosphere_rIR_radiation} * \text{Atmos_Absc_Coef}$$

$$\text{Solar_to_Surface} = (\text{Sdlar_input} - \text{Reflected_insolation} - \text{Insol_reflect_surf}) * \text{Insol_absorb_atmos}$$

OUTFLOWS:

$$\text{Surface_to_Atmosphere} = \text{Atmos_Absc_Coef} * \text{Surface_radiation}$$

$$\text{Surface_to_Space} = (1 - \text{Atmos_Absc_Coef}) * \text{Surface_radiation} \text{ \{J/yr\}}$$

$$a = 1$$

$$\text{Atmosphere_rIR_radiation} = \text{Stefan_Boltzma_Law}$$

$$\text{Atmosphere_Temperature} = \text{Atmosphere_Energy} / \text{Atm_Heat_Capc} + 246$$

$$\text{Atmos_Absc_Coef} = \text{Atm_Abs_Coef_now} + \text{CO2_Increase}$$

$$\text{Atm_Abs_Coef_now} = 0.8$$

$$\text{Atm_Heat_Capc} = 5.16\text{E}21$$

$$b = 2\text{E}-3$$

$$\text{Cloud_albedo} = 0.5 * \text{Parameter_1}$$

$$\text{Cloud_cover} = 0.6$$

$$\text{CO2_Abs_Calibration} = 0.00008$$

$$\text{CO2_Coal_Rate} = 0.0374$$

$$\text{CO2_Emis_fossil_fuels} = \text{CO2_Emiss_Coal} + \text{CO2_Emiss_Nat_Gas} + \text{CO2_Emiss_Petroleum}$$

$$\text{CO2_Fossil_Fuel_Rate} = 0.0287$$

$$\text{CO2_Increase} = \text{CO2_Abs_Calibration} *$$

$$(\text{CO2_Emiss_Foss_fuel} - 1)$$

$$\text{CO2_Nat_Gas_Rate} = 0.0425$$

$$\text{CO2_Rate_Petroleum} = 0.0152$$

$$\text{Coal_Rate} = 0.02$$

$$\text{Earth_Albedo} = a - b * \text{Surface_Temperature}$$

$$\text{Global_mean_temperature} = (\text{Surface_Temperature} + \text{Atmosphere_Temperature}) / 2$$

$$\text{Heat_Capacity} = 2.15\text{E}23$$

$$\text{Insol_absorb_atmos} = \text{Atmos_Absc_Coef}$$

$$\text{Insol_reflect_surf} = \text{Earth_Albedo} * (\text{Sdlar_input} - \text{Reflected_insolation} - \text{Insol_absorb_atmos} - \text{Inso_absorb_surfacel})$$

$$\text{Inso_absorb_surfacel} = 0.51 * 5.56\text{E}24$$

$$\text{Nat_Gas_Rate} = 0.022$$

$$\text{Parameter_1} = 0.6$$

$$\text{Petroleum_Rate} = 0.014$$

$$\text{Prim_Energy_Rate} = 0.0184$$

$$\text{Reflected_insolation} = \text{Sdlar_input} * \text{Cloud_cover} * \text{Cloud_albedo}$$

$$\text{Sdlar_input} = 5.56\text{E}24$$

$$\text{Stefan_Boltzman_Law} = 5.1\text{E}14 * 5.67\text{E}-8 \text{ \{J/m}^2 \text{ s K}^4\} * 3.15576\text{E}7 \text{ \{s/yr\}} *$$

$$\text{Surface_Temperature}^4 \text{ \{K}^4\}$$

$$\text{Stefan_Boltzma_Law} = 5.1\text{E}14 * 5.67\text{E}-8 \text{ \{J/m}^2 \text{ s K}^4\} * 3.15576\text{E}7 \text{ \{s/yr\}} *$$

$$\text{Atmosphere_Temperature}^4 \text{ \{K}^4\}$$

$$\text{Surface_radiation} = \text{Stefan_Boltzman_Law}$$

$$\text{Surface_Temperature} = \text{Surface_Energy} / \text{Heat_Capacity}$$

$$\text{Totl_Fossil_Fuel_Product} = \text{Coa_Productl} + \text{Natural_Gas_Product} + \text{Petroleum_Product}$$

$$\text{Var_Atm_Temp} = 249 + \text{Atmosphere_Temperature}$$

$$\text{Var_Eart_Temp} = 288 + \text{Surface_Temperature}$$

3.5 Results and Model Simulations

After the running of the climate model (i.e. global model in which the influence of emission of CO₂ is not taken into consideration) (Figure 23), the graphs as in Figure 25 are obtained. In this case, we have to deal with the zero-energy balance model for which constant temperatures are obtained for the temperature of the atmosphere 255 K = -18 °C and 288 K = 15 °C for the temperature of the Earth.

Graph (Figure 26) is obtained after the execution of the GEC model (Figure 24). From this graphs we see a gradual increase in atmosphere's and Earth's temperatures. This increase is due to the connection between the sectors of CO₂ emission and climate system. This increase in temperature is a consequence of the increase of CO₂ 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 °C, which is in accordance with the data obtained from IPCC for the same time interval, which is approximately 7 °C. 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 CO₂ emission is not taken into consideration is shown in Figure 27.

In climate change simulations assumed changes of the forcing are tested and the obtained results are analyzed. These changes are “scenarios” of possible and plausible changes. The output of the climate models is then named a “climate change scenario” of a possible and plausible future climate. Scenarios are “coherent, internally consistent and plausible descriptions of possible future states of the world” (IPCC, 1994). The scenarios are not predictions; they do not describe the most probable development; instead usually several different scenarios are presented, which differ significantly from each other. Scenarios are images of a possible future; as such they have an impact on the future itself. Thus, scenarios are not only depictions of possible futures, but also active agents forming the future. Now, a whole series of model simulations with specified changes in certain variables could be generated.

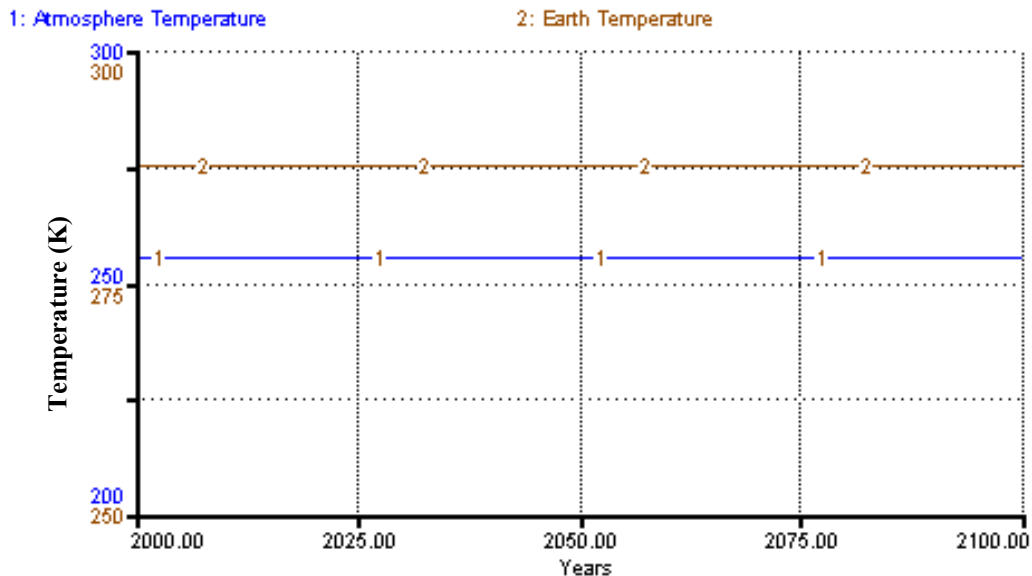


Figure 25: Values obtained from the GEC model (CO₂ emission is not taken into consideration): a) Global Earth's temperature, which is a constant and has the value 288 K (blue line - 1), b) Global Earth's temperature, which is a constant and has the value 255 K (brown line - 2)

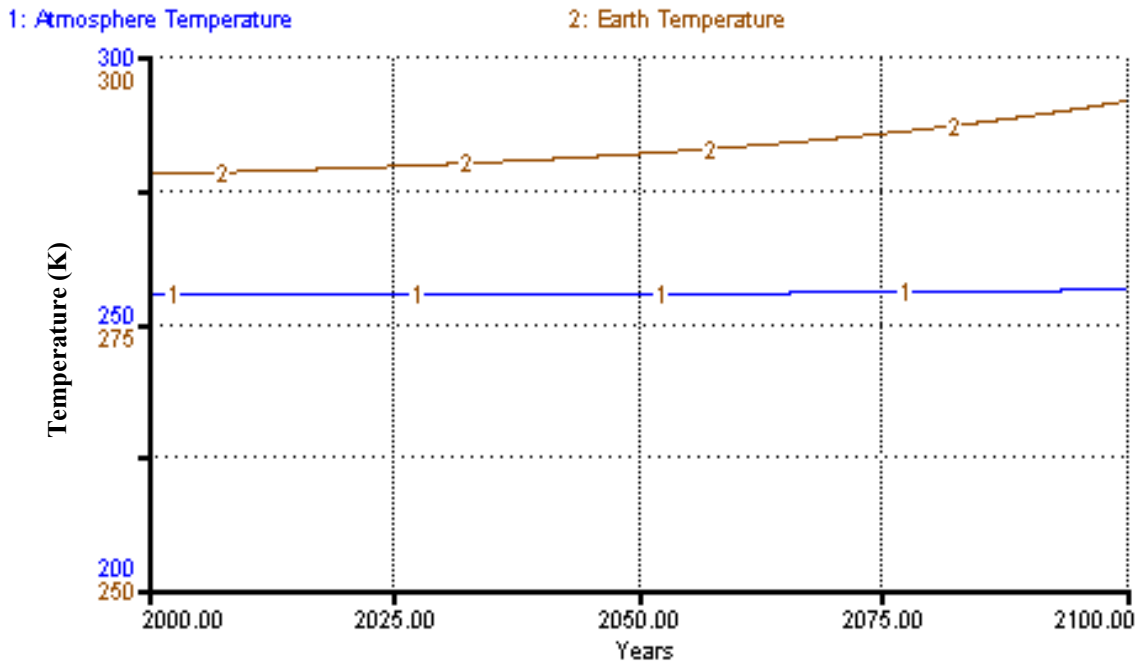


Figure 26; Values obtained from the GEC model (CO₂ emission in atmosphere is taken into consideration): a) Global atmosphere’s temperature (blue line-1) b) Global Earth’s temperature (brown line-2).

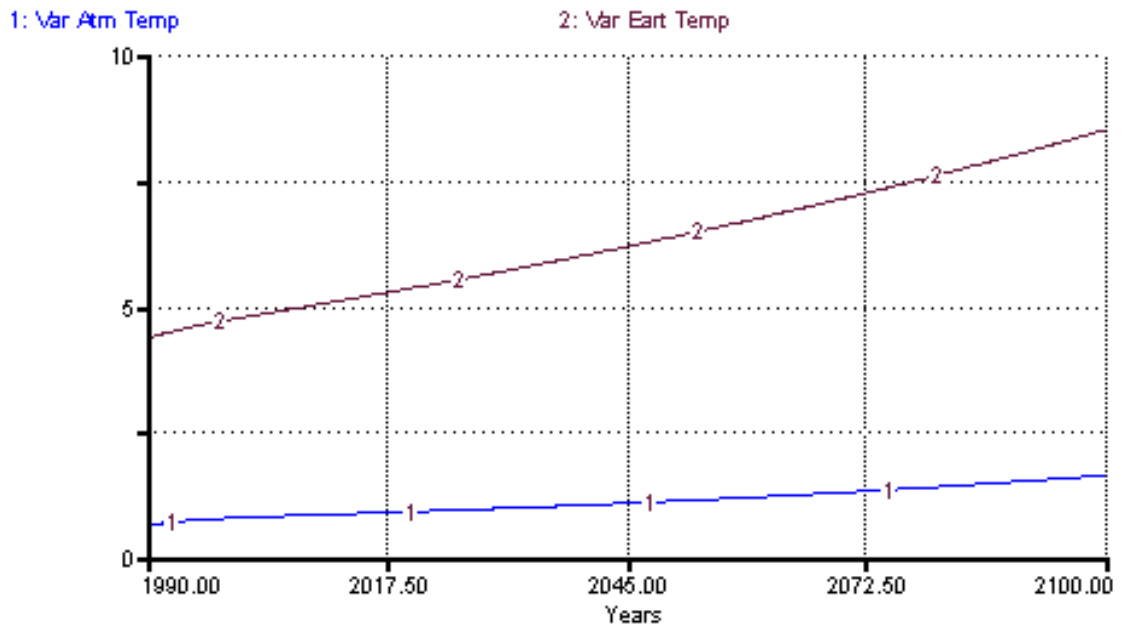


Figure 27; Values obtained from the GEC model (CO₂ emission in atmosphere is taken into consideration): a) Variations of global atmosphere’s temperature (blue line-1) b) Variations of global Earth’s temperature (brown line-2).

Below, we have represented graphically the fluxes used in GEC model, taking into consideration the CO₂ emission (Figures 28a – 32a), and the same fluxes obtained from this model, where the CO₂ emission is not taken into consideration (Figures 28b – 32b),

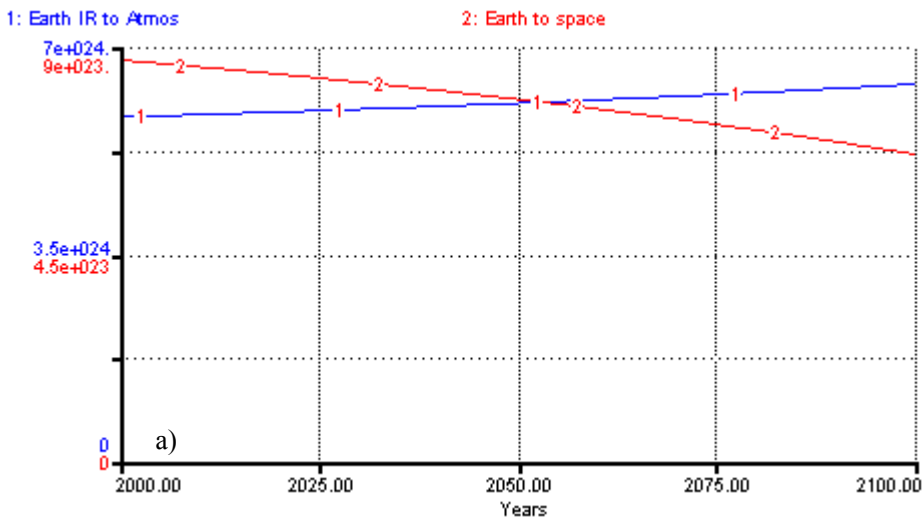
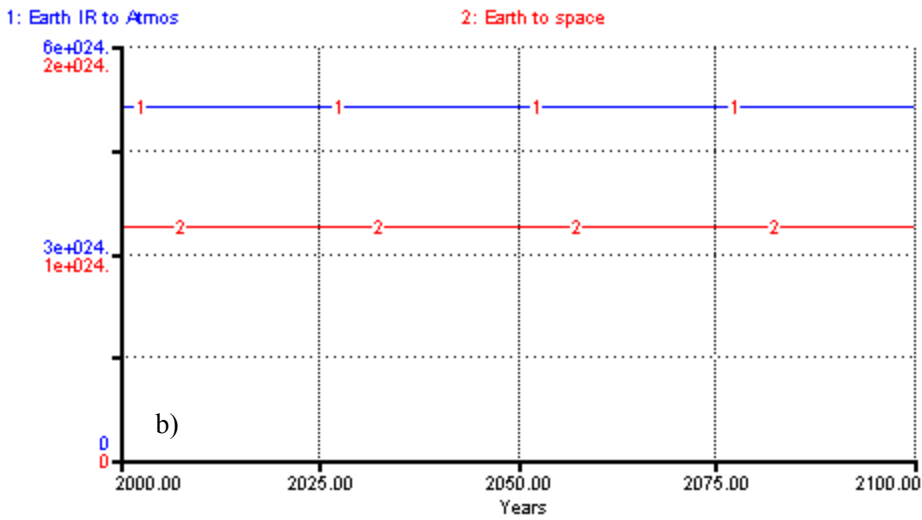


Figure 28: Graphical representation of the fluxes obtained from the GEC model: Earth IR Atmosphere (blue line-1) and Earth to Space (red line-2), a) CO₂ emission is taken into consideration, b) CO₂ emission is not taken into consideration.

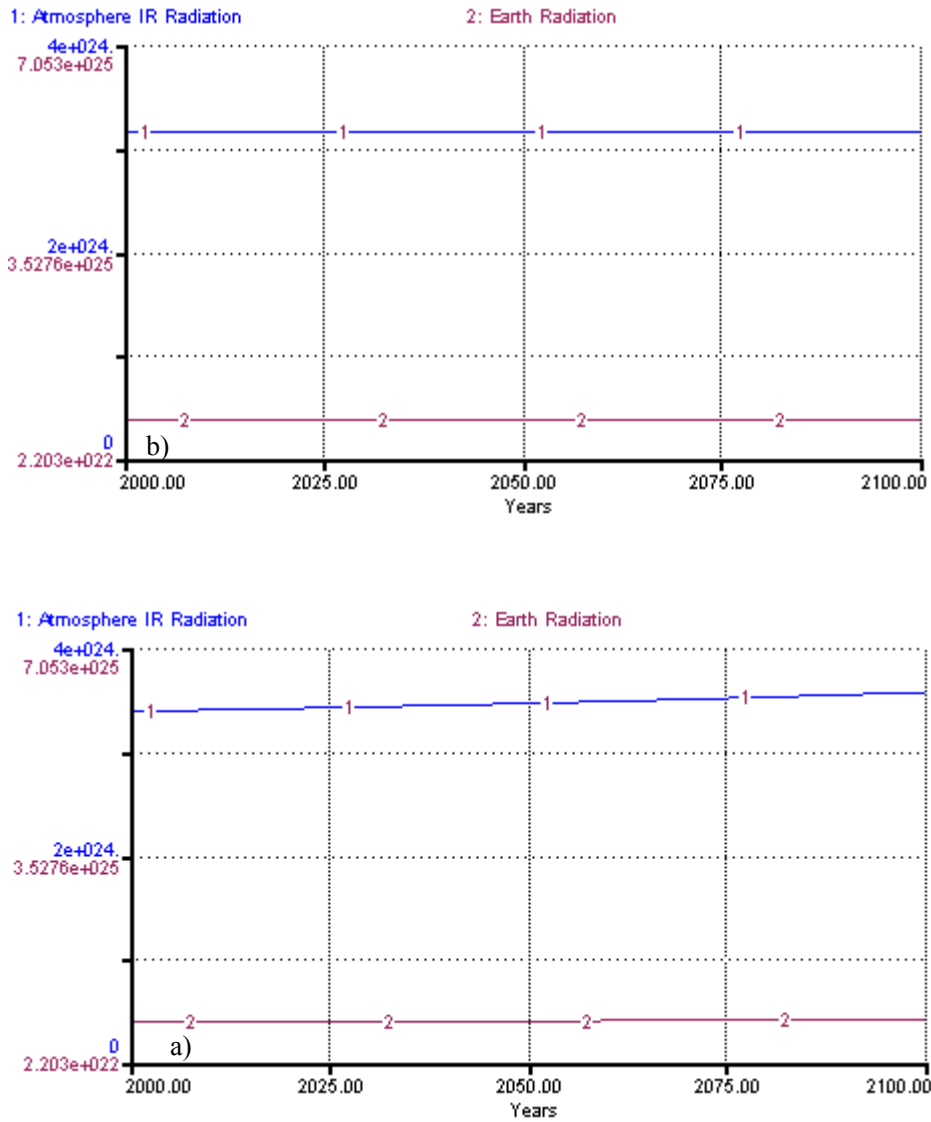


Figure 29: Graphical representation of the fluxes obtained from the GEC model: Atmosphere IR radiation (blue line-1), and Earth Radiation (pink line-2), a) CO₂ emission is taken into consideration, b) CO₂ emission is not taken into consideration.

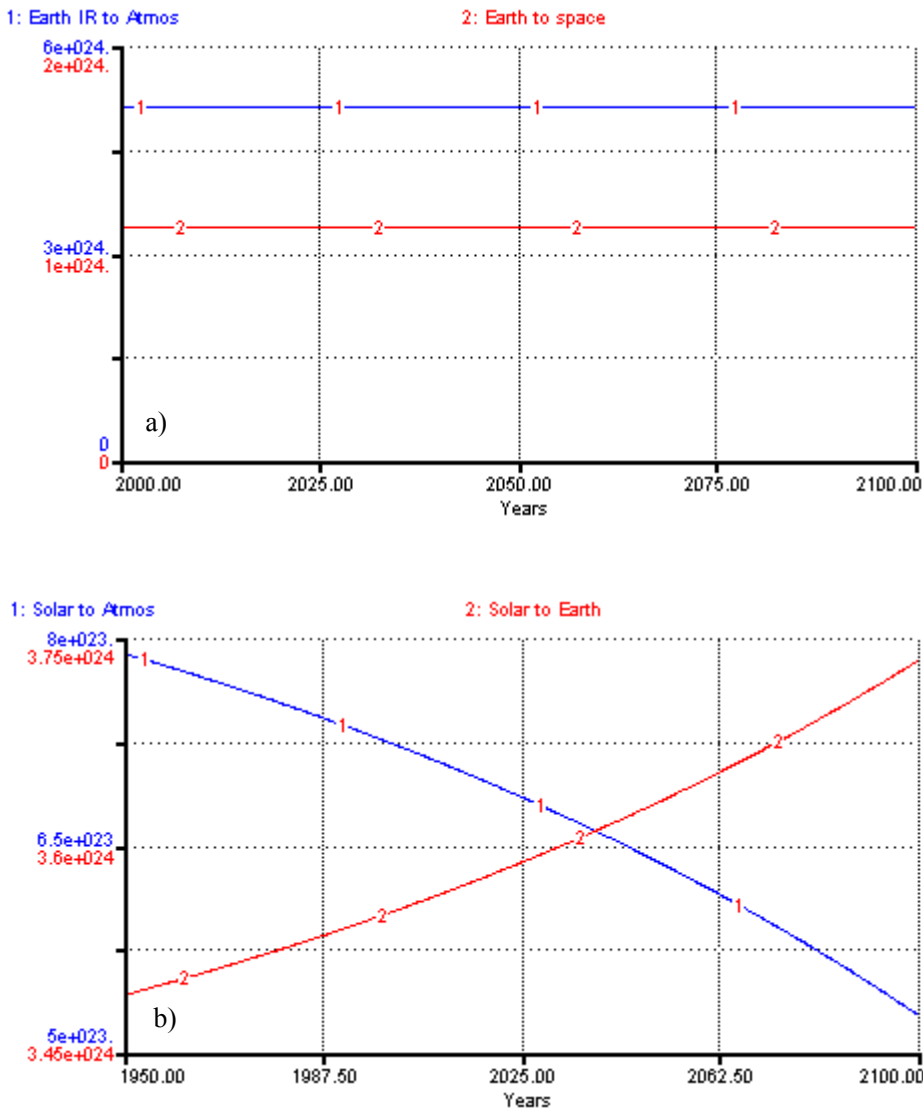


Figure 30: Graphical representation of the fluxes obtained from the GEC model: Solar to Atmosphere (blue line-1) and Solar to Earth (red line-2), a) CO₂ emission is taken into consideration, b) CO₂ emission is not taken into consideration.

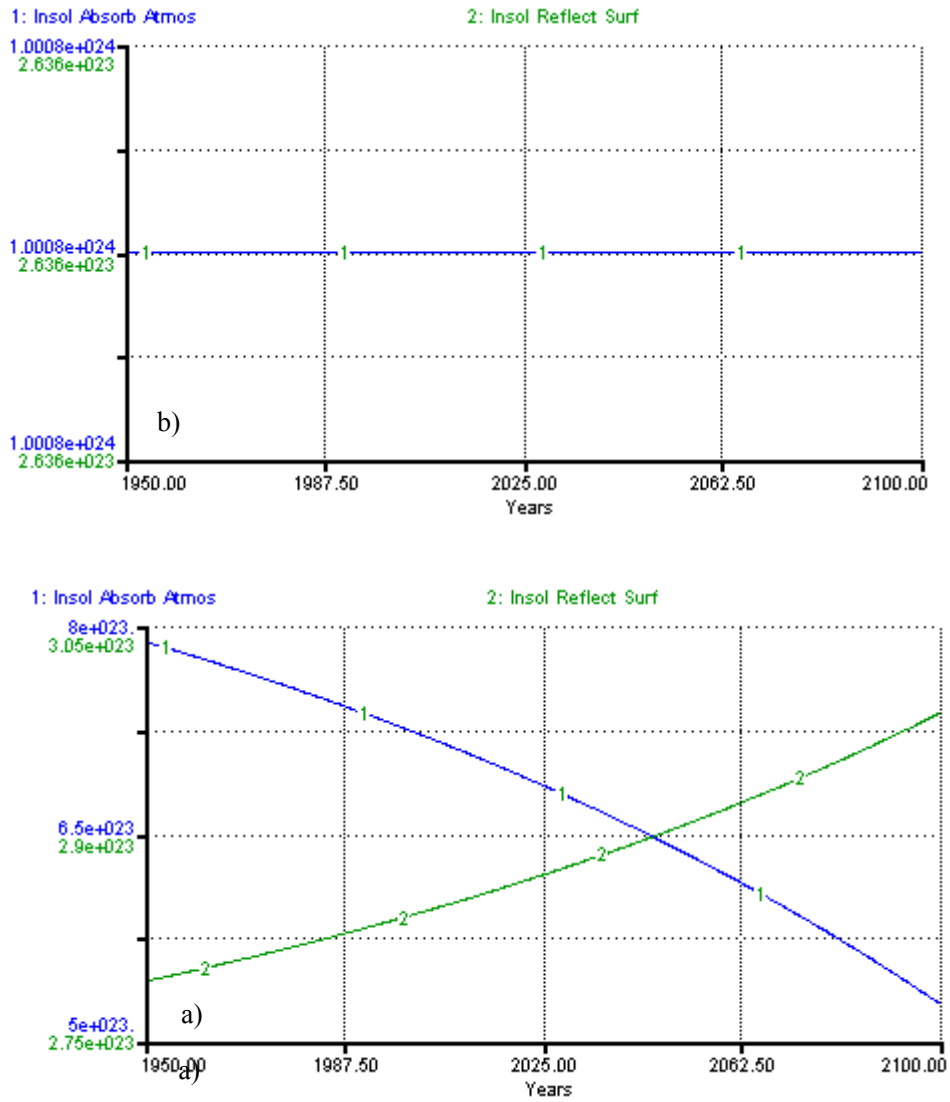


Figure 31: Graphical representation of the fluxes obtained from the GEC model: Insol Absorb Atmos (blue line-1), Insol Reflect Surf (green line-2), a) CO₂ emission is taken into consideration, b) CO₂ emission is not taken into consideration.

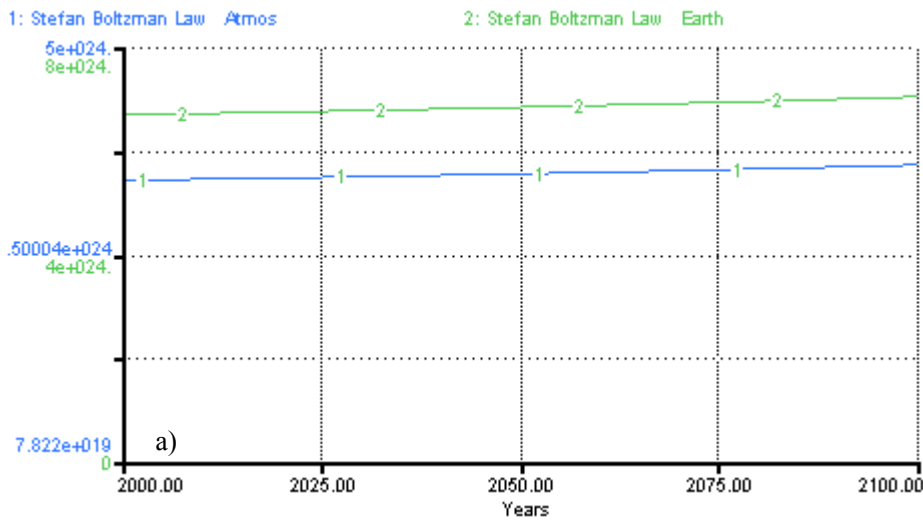
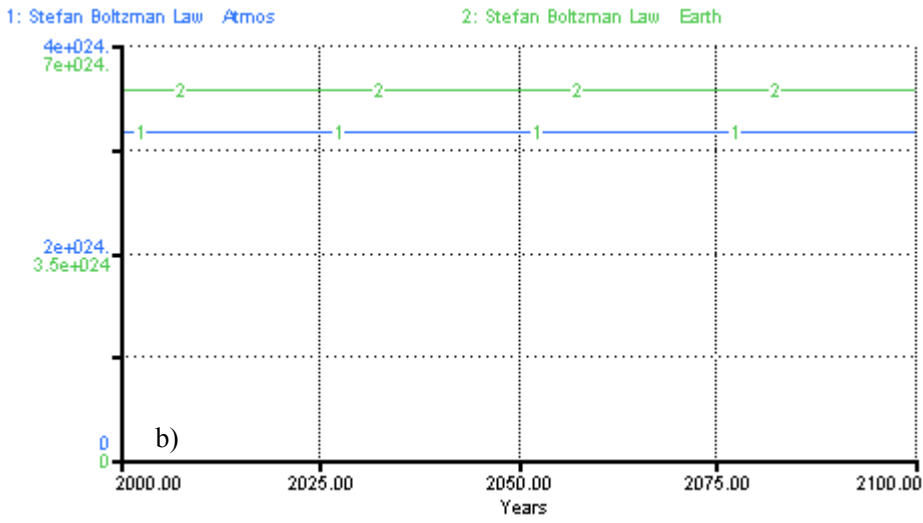


Figure 32: Graphical representation of the fluxes obtained from the GEC model: Stefan Boltzman Law Atmos (blue line-1), Stefan Boltzman Law Earth (green line-2), a) CO₂ emission is taken into consideration, b) CO₂ emission is not taken into consideration.

3.5.1 Earth's Temperatures to Variable Solar Input

Scenario 1a. Altering the Solar Input. A possible source of climate variations are fluctuations in the stream of energy from the sun. In this way the impact on global temperatures of fluctuations of magnitude ± 0.03 of radiant energy can be investigated. Respective change of temperatures varies from 290 K for the increase of the solar input by 3%, up to 286 K for the decrease of the solar input by 3% (Figure 33).

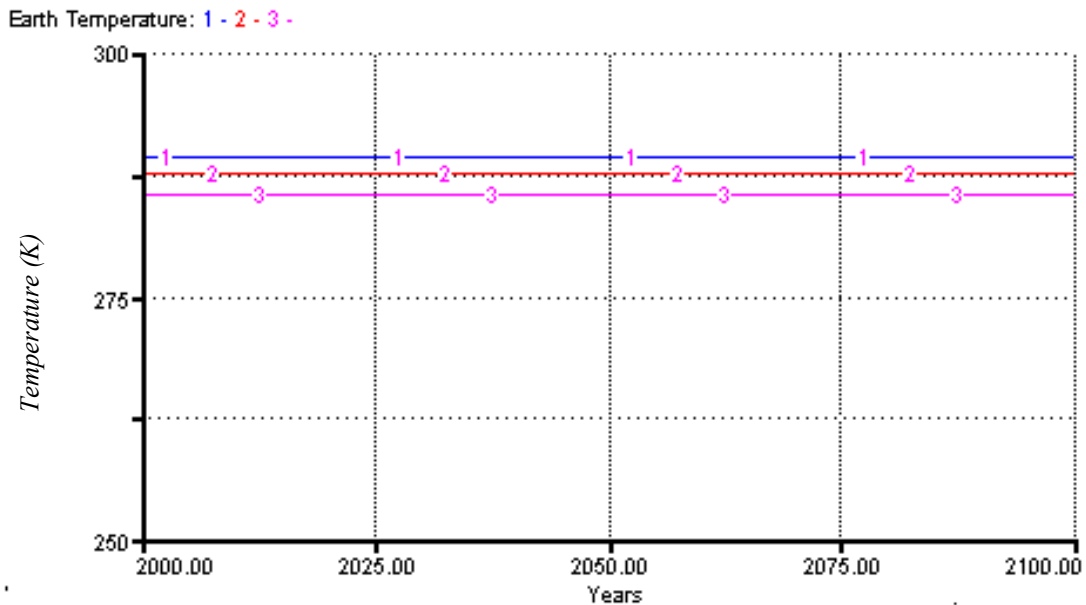


Figure 33: Earth's temperatures to variable solar input with increasing of the solar input by 3%, (blue line -1) without change in solar input (red line -2) with decreasing of the solar input by 3% (pink line -3)

Scenario 1b. The cool sun. Astronomers believe that if the sun behave like other stars of its type, some billions years ago, the solar constant S_0 must have been considerably smaller than it is nowadays. Two billions years ago, for example it would have been 85% of its presents value and 4 billions years ago some 72% of a present value. In this model this would lead to temperatures of 283 K and 279 K respectively (Figure 34). However, life existed, requiring temperatures well above the freezing point of water. It is therefore believed, that due to an elevated concentration of the greenhouse gases in the atmosphere represented by a smaller transmission t and a higher albedo A this effects a largely compensated for. The increase of a solar constant with time must to some extent have been compensated for by the binding greenhouse gases, in particular CO_2 .

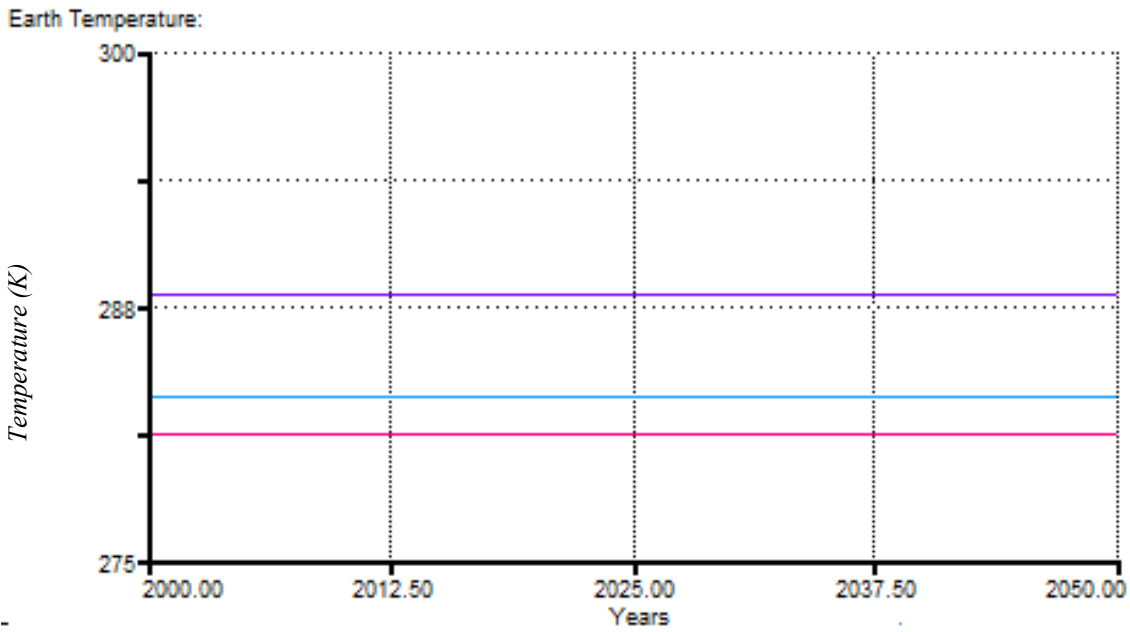


Figure 34: Earth's temperatures to variable solar input with decrease of the solar input by 85% (red line), 72% (light blue line), and without any decrease (pink line).

Scenario 1c Next, we change the solar onput in the form of a sinusoidal variation, to mimic the seasons (Figure 35):.

$$S_0 = 5.56E24 + \text{SINWAVE}(0.1 * 5.56E24, 1) \tag{36}$$

This adds a sine wave variation with an amplitude of 1 % and a period of 1 year to the base of 100 units of energy. The atmosphere and surface peak temperatures are time separated from the solar input peaks.

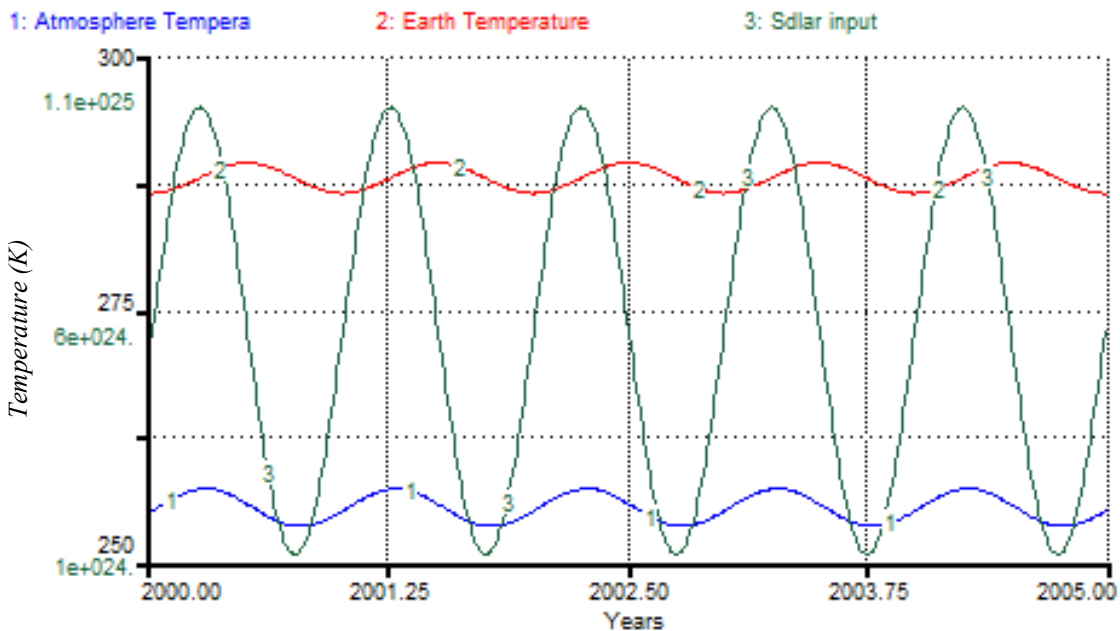


Figure 35: Atmosphere's (blue line-1) and Earth's temperatures (red line-2) to variable solar input with the change of the solar input in a sinusoidal form (green line-3).

3.5.2 Earth's Temperature to variable atmospheric absorption coefficient

Scenario 2a. The nuclear winter. The climatic consequences of nuclear war were seriously discussed in the 1980s. It was argued that the explosion of a few hundred nuclear warheads would result in enormous

fires which would bring great quantities of small particles of dust and smoke into the upper atmosphere, essentially cutting the earth off from sunlight. In most scenarios this would reduce the transmission of visible light for many months. In the model this can be taken into account by decreasing the value of the atmospheric absorption coefficient, i.e. changes from 0.82 to 0.79. One finds a surface temperature of $T=285$ K and a cooling of 3 K (Figure 36).

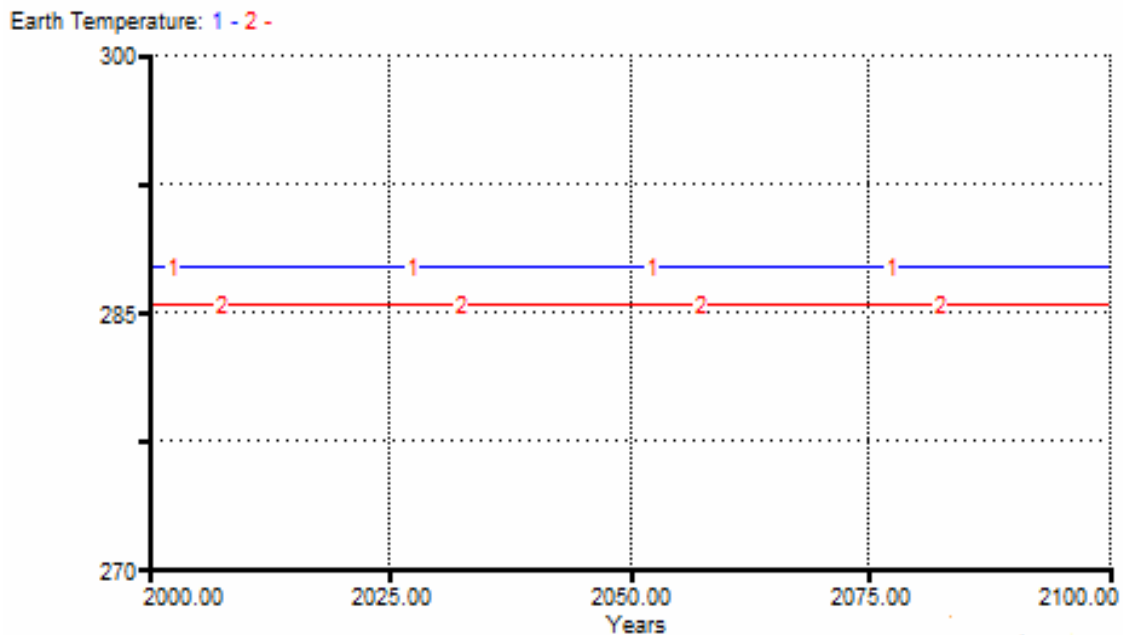


Figure 36: Earth's Temperature to variable atmospheric absorption coefficient. Atmospheric absorption coefficient changes from 0.79 (blue line – 1 to 0.82 (red line - 2)

Scenario 2b. Volcanoes. Rapid climate changes have occurred in the past - in 1816, called “The Year Without a Summer” from volcanic eruption of Tambora volcano in Indonesia. Aerosols from the Tambora eruption blocked out sunlight and reduced global temperatures by 3 K. The atmospheric absorption coefficient of the atmosphere is decreased by volcanic aerosol loading after an eruption. A formula to simulate a volcanic eruption at 3 years into the simulation which decreases the atmospheric absorption coefficient has the form:

$$\begin{aligned}
 &\text{if (time>3) then} \\
 &\quad 0.79+\exp(-(\text{time}-3)) \\
 &\text{else } 0.79
 \end{aligned}
 \tag{37}$$

Earth's temperature decreases to 285 K

3.5.3 Earth's Temperatures to Variable Cloud Cover

Scenario 3a. Global warming I. Since a global warming will result in more evaporation from Earth's oceans, it is reasonable to anticipate that the global cloud cover will increase. It is generally believed that at lower temperatures, the cloud cover will decrease and at higher temperatures, it will increase (Dickinson et al., 1996).

In this scenario, we ask what will happen if we change the percentage of the surface covered by clouds. We can easily explore this question by first increasing and then decreasing the percent cloud cover converter -- up to 65% and then down to 55%.

If cloud cover changes from 55% to 65%, then the Earth temperature will change from 289 K to 287 K (Figure 37).

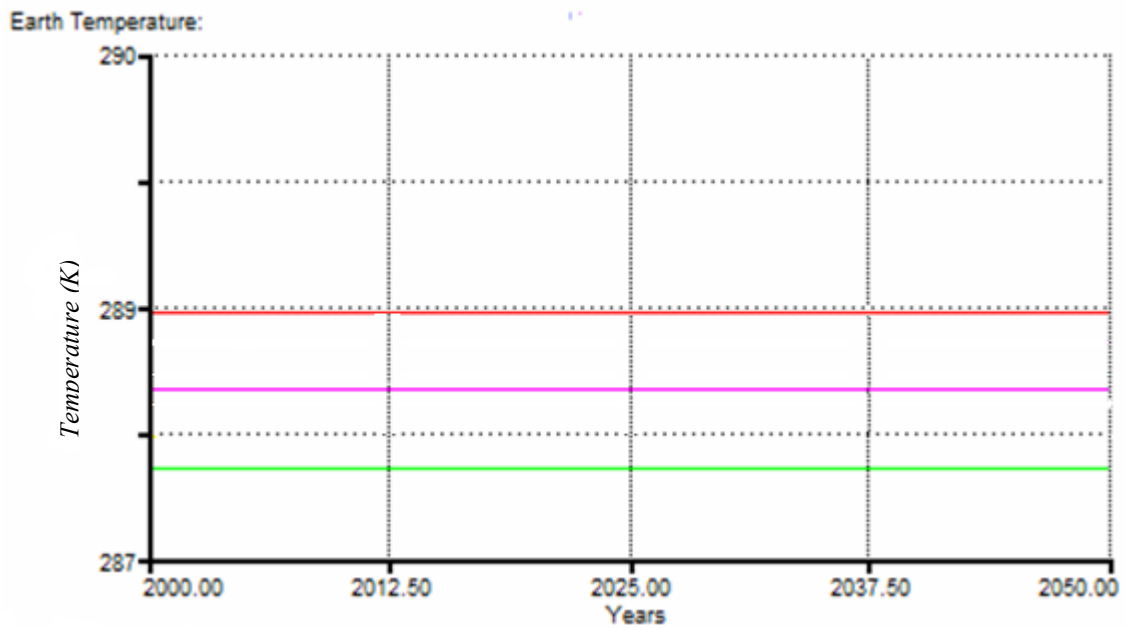


Figure 37: Earth's temperature to variable cloud cover with altering cloud cover by $\pm 5\%$; pink line representing cloud cover without change, whereas red and light green representing cloud cover with increase and decrease of 5%, respectively

Scenario 3b. Global warming II. Let us now discuss the impact of clouds and water vapor, on the Earth's temperature. It is clear that clouds play an important role in the Earth's temperature, because a part of radiation coming from the Sun is reflected from the clouds. From the GEC model we obtain that if we had no clouds, the Earth's temperature would be 304 K (Figure 38). It is quite obvious that the influence of clouds and water vapor to the Earth's temperature is very important.

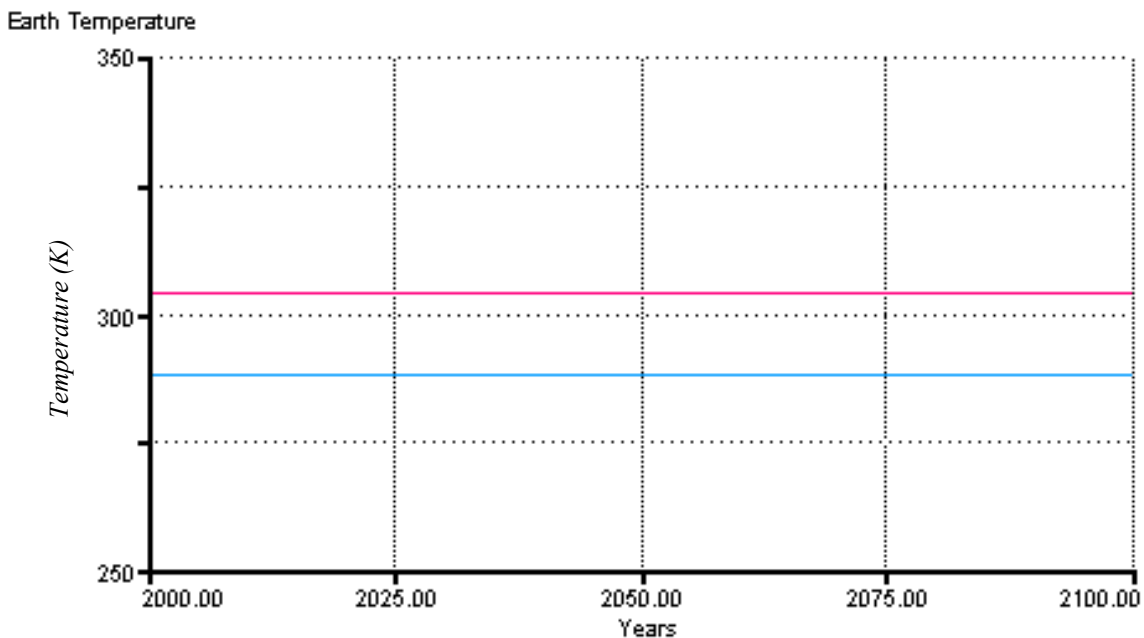


Figure 38: Earth's temperature to variable cloud cover with no cloud cover (pink line).without change in cloud cover (blue line).

3.6 Modeling Rapid Climate Changes

Until the 1990s, the dominant view of climate change was that Earth's climate system has changed gradually in response to both natural and human-induced processes. Earth's climate turned out to be variable on the timescale of tens of thousands of years. Paleoclimate records extending back more than two and a half million years show many global climate oscillations, between warmer and cooler conditions (Mitchell, 1976; Siegenthaler *et al.*, 2005). During the last few million years, the length and the amplitude of these climate cycles has increased (Crowley and North, 1991; Hodell and Venz, 1992). Specifically the last 150,000 years turned out to show the tendency of climate to change relatively suddenly (Taylor *et al.*, 1993). Rapid climate changes (RCC) with major impacts have occurred repeatedly in the past (Broecker, 1997). Ice core data from Greenland demonstrated that climate had changed rapidly on time scales shorter than a century in the past (Dansgaard *et al.*, 1993; Grootes *et al.*, 1993). Even in the course of a single season, a rapid rise of tens of degrees was found (Brooks, 1983). Rise in temperature of 8 K to 16 K has occurred repeatedly in some regions because of climate changes. This increase in temperature has occurred within time periods as short as decades to years (Severinghaus *et al.*, 1998; Socker, 2000). The report of IPCC (Houghton *et al.*, 2001) noticed that future unexpected, large and abrupt climate changes are possible. It is reported (National Academy of Sciences, 2002) that abrupt climate change, potentially with large impacts on ecosystems and societies, was possible at any time. Among climate feedbacks with the potential to cause sudden climate change, the response of ocean circulation may have received the greatest attention (Broecker, 1997; Taylor, 1999; Clark *et al.*, 2002). Recent research (Schwartz and Randall, 2003), suggests that there is a possibility that human-caused global warming leads to a relatively abrupt slowing of the ocean's thermohaline circulation. The authors predict impacts such as harsher winter weather conditions, greatly diminished rainfall and more intense winds in many important agricultural regions that will cause consequent disruptions in food supply and diminished world's food production.

Future sudden climate changes, with a lesser rate and in the course of one year time period, could be caused by the increase in volcanism that could have thrown more airborne volcanic material into the stratosphere, thereby creating a dust veil and lowered temperatures (Collins, 2003). Such rapid climate changes have occurred in the past, in 1816, called "The Year Without a Summer" from volcanic eruption of Tambora volcano in Indonesia. Aerosols from the Tambora eruption blocked out sunlight and reduced global temperatures by 3 K. Throughout Europe, there were recorded low temperatures and above average rainfall, which caused widespread crop failures and famine with consequences for ecosystems and economy.

Rapid climate changes typically have detrimental effects on ecological and economic systems. Most of ecosystems and economies have the ability to adapt to a changing environment. This ability to adapt to or mitigate the impacts of RCC will be improved if we know which are the factors that are mostly affected by RCC.

It is very hard to make reliable predictions about impacts of RCC in ecosystems and economies, because we do not yet understand it completely. This difficulty lies in the fact that there is no evidence of how these systems responded during the RCC in the past, so that the results could be compared. (Bekteshi *et al.*, 2008). For Modeling impacts of the RCC the model WORLD3 (Meadows *et al.*, 1972) has been used in this paper. WORLD3 is a system dynamics model of the world's socioeconomic system. This model connects important interactions between world population, industrial production, pollution, nonrenewable resources and food. One of the main assumptions underlying this model is that the earth's natural resources are, at some level, finite and that the exponential growth in their use could ultimately lead to their depletion (Meadows *et al.*, 1992).

Since it is expected that the greatest impacts of RCC be on food, the WORLD3 model has been used under the assumption that RCC influences the rapid decrease of food during a time period of one year. The results will be more explicit than in the case when the change occurs gradually during a longer time period. Since we don't know the rate of decreasing of food due to RCC, scenarios that these changes affect the rapid decrease of food by the rate of 10%, 25% and 50%, are generated. Thus, we can suppose that a scenario of 10% corresponds to the decrease of food due to the inconvenient climate changes for food, which occurs frequently. Decrease of 25% corresponds to the climate changes due to the volcanic eruptions, and a decrease of 50% corresponds to the drastic climate changes, for instance the rapid slowing of the ocean's thermohaline circulation. Scenarios are generated for the years 2010, 2025, 2050 and 2075, since we don't know when the RCC are supposed to occur, so we could predict the response of the ecological and economic factors in different years of the time scale. Thus, with this model we will explore a variety of possible scenarios, investigating the response of factors such as: food, population, pollution, industrial output and nonrenewable resources, to an RCC

Below are shown graphs (Figures 39 - 42) created using the baseline assumptions of the model with the

food decreases rapidly by the rate of 10%, 25% and 50% for the years 2010, 2025, 2050, and 2075 for world population, industrial production, pollution, nonrenewable resources and food.

3.6.1 Analysis of data at the end of the time period

Now, it is important to analyze the results at the end of the time period, i.e., in the year 2100. In this year, all factors are almost stabilized, and we can clearly see the long-term impacts of RCC on these factors. It can be seen also, which factors are more quickly stabilized, in a longer time-scale.

Food and population - Regardless of the year when the RCC occurs, decrease of food and population in the year 2100 is approximately proportional to increasing of the RCC rate, and half rate, respectively, comparing to the no-RCC case (Figures 39 and 40). For the RCC rate of 50%, if RCC occurs in the year 2050, decrease of population is the greatest, i.e., about 35% (Figure 40c). For the same rate of RCC, the values of food and population change very slightly, regardless of the year when the RCC occurs. The greatest change doesn't exceed the value of 10%. Although there is a decrease in food the later the RCC occurs, a small increase of the value of food in comparison with other values of food exists, which corresponds to the RCC of the year 2075. Such an increase occurs also for the population. For example, for the same rate of RCC, the number of population in the year 2100 is greater for the RCC that occurs in the year 2075 than for the RCC that occurs in the year 2010, although a time period of 65 years has elapsed. Therefore, the consequences are lesser if the RCC occurs later within the time-scale considered.

Industrial output and nonrenewable resources - Values of industrial output and nonrenewable resources are approximately the same as in the no-RCC case (Figures 41 and 42). Therefore, the impact of the RCC on industrial output and nonrenewable resources is small regardless when and at what rate the RCC occurs. The exception is the case when RCC occurs in the year 2010 (Figure 41a). In this case the values for the industrial output and nonrenewable resources are even greater than in the no-RCC case.

Pollution - The values of pollution are always greater than in the no-RCC case regardless of the year of RCC occurrence (Figure 43). Therefore, the RCC occurrence always has as a consequence the increase of pollution. The increase of pollution is greater if the RCC rate is greater. The values of pollution decrease if the RCC occurs later within the time-scale considered. Therefore, the consequences are lesser if the RCC occurs later within the time-scale considered.

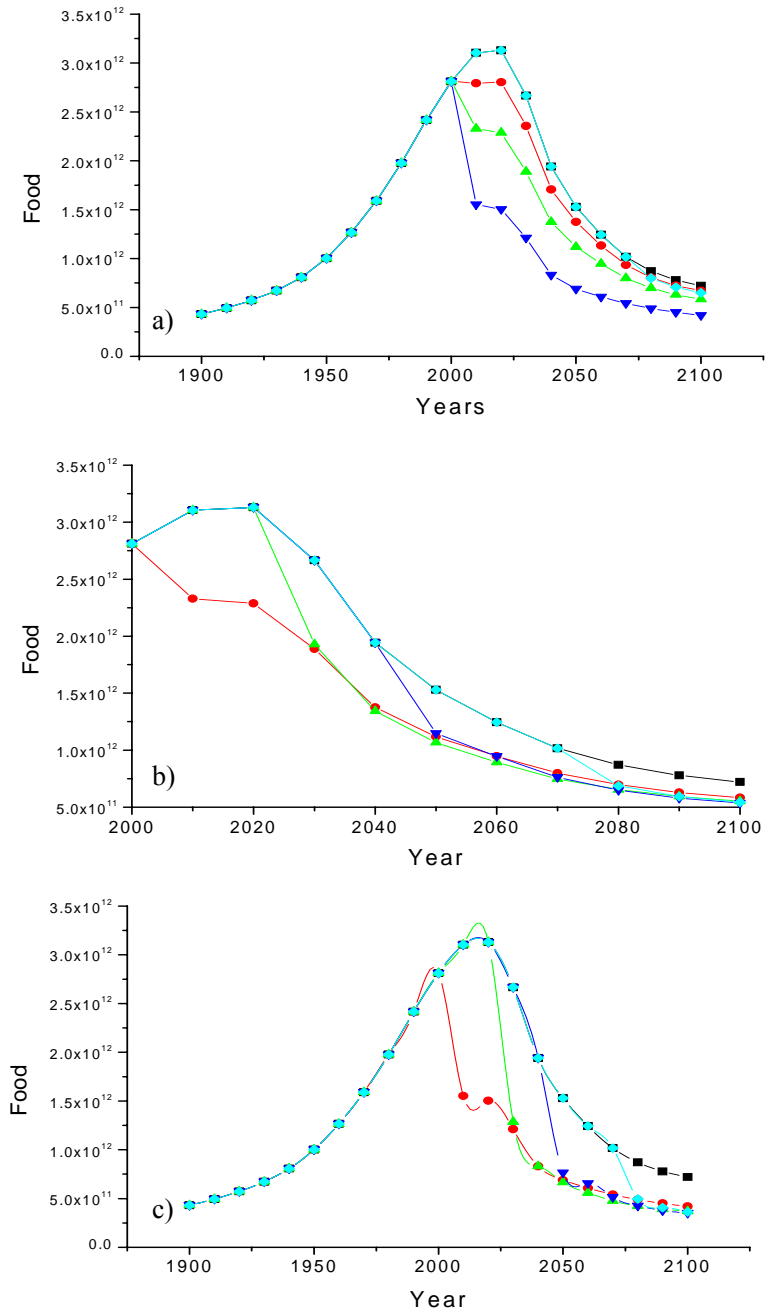


Figure 39: Values of food for RCC with decreasing rate: a) 10%, b) 25% and c) 50%. Data: RCC occurrence in: ● 2010, ▲ 2025, ▼ 2050, ◆ 2075, ■ no-RCC case.

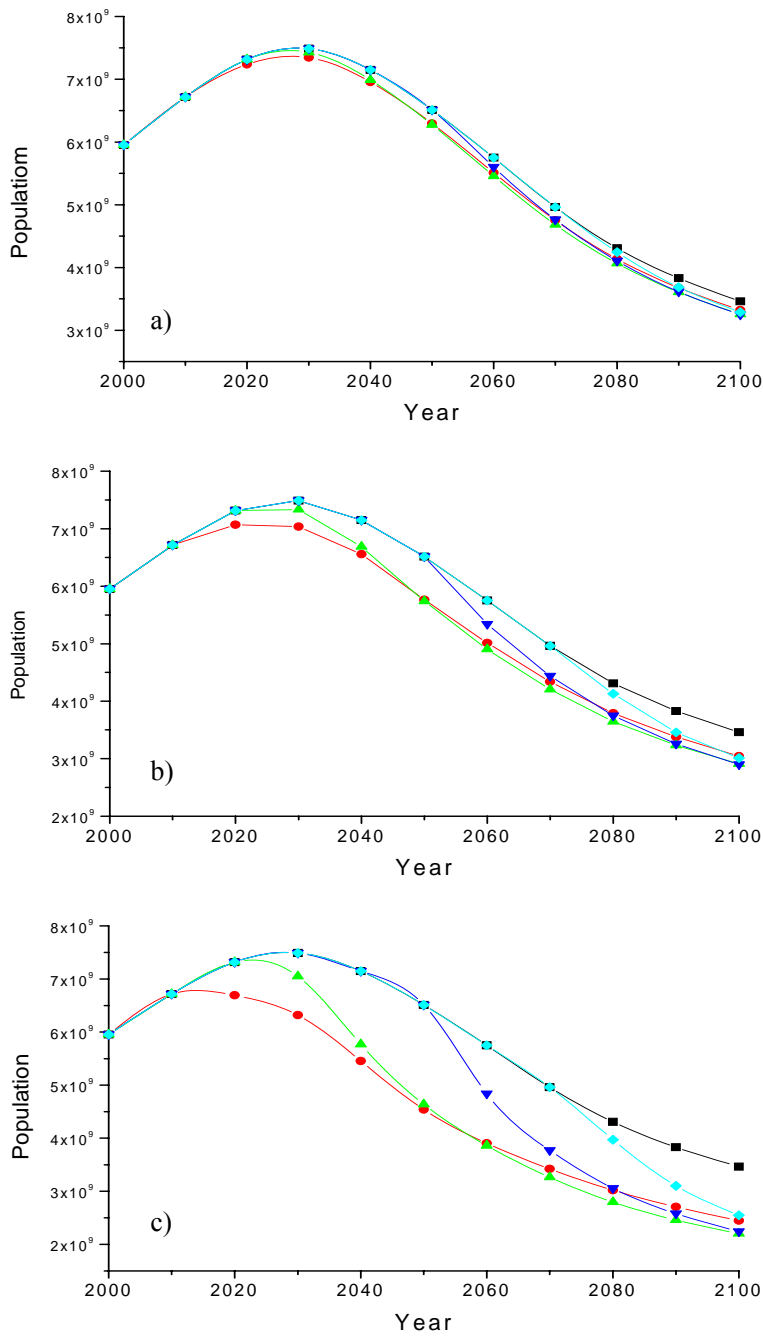


Figure 40: Values of population for RCC with decreasing rate: a) 10%, b) 25% and c) 50%. Data: same as in Figure 39.

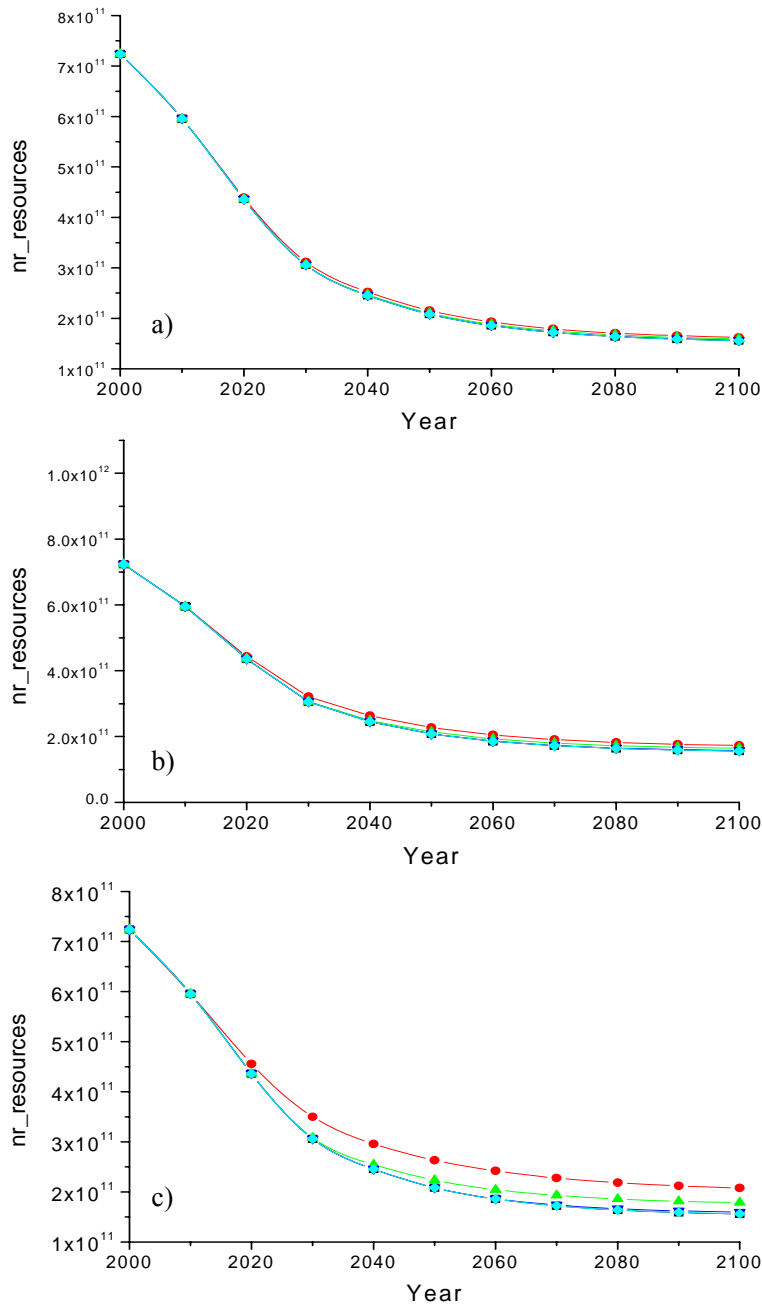


Figure 41: Values of nonrenewable resources for RCC with decreasing rate: a) 10%, b) 25% and c) 50%. Data: same as in Figure 39.

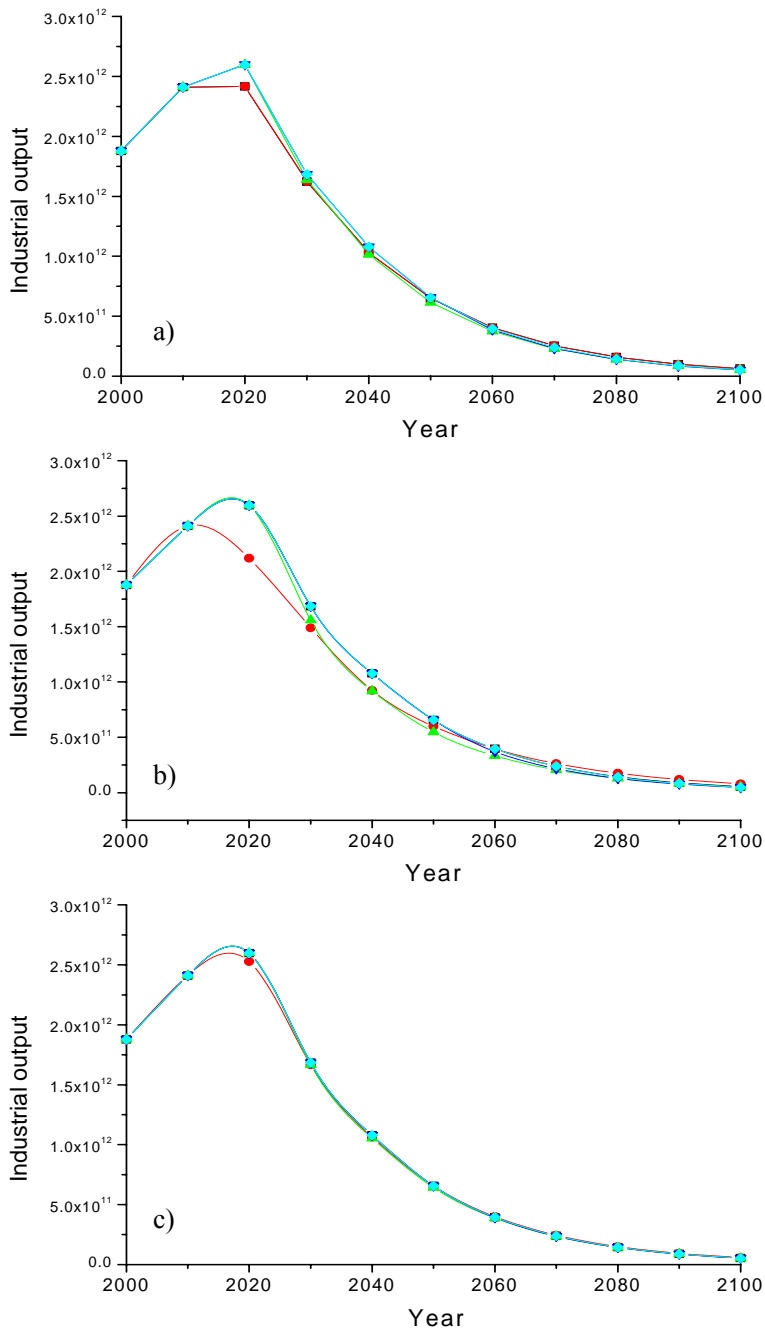


Figure 42: Values of industrial output for RCC with decreasing rate: a) 10%, b) 25% and c) 50%. Data: same as in Figure 39.

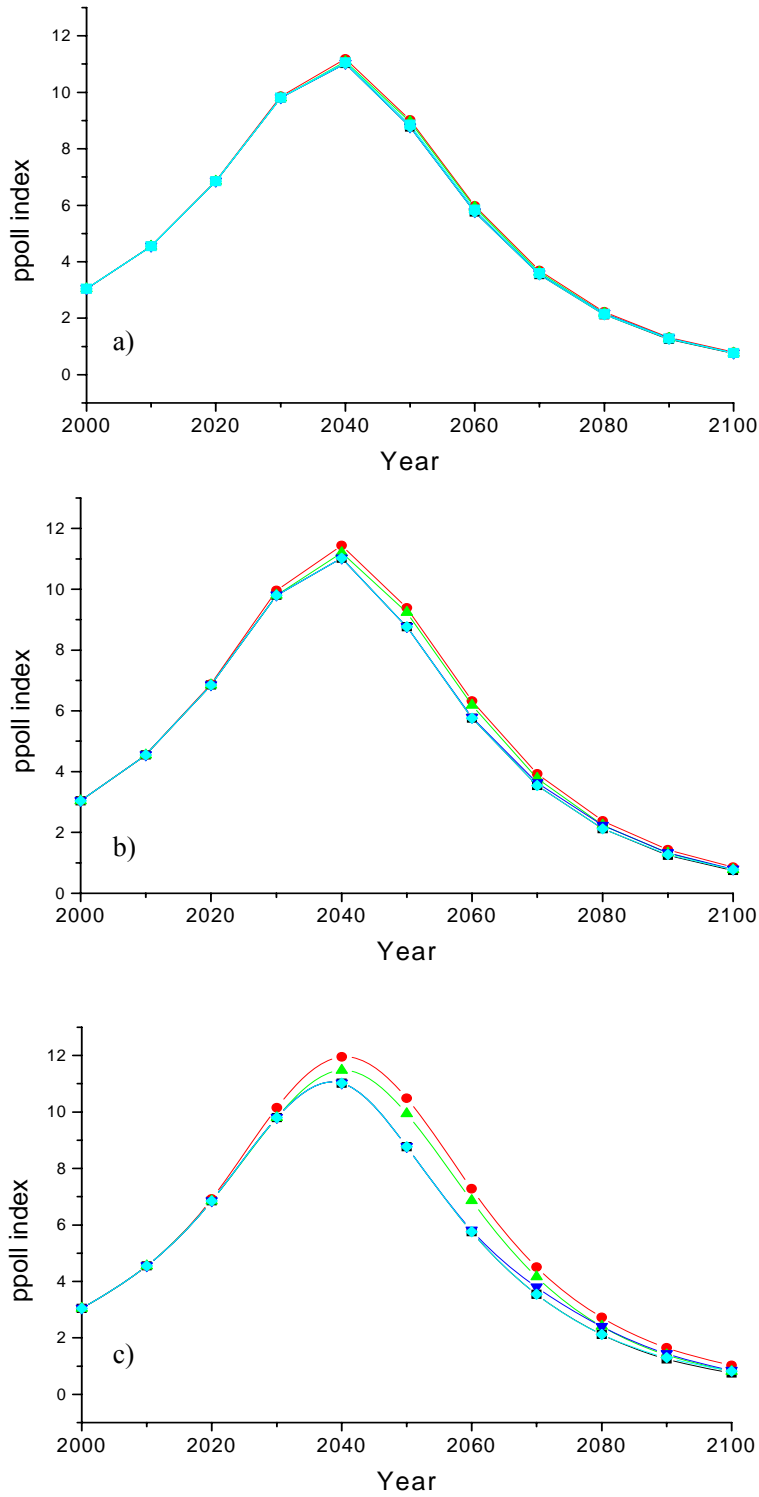


Figure 43: Values of pollution for RCC with decreasing rate: a) 10%, b) 25% and c) 50%. Data: same as in Figure 39.

3.6.2 Analysis of data 10 years after the occurrence of RCC

In order to explicitly view consequences of RCC, we will discuss the values of food, population, industrial output, nonrenewable resources and pollution for a time period 10 years after the occurrence of RCC, comparing them with the data of an assumed »no RCC« occurrence.

Scenario 1: The year 2010. We will suppose that the RCC with rate 10%, 25% and 50% occurs in 2010 and analyze the data for the year 2020. Decrease of food and industrial output are approximately proportional to the increasing rate, and half-rate of RCC, respectively, whereas nonrenewable resources and pollution increases slightly, comparing to the no-RCC case. With an increase of RCC rate, decrease in population is moderate. The greatest decrease in population is about 10% for the rate of 50%.

Scenario 2: The year 2025. The values of food for the year 2035 decrease approximately proportionally with increasing the rate of RCC. Population and the industrial output have the values that differ in comparison with the no-RCC case. For a greater rate (50%), the greatest decrease of these values is about 10%. Nonrenewable resources and pollution have the values that are slightly greater in comparison with the no-RCC case.

Scenario 3: The year 2050. Decrease of food is proportional with increasing the rate of RCC, for the greatest rate (50%), decrease in population reaches the values up to 20%, comparing to the no-RCC case. Nonrenewable resources, industrial output, and pollution have approximately the same values as in the no-RCC case.

Scenario 4: The year 2075. Comparing to the no-RCC case, decrease of food is proportional to increasing of the RCC rate, population decreases up to 15% for the rate of 50%, regardless of the rate of RCC, whereas nonrenewable resources, industrial output and pollution have the values approximately the same as in the no-RCC case.

It is clear that the consequences for the factors discussed depend mainly on the RCC rate, as well as on the year when the RCC occurs. For the same rate of RCC, from the cases discussed, we see that the consequences would be lesser if RCC occurs in the year 2075. In general, decrease of food is proportional with increasing of the rate of RCC, nonrenewable resources and pollution have approximately the same values with no RCC case, regardless of the year when the RCC occurs. The later the RCC occurs, the values of industrial output approach the values of a no-RCC case, whereas the decrease in population continues up to the year 2050 and this decrease gradually approaches the values of a no-RCC case. We can conclude that the later the RCC occurs in the time scale, the lesser the consequences of the factors discussed will be.

From the analysis of the results obtained, it implies that after one decade, the factors that are the least affected are pollution and nonrenewable resources. Nonrenewable resources and pollution have approximately the same values for both RCC and no-RCC case, regardless the year of occurrence and the rate of the rapid. Decrease of food even after ten years is proportional to the rate of the RCC, whereas the industrial output and population depends largely on the time when the RCC occurs. Decrease of the industrial output is lesser the later the RCC occurs. For the same rate of RCC, in the course of years, number of population continues to decrease up to the year 2050, and thereafter begins to increase.

The long-term impacts of the RCC on industrial output and nonrenewable resources are small regardless when and at what rate the RCC occurs. Decrease of food and population in the year 2100 is approximately proportional with increasing of the RCC rate, and half rate, respectively, comparing to the no-RCC case. The values of pollution are always greater than in the no-RCC case regardless the year of RCC occurrence.

From the analysis of the results obtained, in general, we can conclude that:

1. The later the RCC occur in time scale considered, the lesser the consequences for the ecological and economic systems. Therefore, efforts must be reinforced to reduce the causes of RCC.
2. From the considered factors, in the year 2100, the greater the RCC rate, the greater will the decrease of population and food be, whereas industrial output, nonrenewable resources, and pollution will change lesser in comparison with no-RCC case.

In general, RCC causes the decrease of all considered factors, except pollution, at different rates. The results obtained in this paper show that increasing the rate of rapid climate changes can be associated with nonlinear responses of economic and ecological factors. Food and population are the two factors that are the most affected by RCC, whereas the nonrenewable resources, industrial output the pollution are moderately affected by RCC. In order to reduce the impacts of RCC on the ecological and economic systems:

- Adaptability and resilience of ecosystems and economies is needed, especially for the factors that are the most affected by RCC – in our case the population and food,
- Exert efforts for reducing the causes of RCC - prompt action to mitigate global warming as the main cause of RCC.

It should be clear from the above discussion of the construction of the model and the reasoning behind it that the results of the model are not to be taken as real predictions of what the future holds. These results only present a possibility of interaction between different factors considered, under the assumption stated initially. For the models to give reliable predictions about the impacts of RCC, the following must be carried out:

- Advanced developing theoretical and empirical models and associated analysis to understand impacts of RCC in ecological, economic and social systems is needed.

Policymakers must take into the consideration that to reduce the impacts of RCC on ecological and economic systems, necessary actions in due time must be undertaken in the future.

3.7 Modeling Pollution Emission Reduction

It is evident that the worldwide average temperature is rising and climate is changing (WMO, 2003) and it is believed that there is sufficient evidence that this is due to human activities (IPCC 2001). Human activities are primarily responsible for the release of carbon dioxide and other global warming pollutants which are causing a change in the composition of the atmosphere and its properties [Zidansek et al. 2008]. Since pre-industrial times (around 1750), carbon dioxide concentrations have increased by just over one third from 280 parts per million (ppm) to 380 ppm today, predominantly as a result of burning fossil fuels, deforestation, and other changes in land-use that are causing global mean temperatures to rise. From 1900 to the present those temperatures have risen by almost 0.7 K. Over the past 30 years, global temperatures have risen rapidly and continuously at around 0.2 K per decade. Even if annual global warming pollution emissions remained at the current level of 42Gt CO₂ equivalent (CO₂e), its concentrations in the atmosphere could reach more than 600 ppm in carbon dioxide equivalent, and (IPCC) has predicted an average global rise in mean temperature of 1.4 K to 5.8 K between 1990 and 2100.

It is clear that pollution emission reduction (PER) is characterized by its impact on the environment and economic system. These reductions will help to slow down global warming, thus avoiding the consequences of climate change to be revealed in melting ice, rising seas, changing currents, greater storms and shifting rainfall. On the other hand, there is also a key objection that reducing emissions would impose unacceptable detrimental effects on the economic system. The aim of this research is to find out which of the discussed factors are the most affected by PER, in order that mid-term and long-term pollution emission reduction could be implemented without significantly harming the world economic growth.

Reducing emissions for a small percentage below 1990 levels over the next 5 to 25 years could be one way to react and prevent negative impacts of climate change. These negative impacts affect mainly economic and ecologic systems. Thus, sharply reducing carbon dioxide and other global warming pollutants emissions would slow global growth projected by International Monetary Fund. However, economic policies should be designed so this could happen only to a minimum. The policies needed to reduce emissions by 60% from 2002 would leave the global economy about 2.6% smaller than it otherwise would be in 2040. Even so the global economy would grow to about 2.3 times its current size between 2007 and 2040.

Because these reductions must take place in the face of economic growth, there is a disagreement about the concrete time among different countries, the rate of the PER and the responsibilities of specific countries for the emission reductions compared to the business-as-usual (BAU) case. Eventually, developed countries are committed to emissions reductions and there seems to be a consensus that industrial output be reduced to a greater extent by most industrialized states [Langer, 2008]. These are considered important first steps towards a significant emission reductions that are needed. so that a couple of most industrialized states have also set long-term targets. Thus, for example, recently, the UK government has defined long-term emission targets in order to reduce carbon dioxide emissions of some 60 % from current levels by about 2050 [UK 2003 and RCEP 2003].

One must recall that if the present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, in the context of a longer term perspective, the limits to growth will be reached [Meadows et al. 1972, Meadows et al. 2004]. Nevertheless, it is possible to establish conditions of ecological and economic stability, that is, a sustainable development [Blinic et al. 2008]. One of the conditions is the stabilization of the concentration of carbon dioxide and other global warming pollutants in the atmosphere at such a level and to be reached in due time, that could allow ecosystems to adapt in a natural way to climate changes and provide sustainable development [UNFCCC 1992].

For modelling pollution emission reduction the model WORLD3 [8, 9] has been used in this research. WORLD3 is a system dynamics model of the world's socioeconomic system. This model makes use of Systems Dynamics Modelling (SDM) developed by Jay Forrester at MIT as a methodology (Forrester, 2003). Systems thinking has been defined as "the ability to see things as a whole" (Maani and Cavana, 2000). System Dynamics attempts to model the basic structure of a system so as to be able to capture the behaviour that the system produces (Sterman, 2000). Interactions between objects are accomplished by feedback loops that exist between objects within the system. In feedback loops a change in one variable affects other variables in the system over time (often including delays), which in turn affects the original variable. WORLD3 model connects important interactions between world population, industrial production, pollution and nonrenewable resources. One of the main assumptions underlying this model is that the earth's natural resources are finite and that the exponential growth in their use could ultimately lead to their depletion. In general, it is said for this model that it captures major factors and gives some insights on future possibilities that seems to fit our general knowledge.

Scenarios are generated for the years 2012 and 2025 with emission reductions 5%, 10% and 20%, 30% respectively, below the 1990 level (1990 is chosen because it is the base year for the UNFCCC). The four modelled scenarios (Figure. 44) are divided as follows:

Medium Term Scenarios - Medium term scenarios are: the scenario that corresponds to emission reduction of 5% until the year 2012 (scenario MA), and the scenario that corresponds to emission reduction of 10% until the year 2012 below the 1990 level (scenario MB).

Longer Term Scenarios - Longer term scenarios are: the scenario LA that corresponds to emission reduction of 20% until the year 2025 (scenario LA), and scenario that corresponds to emission reduction of 30% until the year 2025 below the 1990 level (scenario LB).

All the scenarios assume that PER is achieved at a global level.

Thus, with this model we will explore a variety of possible scenarios, investigating the response of factors such as: population, pollution, industrial output and nonrenewable resources, to a PER.

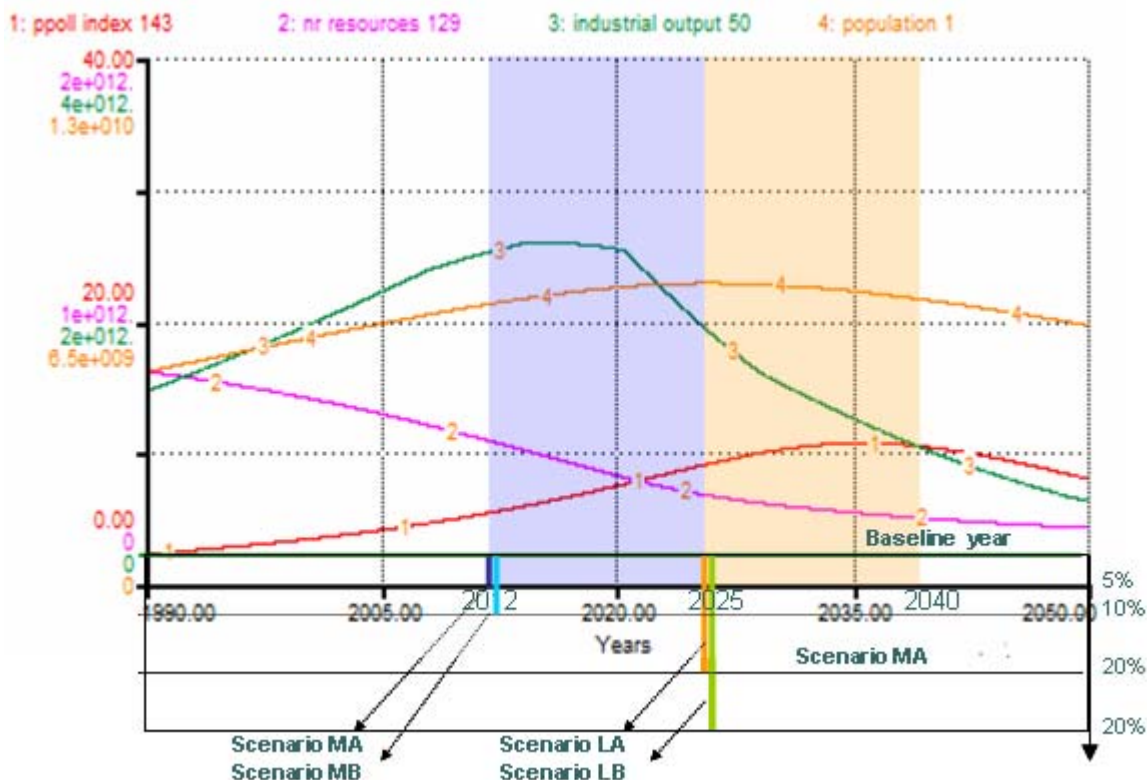


Figure 44: Graphical representation of pollution emission reduction scenarios. The business-as-usual case for: population (orange line-1), pollution (red line-2), industrial output (green line-3) and nonrenewable resources (pink line-4)

Below are (Figures 45 - 48) from the model (Meadows et al., 1972). These graphs (Fig. 45 - 48) are created from a run using the baseline assumptions of the model with the pollution emission reduction at the rates mentioned according to scenarios.

3.7.1 Analysis of Data for Medium Term Pollution Emission Reduction until 2025

We now analyze the results for medium term pollution emission reduction until 2025. The assumption is that until the year 2012 the pollution emission reduction is achieved, according to the scenario MA and scenario MB. In this way, we can clearly see the impacts of medium-term pollution emission reduction on these factors. It can be seen also, which factors are more quickly stabilized, in a medium time-scale.

Pollution and Population - With the assumption that further emission reduction after the year 2012 is not continued, an increase in pollution will continue as a consequence, almost linearly, so that the pollution values will be 60% and 65% for the scenario MA and scenario MB, respectively, until the year 2025 in comparison with the BAU case. This increase will reach the value of 67-68% until the year 2040 (Figure 45a). PER is followed by the increase in population. Values of population are increased gradually, so that for the same scenario the increasing rate of population in 2025 is about 4 times greater that that of the year 2012 in comparison with BAU case (Figure 45b). The difference between various scenarios is insignificant.

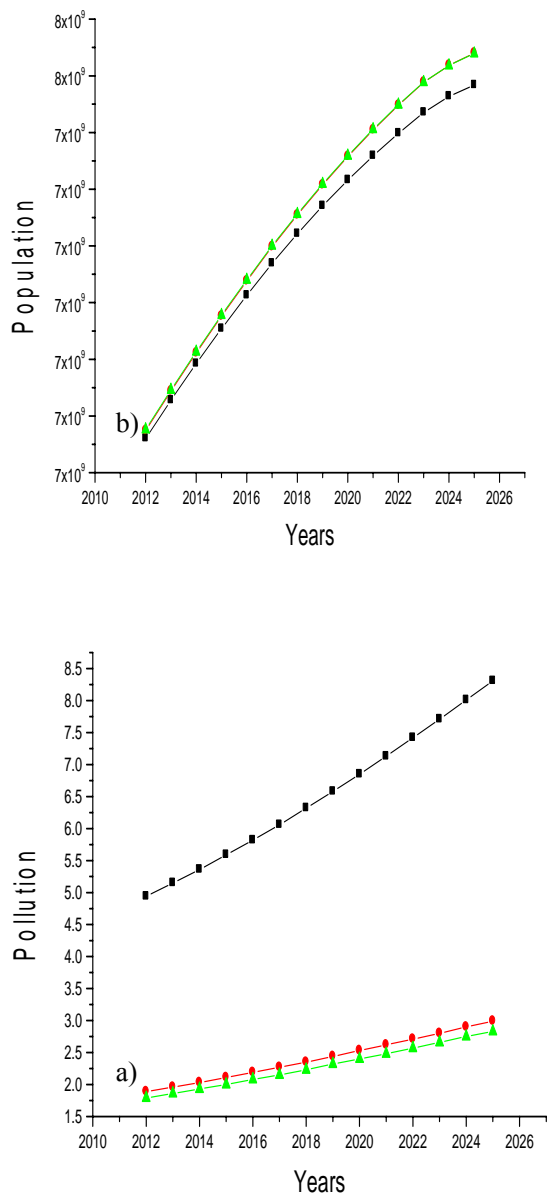


Figure 45: Values of a) Pollution and b) Population with decreasing rate: ● 5%, ▲ 10% and ■ business-as-usual case.

Nonrenewable Resources and Industrial Output - The values of nonrenewable resources in the year 2012 are slightly different from the values of BAU case for both scenarios. Nevertheless, these values drop rapidly and their decreasing rate in the year 2025 is about 6 times greater than that of the year 2012 (Figure 46a). This significant decrease continues further in time. For the same year, the difference in values of nonrenewable resources for various scenarios is significant. Analysis of data for the year 2012 shows that the values of nonrenewable resources for the scenario MA are about 25% greater than those for the scenario MB. Gradual decrease of nonrenewable resources with time causes that this difference in values for scenarios MA and MB would reach about 75% in the year 2025.

Success in PER is followed by an increase in industrial output for both scenarios. Industrial output values for scenario MB are about 10% greater than those for scenario MA. This difference is preserved almost all the time (Figure 46b). The greatest values of industrial output are about 1.4%, which are obtained for the scenario MA.

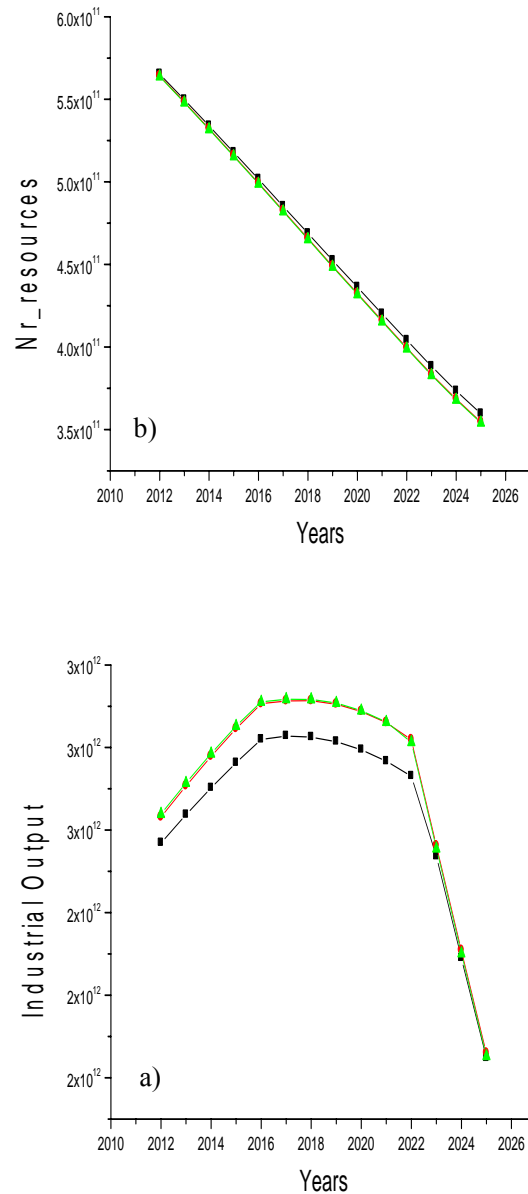


Figure 46: Values of a) Industrial Output and b) Nonrenewable resources with decreasing rate: ● 5%, ▲ 10% and ■ business-as-usual case.

3.7.2 Analysis of Data for Long Term Pollution Emission Reduction until 2040

Pollution and Population-Values of population are increased gradually. These values are 80-90% lesser than the values in BAU case.

The values of population follow the values of the BAU case. Increasing rate of population in the year 2040 is about 5 times greater in comparison with the year 2012. The difference between the values for pollution and population for the same year but for different scenarios is small (see Figures 47a and 47b).

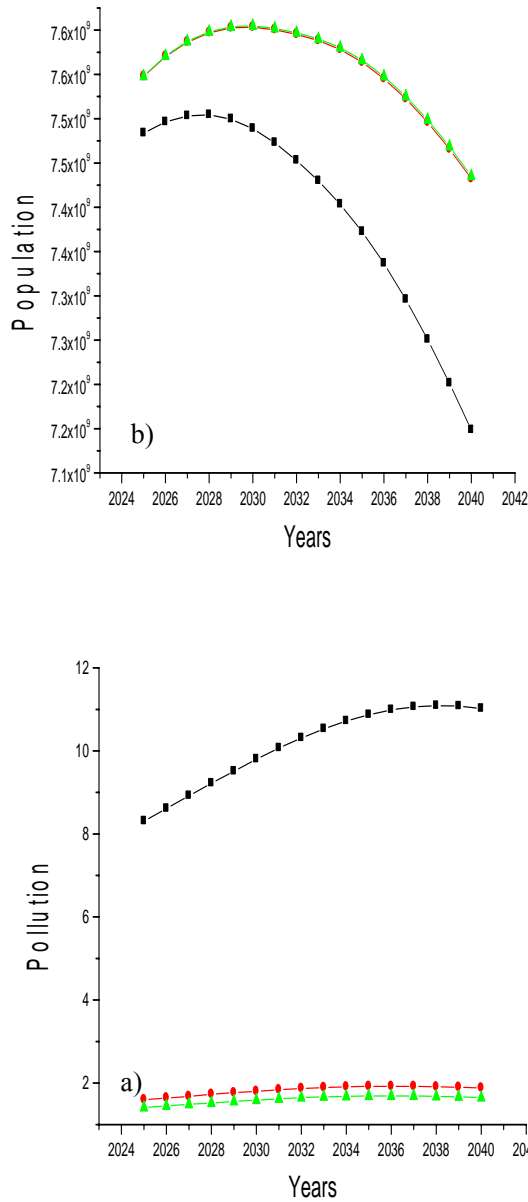


Figure 47: Values of a) Pollution and b) Population with decreasing rate: ● 5%, ▲ 10% and ■ business-as-usual case.

Nonrenewable Resources and Industrial Output-Values of nonrenewable resources are significantly decreased with time. Decreasing rate of nonrenewable resources for the year 2040 is approximately 5 times greater than that of the year 2025 (Figure 47a).

By decreasing the pollution the industrial output is increased. This increase is approximately twice as greater in the year 2040 as that in the year 2025. The values for the same year for the scenario LB are about 2% greater than those for the scenario LA (Figure 48b). The difference between the values for nonrenewable resources and industrial output for the same year but for different scenarios is small (Figures 48a and 48b).

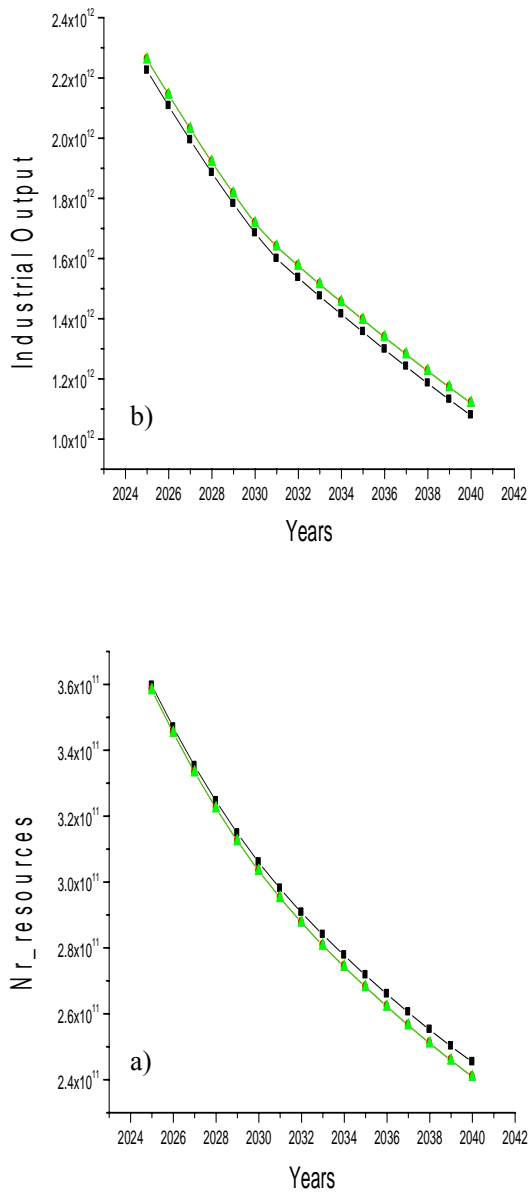


Figure 48: Values of a) Nonrenewable resources and b) Industrial Output with decreasing rate: ● 5%, ▲ 10% and ■ business-as-usual case.

It is clear that the consequences for the factors discussed mid term PER depend mainly on the year when the decrease in pollution is achieved as well as the rate of decrease. In long term scenarios, the values of the factors discussed depend mainly on the year when the pollution reduction is achieved, and very little on the rate of emission reduction. For the same rate of PER, from the cases discussed, we see that the consequences would be lesser if reduction emission is achieved earlier in time scale.

From the analysis of the results obtained, we can conclude that the impact of mid-term PER is more significant in population, pollution, and nonrenewable resources, and less significant in industrial output. The difference between the values for different scenarios is more significant particularly for nonrenewable

resources and industrial output in mid-term. This impact is valid also in long-term with the exception that in this case the influence of small, which means that in long-term the decreasing rate of PER is less important. For the same rate of PER, from the cases discussed, we see that the consequences would be lesser if reduction emission is achieved earlier in time scale.

The long-term impacts of the PER on industrial output are small regardless of the applied scenario on PER. From the factors discussed, the difference in values for pollution and population in the year 2040 is the greatest, which clearly shows that these two factors are mostly influenced. Values of population are greater and greater in comparison with BAU, which shows that PER influences in the population growth. Values of nonrenewable resources are smaller and smaller than in BAU case, which shows that if there is no emission reduction, then the pollution values will be greater as a consequence of greater exploration of nonrenewable resources.

From the analysis of the results obtained, we can conclude that:

1. For the factors discussed, there is no doubt that a great impact on them has the decreasing rate of pollution, but in long-term, of much more importance is the year of achieving the pollution reduction.
2. PER has as a consequence the increase of population and industrial output, and the pollution and nonrenewable resources reduction in comparison with BAU case.
3. Of the factors discussed, pollution, nonrenewable resources and population are influenced the most, and industrial output the least.

In general, PER causes the decrease of pollution and nonrenewable resources, and the increase in population and industrial output, at different rates. The results obtained in this paper show that increasing the rate of PER can be associated with nonlinear responses of economic and ecological factors. From the factors considered, population, pollution and nonrenewable resources are the most affected by PER, whereas the industrial output are moderately affected by PER.

There exists a series of technological options for use in reducing global warming pollution emissions, and significant reductions can be attained in such manner that negative impacts on the economy and ecological systems will be minimal. Nevertheless, policymakers must take into the consideration that to reduce the impacts of PER on ecological and economic systems, necessary actions in due time must be undertaken in the future.

4 Discussion

From the data presented in this thesis, it is clear that increasing fossil fuel emissions, raises the percentage of carbon dioxide in the atmosphere. This increase in carbon dioxide is associated with changes in the radiative energy budget of the Earth's climate system, which as a consequence has an increase in Earth's mean temperature. The response of the climate system includes the potential for rapid large-scale changes in the climate system in response to gradual changes in its forcing. In this case, it is of interest to know which would be the impacts on certain economic and ecological factors. Some countries are working together to lower emissions of carbon dioxide from fossil fuels in order to prevent negative impacts from climate change. In this case, again, it is of interest to know how would certain factors respond on PER. Therefore, results and research carried out in this work could be divided in three major groups:

1. Modeling of the energy-climate system, i.e., construction of the GEC model
2. Analysis of certain factors after the rapid climate changes
3. Analysis of certain factors after the reduction of pollution

From the obtained results it follows that the GEC model yields good results about the Earth's and the atmosphere's temperatures. The GEC model computes predictions of anthropogenic emissions of the CO₂ emissions generated from world's energy consumption. It supports examination of potential feedbacks of climate model onto predicted emission rates. This model is convenient enough for generation of various scenarios by which the behaviour of various sectors and various variables within certain sectors, under certain conditions, can be investigated.

This model can serve also as a basis for a extended model that could include other sectors, e.g. the sector of resources and energy reserves, economic sector, sector of population, etc., that could more exactly define the increase of energy consumption and CO₂ emission.

Although causes for rapid climate changes (RCC) are different, it is conceivable that human forcing of climate changes increases the probability of abrupt events. Rapid climate changes with their impacts are investigated in this thesis. From the analysis of the results obtained, it follows that after one decade, the factors that are the least affected are pollution and nonrenewable resources. Nonrenewable resources and pollution have approximately the same values for both RCC and no-RCC case, regardless of the year of occurrence and the rate of the RCC. Decrease of food even after ten years is proportional to the rate of the RCC, whereas the industrial output and population depends largely on the time when the RCC occurs. Decrease of the industrial output is lesser the later the RCC occurs. For the same rate of RCC, in the course of years, population continues to decrease up to the year 2050, and thereafter begins to increase.

In general, RCC causes the decrease of all considered factors, except pollution, at different rates. The results obtained in this thesis show that increasing the rate of rapid climate changes can be associated with nonlinear responses of economic and ecological factors. Food and population are the two factors that are the most affected by RCC, whereas the nonrenewable resources, industrial output the pollution are moderately affected by RCC. In order to reduce the impacts of RCC on the ecological and economic systems:

- Adaptability and resilience of ecosystems and economies is needed, especially for the factors that are the most affected by RCC – in our case the population and food,
- Exert efforts for reducing the causes of RCC - prompt action to mitigate global warming as the main cause of RCC.

The results obtained in this thesis show that increasing the rate of rapid climate changes can be associated also with nonlinear responses of economic and ecological factors. It is seen from the analysis that the later the RCC occurs in the time scale considered, the lesser the consequences for ecological and economic systems. From these results, we can conclude that adaptability and resilience of ecosystems and economies is needed, especially for the factors that are more affected by the RCC.

On the other hand, by modeling of medium and longer term pollution emission reduction (PER) scenarios, referring to the results obtained, we can conclude that the impact of mid-term PER is more significant on population, pollution, and nonrenewable resources and less significant in industrial output. The difference between the values for different scenarios is more significant particularly for nonrenewable resources and industrial output in mid-term. This impact is valid also in long-term with the exception that

in this case the influence is small, which means that in long-term the decreasing rate of PER is less important. For the same rate of PER, from the cases discussed, we see that the consequences would be lesser if reduction emission is achieved earlier in time scale.

5 Conclusions

In this thesis, the model climate-energy is presented, and the results obtained. This model consists of three sectors: climate sector, energy consumption sector from fossil fuel and CO₂ emission from fossil fuel sector. These sectors consist of different reservoirs and fluxes. Results from this model show that until the year 2100, the Earth's temperature will be increased by 5 K, for predicted values of the increase in energy consumption from fossil fuels and the increase of CO₂ emission for the case business as usual. Results obtained for the increase of the Earth's temperature are in agreement with predicted results of IPCC, where the range of projected global temperature change between 1990 and 2100 for all scenarios is 1.4 K to 5.8 K [IPCC]. Predicted rates of the increase in energy consumption and CO₂ emission, are close to the predicted rates of the increase in energy consumption and CO₂ emission in the latest predictions made in this field. I have applied the GEC model also for some special cases, »scenarios«, encountered in modern literature, showing a good agreement between them. According to the results obtained here, we can conclude that GEC is a simple model, giving good results for dependence of Earth's and atmosphere's temperature on CO₂ emission, and applicable to various scenarios of interest.

With this model the dependence of increase in the Earth's temperature and the impacts on the Earth's climate, on the increase of the energy and CO₂ emission at different rates can be investigated, for example for replacing the fossil fuel energy with nonrenewable energy.

The long-term impacts of the RCC on industrial output and nonrenewable resources are small regardless when and at what rate the RCC occurs. Decrease of energy and population in the year 2100 is approximately proportional with increasing of the RCC rate, and half rate, respectively, comparing to the no-RCC case. The values of pollution are always greater than in the no-RCC case regardless the year of RCC occurrence.

Thus, we can conclude that:

1. The later the RCC occurs in time scale considered, the lesser the consequences for the ecological and economic systems. Therefore, efforts must be reinforced to reduce the causes of RCC.
2. From the considered factors, in the year 2100, the greater the RCC rate, the greater will the decrease of population and food be, whereas industrial output, nonrenewable resources, and pollution will change lesser in comparison with no-RCC case.

The long-term impacts of the PER on industrial output are small regardless of the applied scenario on PER. From the factors discussed, the difference in values for pollution and population in the year 2040 is the greatest, which clearly shows that these two factors are mostly influenced. Values of population are greater and greater in comparison with BAU, which shows that PER influences in the population growth. Values of nonrenewable resources are smaller and smaller than in BAU case, which shows that if there is no emission reduction, then the pollution values will be greater as a consequence of greater exploration of nonrenewable resources.

From the analysis of the results obtained, we can conclude that:

1. For the factors discussed, there is no doubt that a great impact on them has the decreasing rate of pollution, but in long-term of much more importance is the year of achieving the pollution reduction.
2. PER has as a consequence the increase of population and industrial output, and the pollution and nonrenewable resources reduction in comparison with BAU case.
3. Of the factors discussed, pollution, nonrenewable resources and population are influenced the most, and industrial output the least.

In general, PER causes the decrease of pollution and nonrenewable resources, and the increase in population and industrial output, at different rates. From the factors considered, population, pollution and nonrenewable resources are the most affected by PER, whereas the industrial output are moderately affected by PER. There is no doubt that a great influence on the discussed factors has the rate of pollution reduction; nevertheless, in long-term, of much greater importance is the target year of achieving the pollution reduction.

There exists an array of technological options for use in reducing global warming pollution emissions, and significant reductions can be attained in such manner that will not adversely impact the economy and

ecological systems.

The results obtained in this thesis show that increasing the rate of PER and RCC can be associated with nonlinear responses of economic and ecological factors. Nevertheless, policymakers must take into the consideration that to reduce the impacts of PER and RCC on ecological and economic systems, necessary actions in due time must be undertaken in the future.

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Appendix A

List of publications

Papers 1 and 2 and conference proceeding 9 are part of the Doctoral Dissertation

1. Sadik Bekteshi, Skender Kabashi, Ivo Šlaus, Aleksander Zidanšek, Dimitrij Najdovski, Modeling rapid climate changes and analyzing their impacts. *Management of Environmental Quality*, Bradford: Emerald, 2008, vol. 19, no. 4, pp. 422-432
2. Aleksander Zidanšek, Robert Blinc, Anton Jeglič, Skender Kabashi, Sadik Bekteshi, Ivo Šlaus, Climate Changes, Biofuels and the Sustainable Future. Accepted to *International Journal of Hydrogen Energy*, doi: 10.1016/j.ijhydene.2008 (IF = 2.725)
3. Robert Blinc, Dimitrij Najdovski, Sadik Bekteshi, Skender Kabashi, Ivo Šlaus, Aleksander Zidanšek, How to achieve a sustainable future for Europe, *Thermal Science* 12, 19-25, 2008 (Indexed in Science Citation Index Expanded)
4. Skender Kabashi, Sadik Bekteshi, Shukri Klinaku, Treatment of some electric properties in carbon nanotube, *Kërkime - Research* 14, 191-197, 2006
5. Skender Kabashi, Sadik Bekteshi, Shukri Klinaku, Analysis of some properties of nuclear interactions from nucleon-nucleon elastic scattering data, *Kërkime - Research* 14, 199-207, 2006
6. Skender Kabashi, Ymer Halimi, Sadik Bekteshi, Level density in interacting boson-fermion-fermion model (IBFFM) of the odd-odd nucleus ^{196}Au , *Albanian Journal of Natural and Technical Sciences*, 2006, vol. XI (19 – 20), pp. 3-12
7. Skender Ahmetaj, Skender Kabashi, Sadik Bekteshi, Gravitational field in a 5-dimensional manifold of space-time-mass, *Kërkime - Research* 15, 191-197, 2007
8. Sadik Bekteshi, Skender Kabashi, Burim Kamishi, Advanced in Nucleon-Nucleon Scattering Experiments and their Theoretical Consequences, *Sixth International Conference of the Balkan Physical Union American Institute of Physics Proc.-April 23,2007-Volume 899*, pp.93-94
9. Sadik Bekteshi, Skender Kabashi, Modeling Abrupt Climate Changes and Analysis of Their Impacts, *Sustainable Development of Energy, Water and Environment systems: Proceedings of the 4th Dubrovnik Conference SDEWES, Dubrovnik, Croatia (2007)*
10. Dimitrij Najdovski, Robert Blinc, Sadik Bekteshi, Skender Kabashi, Ivo Šlaus, Aleksander Zidanšek, Standardisation, Environmentally Friendly Technologies and Sustainable Development, in *Sustainable Development of Energy, Water and Environment Systems: Proceedings of the 3rd Dubrovnik Conference, Dubrovnik, Croatia, 5-10 June 2005*, Naim Afgan, Zeljko Bogdan, Neven Duic (Eds), World Scientific, 2007, ISBN 9812706402, 9789812706409

Submitted:

Sadik Bekteshi, Skender Kabashi, Ivo Šlaus, Aleksander Zidanšek, Dimitrij Najdovski, Modeling and Analysis of Post-2012 Scenarios for Medium and Longer Term Pollution Emission Reduction, submitted to *Climate Policy*

Skender Kabashi, Sadik Bekteshi, Dimitrij Najdovski, Robert Blinc, Ivo Šlaus, Aleksander Zidanšek, Dynamic Modeling the Climate Change Impacts on Sustainable Energy Demand-Supply in Kosovo,

submitted to Global Environmental Change

Appendix B

Algorithm 3: Stella Equations for Modeling Rapid Climate Changes

$Atmosphere_Energy(t) = Atmosphere_Energy(t - dt) + (Surface_to_Atmosphere + Solar_to_atmos - Atmos_LW_to_Surface - Atmos_LW_to_Space) * dt$
 $agr_inp_99(t) = agr_inp_99(t - dt) + (chg_agr_inp_99) * dt$
 INIT $agr_inp_99 = 5e9$
 INFLOWS:
 $chg_agr_inp_99 = (current_agr_inp_98 - agr_inp_99) / s_avg_life_agr_inp_100$
 $arable_land_85(t) = arable_land_85(t - dt) + (land_devel_rt_96 - land_rem_urb_ind_use_119 - land_erosion_rt_116) * dt$
 INIT $arable_land_85 = .9e9$
 INFLOWS:
 $land_devel_rt_96 = tot_agric_invest_92 * fr_inp_al_land_dev_108 / dev_cost_per_hect_97$
 OUTFLOWS:
 $land_rem_urb_ind_use_119 = (urb_ind_land_req_118 - urban_ind_land_120) / urb_ind_land_dev_time_119$
 $land_erosion_rt_116 = arable_land_85 / avg_life_land_112$
 $industrial_capital_52(t) = industrial_capital_52(t - dt) + (ind_cap_invest_55 - ind_cap_deprec_53) * dt$
 INIT $industrial_capital_52 = 2.1E11$
 INFLOWS:
 $ind_cap_invest_55 = fioa_ind_56 * industrial_output_50$
 OUTFLOWS:
 $ind_cap_deprec_53 = industrial_capital_52 / s_avg_life_ind_cap_54$
 $labor_util_fr_del_82(t) = labor_util_fr_del_82(t - dt) + (chg_lab_util_fr_del_82) * dt$
 INIT $labor_util_fr_del_82 = 1$
 INFLOWS:
 $chg_lab_util_fr_del_82 = (labor_util_fr_81 - labor_util_fr_del_82) / labor_util_fr_del_time_82$
 $land_fertility_121(t) = land_fertility_121(t - dt) + (land_fert_regen_124 - land_fert_degr_123) * dt$
 INIT $land_fertility_121 = 600$
 INFLOWS:
 $land_fert_regen_124 = (inherent_land_fert_124 - land_fertility_121) / land_fert_regen_time_125$
 OUTFLOWS:
 $land_fert_degr_123 = land_fertility_121 * land_fert_degr_rt_122$
 $nr_resources_129(t) = nr_resources_129(t - dt) + (-nr_res_use_rate_130) * dt$

```

INIT nr_resources_129 = 1e12
OUTFLOWS:
nr_res_use_rate_130 = population_1*pc_res_use_mlt_132*s_nr_res_use_fact_131
perc_food_ratio_128(t) = perc_food_ratio_128(t - dt) + (chg_perc_food_ratio) * dt
INIT perc_food_ratio_128 = 1
INFLOWS:
chg_perc_food_ratio = (food_ratio_127-perc_food_ratio_128)/food_short_perc_del_128
pers_pollution_142(t) = pers_pollution_142(t - dt) + (ppoll_appear_rt_141 - ppoll_assim_rt_144) * dt
INIT pers_pollution_142 = 2.5e7
INFLOWS:
ppoll_appear_rt_141 = SMTH3(ppoll_gen_rt_137,ppoll_trans_del_141)
OUTFLOWS:
ppoll_assim_rt_144 = pers_pollution_142/(assim_half_life_146*1.4)
pop_0_to_14_2(t) = pop_0_to_14_2(t - dt) + (births_30 - matur_14_to_15_5 - deaths_0_to_14_3) * dt
INIT pop_0_to_14_2 = 65E7
INFLOWS:
births_30 = IF ( TIME > t_pop_equil_time_30) THEN deaths_17 ELSE
(total_fertility_32*pop_15_to_44_6*0.5/reproductive_lifetime_30)
OUTFLOWS:
matur_14_to_15_5 = pop_0_to_14_2*(1-mortal_0_to_14_4)/15
deaths_0_to_14_3 = pop_0_to_14_2*mortal_0_to_14_4
pop_15_to_44_6(t) = pop_15_to_44_6(t - dt) + (matur_14_to_15_5 - matur_44_to_45_9 -
deaths_15_to_44_7) * dt
INIT pop_15_to_44_6 = 70E7
INFLOWS:
matur_14_to_15_5 = pop_0_to_14_2*(1-mortal_0_to_14_4)/15
OUTFLOWS:
matur_44_to_45_9 = pop_15_to_44_6*(1-mortal_15_to_44_8)/30
deaths_15_to_44_7 = pop_15_to_44_6*mortal_15_to_44_8
pop_45_to_64_10(t) = pop_45_to_64_10(t - dt) + (matur_44_to_45_9 - matur_64_to_65_13 -
deaths_45_to_64_11) * dt
INIT pop_45_to_64_10 = 19E7
INFLOWS:
matur_44_to_45_9 = pop_15_to_44_6*(1-mortal_15_to_44_8)/30
OUTFLOWS:
matur_64_to_65_13 = pop_45_to_64_10*(1-mortal_45_to_64_12)/20
deaths_45_to_64_11 = pop_45_to_64_10*mortal_45_to_64_12
pop_65_plus_14(t) = pop_65_plus_14(t - dt) + (matur_64_to_65_13 - deaths_65_plus_15) * dt
INIT pop_65_plus_14 = 6E7
INFLOWS:
matur_64_to_65_13 = pop_45_to_64_10*(1-mortal_45_to_64_12)/20
OUTFLOWS:
deaths_65_plus_15 = pop_65_plus_14*mortal_65_plus_16
pot_arable_land_86(t) = pot_arable_land_86(t - dt) + (- land_devel_rt_96) * dt
INIT pot_arable_land_86 = 2.3e9
OUTFLOWS:
land_devel_rt_96 = tot_agric_invest_92*fr_inp_al_land_dev_108/dev_cost_per_hect_97
ppoll_tech_PTD(t) = ppoll_tech_PTD(t - dt) + (ppoll_tech_chg_rt_PTDR) * dt
INIT ppoll_tech_PTD = 1
INFLOWS:
ppoll_tech_chg_rt_PTDR = if (time > t_policy_year_150) then
p_ppoll_tech_chg_mlt_POLGFM*ppoll_tech_PTD else 0

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res_tech_NRTD(t) = res_tech_NRTD(t - dt) + (res_tech_chg_rt_NRATE) * dt
INIT res_tech_NRTD = 1
INFLOWS:
res_tech_chg_rt_NRATE = if (time > t_policy_year_150) then
p_res_tech_chg_mlt_NRCM*res_tech_NRTD else 0
service_capital_67(t) = service_capital_67(t - dt) + (serv_cap_invest_66 - serv_cap_deprec_68) * dt
INIT service_capital_67 = 1.44E11

INFLOWS:
serv_cap_invest_66 = industrial_output_50*s_fioa_serv_63
OUTFLOWS:
serv_cap_deprec_68 = service_capital_67/s_avg_life_serv_cap_69
urban_ind_land_120(t) = urban_ind_land_120(t - dt) + (land_rem_urb_ind_use_119) * dt
INIT urban_ind_land_120 = 8.2e6
INFLOWS:
land_rem_urb_ind_use_119 = (urb_ind_land_req_118-
urban_ind_land_120)/urb_ind_land_dev_time_119
yield_tech_LYTD(t) = yield_tech_LYTD(t - dt) + (yield_tech_chg_rt_LYTDR) * dt
INIT yield_tech_LYTD = 1
INFLOWS:
yield_tech_chg_rt_LYTDR = if (time > t_policy_year_150) then
p_yield_tech_chg_mlt_LYCM*yield_tech_LYTD else 0
Absorption_Land_in_Gha = ppoll_gen_rt_137*Gha_per_unit_of_pollution
agr_inp_per_hect_101 = agr_inp_99*(1-p_fr_inp_for_land_maint_126)/arable_land_85
agr_mtl_toxic_index_140 = 1
Arable_Land_in_Gha = arable_land_85/1e9
assim_half_life_146 = assim_half_life_1970_146*assim_half_life_mlt_145
assim_half_life_1970_146 = 1.5
avg_ind_out_pc_43 = SMTH1(ind_out_pc_49,income_expect_avg_time_43)
avg_life_land_112 = avg_life_land_norm_112*s_land_life_mlt_yield_113
avg_life_land_norm_112 = 1000
birth_rt_31 = 1000*births_30/population_1
cons_ind_out = industrial_output_50*s_fioa_cons_57
cons_ind_out_pc = cons_ind_out/population_1
current_agr_inp_98 = tot_agric_invest_92*(1-fr_inp_al_land_dev_108)
deaths_17 = deaths_0_to_14_3+deaths_15_to_44_7+deaths_45_to_64_11+deaths_65_plus_15
death_rate_18 = 1000*deaths_17/population_1
del_ind_out_pc_40 = SMTH3(ind_out_pc_49,social_adj_del_40)
des_compl_fam_size_38 = if ( time > t_zero_pop_grow_time_38) then 2.0 else
(des_compl_fam_size_norm_38*fam_resp_to_soc_norm_41*soc_fam_size_norm_39)
des_compl_fam_size_norm_38 = 3.8
des_food_ratio_DFR = 2
des_ppoll_index_DPOLX = 1.2
des_res_use_rt_DNRUR = 4.8e9
des_tot_fert_35 = des_compl_fam_size_38*compl_mlt_perc_lifet_36
eff_hlth_serv_pc_22 = SMTH1(hlth_serv_al_pc_21,hlth_serv_impact_del_22)
fam_income_expect_42 = (ind_out_pc_49-avg_ind_out_pc_43)/avg_ind_out_pc_43
fert_cont_al_pc_47 = fr_serv_al_fert_cont_48*serv_out_pc_71
fert_cont_eff_45 = if (time > t_fert_cont_eff_time_45) then 1 else fert_cont_eff_table_45
fert_cont_facil_pc_46 = SMTH3(fert_cont_al_pc_47,hlth_serv_impact_del_22)
fioa_ind_56 = (1-s_fioa_agr_93-s_fioa_serv_63-s_fioa_cons_57)
food_87 = land_yield_103*arable_land_85*land_fr_harvested_87*(1-processing_loss_87)-

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$0.5 * \text{PULSE}(\text{land_yield_103} * \text{arable_land_85} * \text{land_fr_harvested_87} * (1 - \text{processing_loss_87}), 2075)$
 $\text{food_pc_88} = \text{food_87} / \text{population_1}$
 $\text{food_ratio_127} = \text{food_pc_88} / \text{subsist_food_pc_127}$
 $\text{food_short_perc_del_128} = 2$
 $\text{frac_res_pers_mtl_139} = .02$
 $\text{fr_agr_inp_pers_mtl_140} = .001$
 $\text{GDP_Index} = (\text{LOG10}(\text{GDP_per_capita_2}) - \text{LOG10}(24)) / (\text{LOG10}(9508) - \text{LOG10}(24))$
 $\text{Gha_per_unit_of_pollution} = 4 / 1e9$
 $\text{HEF_Human_Ecological_Footprint} =$
 $(\text{Arable_Land_in_Gha} + \text{Urban_Land_in_Gha} + \text{Absorption_Land_in_Gha}) / 1.91$
 $\text{hlth_serv_impact_del_22} = 20$
 $\text{HWI_Human_Welfare_Index} = (\text{Life_Expectancy_Index} + \text{Education_Index} + \text{GDP_Index}) / 3$
 $\text{income_expect_avg_time_43} = 3$
 $\text{industrial_output_50} = \text{industrial_capital_52} * (1 -$
 $\text{s_fr_cap_al_obt_res_134}) * \text{capacity_util_fr_83} / \text{s_ind_cap_out_ratio_51}$
 $\text{ind_mtl_emiss_fact_139} = .1$
 $\text{ind_mtl_toxic_index_139} = 10$
 $\text{ind_out_in_1970_107} = 7.9e11$
 $\text{ind_out_pc_49} = \text{industrial_output_50} / \text{population_1}$
 $\text{ind_out_pc_des_59} = 400$
 $\text{inherent_land_fert_124} = 600$
 $\text{jobs_73} = \text{pot_jobs_ind_sector_74} + \text{pot_jobs_agr_sector_78} + \text{pot_jobs_in_serv_sector_76}$
 $\text{labor_force_80} = (\text{pop_15_to_44_6} + \text{pop_45_to_64_10}) * \text{labor_force_partic_80}$
 $\text{labor_force_partic_80} = .75$
 $\text{labor_util_fr_81} = \text{jobs_73} / \text{labor_force_80}$
 $\text{labor_util_fr_del_time_82} = 2$
 $\text{land_fr_cult_84} = \text{arable_land_85} / \text{pot_arable_land_tot_84}$
 $\text{land_fr_harvested_87} = .7$
 $\text{land_yield_103} =$
 $\text{s_land_yield_fact_104} * \text{land_fertility_121} * \text{land_yield_mlt_cap_102} * \text{s_yield_mlt_air_poll_105}$
 $\text{lifet_mlt_crowd_28} = 1 - (\text{crowd_mult_ind_27} * \text{fr_pop_urban_26})$
 $\text{lifet_mult_hlth_serv_23} = \text{IF}(\text{time} > 1940) \text{ then } \text{lifet_mlt_hlth_serv_2_25} \text{ else}$
 $\text{lifet_mlt_hlth_serv_1_24}$
 $\text{lifet_perc_del_37} = 20$
 $\text{life_expectancy_19} =$
 $\text{life_expect_norm_19} * \text{lifet_mlt_food_20} * \text{lifet_mult_hlth_serv_23} * \text{lifet_mlt_ppoll_29} * \text{lifet_mlt_crowd}$
 _28
 $\text{life_expect_norm_19} = 28$
 $\text{marg_prod_agr_inp_110} =$
 $\text{s_avg_life_agr_inp_100} * \text{land_yield_103} * \text{marg_land_yield_mlt_cap_111} / \text{land_yield_mlt_cap_102}$
 $\text{marg_prod_land_dev_109} = \text{land_yield_103} / (\text{dev_cost_per_hect_97} * \text{social_discount_109})$
 $\text{max_tot_fert_33} = \text{max_tot_fert_norm_33} * \text{fecundity_mult_34}$
 $\text{max_tot_fert_norm_33} = 12$
 $\text{need_for_fert_cont_44} = (\text{max_tot_fert_33} / \text{des_tot_fert_35}) - 1$
 $\text{nr_res_fr_remain_133} = \text{nr_resources_129} / \text{init}(\text{nr_resources_129})$
 $\text{perc_life_expectancy_37} = \text{SMTH3}(\text{life_expectancy_19}, \text{lifet_perc_del_37})$
 $\text{poll_intens_ind} = \text{ppoll_gen_ind_139} * \text{s_ppoll_gen_fact_138} / \text{industrial_output_50}$
 $\text{population_1} = \text{pop_0_to_14_2} + \text{pop_15_to_44_6} + \text{pop_45_to_64_10} + \text{pop_65_plus_14}$
 $\text{pot_arable_land_tot_84} = 3.2e9$
 $\text{pot_jobs_agr_sector_78} = \text{jobs_per_hect_79} * \text{arable_land_85}$
 $\text{pot_jobs_ind_sector_74} = \text{industrial_capital_52} * \text{jobs_per_ind_cap_unit_75}$
 $\text{pot_jobs_in_serv_sector_76} = \text{service_capital_67} * \text{jobs_per_serv_cap_unit_77}$

ppoll_gen_agr_140 =
 agr_inp_per_hect_101*arable_land_85*fr_agr_inp_pers_mtl_140*agr_mtl_toxic_index_140
 ppoll_gen_ind_139 =
 pc_res_use_mlt_132*population_1*frac_res_pers_mtl_139*ind_mtl_emiss_fact_139*ind_mtl_toxic_in
 dex_139
 ppoll_gen_rt_137 = (ppoll_gen_ind_139+ppoll_gen_agr_140)*s_ppoll_gen_fact_138
 ppoll_index_143 = pers_pollution_142/ppoll_in_1970_143
 ppoll_in_1970_143 = 1.36e8
 ppoll_trans_del_141 = 20
 processing_loss_87 = .1
 p_avg_life_agr_inp_1_100 = 2
 p_avg_life_agr_inp_2_100 = 2
 p_avg_life_ind_cap_1_54 = 14
 p_avg_life_ind_cap_2_54 = 14
 p_avg_life_serv_cap_1_69 = 20
 p_avg_life_serv_cap_2_69 = 20
 p_fioa_cons_const_1_58 = .43
 p_fioa_cons_const_2_58 = .43
 p_ind_cap_out_ratio_1_51 = 3
 p_ind_cap_out_ratio_2_51 =
 ind_cap_out_ratio_2_ICOR2T*yield_tech_mult_icor_COYM*ppoll_tech_mult_icor_COPM
 p_land_yield_fact_1_104 = 1
 p_land_yield_fact_2_104 = SMTH3(yield_tech_LYTD,tech_dev_del_TDD)
 p_nr_res_use_fact_1_131 = 1
 p_nr_res_use_fact_2_131 = SMTH3(res_tech_NRTD,tech_dev_del_TDD)
 p_ppoll_gen_fact_1_138 = 1
 p_ppoll_gen_fact_2_138 = SMTH3(ppoll_tech_PTD,tech_dev_del_TDD)
 p_serv_cap_out_ratio_1_72 = 1
 p_serv_cap_out_ratio_2_72 = 1
 reproductive_lifetime_30 = 30
 res_intens = nr_res_use_rate_130/industrial_output_50
 service_output_70 = (service_capital_67*capacity_util_fr_83)/s_serv_cap_out_ratio_72
 serv_out_pc_71 = service_output_70/population_1
 social_adj_del_40 = 20
 social_discount_109 = .07
 subsist_food_pc_127 = 230
 s_avg_life_agr_inp_100 = if (time > t_policy_year_150) then p_avg_life_agr_inp_2_100 else
 p_avg_life_agr_inp_1_100
 s_avg_life_ind_cap_54 = if (time > t_policy_year_150) then p_avg_life_ind_cap_2_54 else
 p_avg_life_ind_cap_1_54
 s_avg_life_serv_cap_69 = if (time > t_policy_year_150) then p_avg_life_serv_cap_2_69 else
 p_avg_life_serv_cap_1_69
 s_fioa_agr_93 = if (time > t_policy_year_150) then p_fr_io_al_agr_2_95 else p_fr_io_al_agr_1_94
 s_fioa_cons_57 = if (time > t_ind_equil_time_57) then p_fioa_cons_var_59 else s_fioa_cons_const_58
 s_fioa_cons_const_58 = if (time > t_policy_year_150) then p_fioa_cons_const_2_58 else
 p_fioa_cons_const_1_58
 s_fioa_serv_63 = if (time > t_policy_year_150) then p_fr_io_al_serv_2_65 else p_fr_io_al_serv_1_64
 s_fr_cap_al_obt_res_134 = if (time > t_fcaor_time) then p_fr_cap_al_obt_res_2_136 else
 p_fr_cap_al_obt_res_1_135
 s_indic_food_pc_89 = if (time > t_policy_year_150) then p_indic_food_pc_2_91 else
 p_indic_food_pc_1_90
 s_indic_serv_pc_60 = if (time > t_policy_year_150) then p_indic_serv_pc_2_62 else
 p_indic_serv_pc_1_61

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s_ind_cap_out_ratio_51 = if (time > t_policy_year_150) then p_ind_cap_out_ratio_2_51 else
p_ind_cap_out_ratio_1_51
s_land_life_mlt_yield_113 = if (time > t_land_life_time) then .95^(time-
t_land_life_time)*p_land_life_mlt_yield_1_114 + (1-.95^(time-
t_land_life_time))*p_land_life_mlt_yield_2_115 else p_land_life_mlt_yield_1_114
s_land_yield_fact_104 = if (time > t_policy_year_150) then p_land_yield_fact_2_104 else
p_land_yield_fact_1_104
s_nr_res_use_fact_131 = if (time > t_policy_year_150) then p_nr_res_use_fact_2_131 else
p_nr_res_use_fact_1_131
s_ppoll_gen_fact_138 = if (time > t_policy_year_150) then p_ppoll_gen_fact_2_138 else
p_ppoll_gen_fact_1_138
s_serv_cap_out_ratio_72 = if (time > t_policy_year_150) then p_serv_cap_out_ratio_2_72 else
p_serv_cap_out_ratio_1_72
s_yield_mlt_air_poll_105 = if (time > t_air_poll_time) then p_yield_mlt_air_poll_2_107 else
p_yield_mlt_air_poll_1_106
tech_dev_del_TDD = 20
total_fertility_32 = MIN(max_tot_fert_33, (max_tot_fert_33*(1-
fert_cont_eff_45)+des_tot_fert_35*fert_cont_eff_45))
tot_agric_invest_92 = industrial_output_50*s_fioa_agr_93
t_air_poll_time = 4000
t_fcaor_time = 4000
t_fert_cont_eff_time_45 = 4000
t_ind_equil_time_57 = 4000
t_land_life_time = 4000
t_policy_year_150 = 4000
t_pop_equil_time_30 = 4000
t_zero_pop_grow_time_38 = 4000
Urban_Land_in_Gha = urban_ind_land_120/1e9
urb_ind_land_dev_time_119 = 10
urb_ind_land_req_118 = urb_ind_land_pc_117*population_1
assim_half_life_mlt_145 = GRAPH(ppoll_index_143)
(1.00, 1.00), (251, 11.0), (501, 21.0), (751, 31.0), (1001, 41.0)
capacity_util_fr_83 = GRAPH(labor_util_fr_del_82)
(1.00, 1.00), (3.00, 0.9), (5.00, 0.7), (7.00, 0.3), (9.00, 0.1), (11.0, 0.1)
compl_mlt_perc_lifet_36 = GRAPH(perc_life_expectancy_37)
(0.00, 3.00), (10.0, 2.10), (20.0, 1.60), (30.0, 1.40), (40.0, 1.30), (50.0, 1.20), (60.0, 1.10), (70.0, 1.05),
(80.0, 1.00)
crowd_mult_ind_27 = GRAPH(ind_out_pc_49)
(0.00, 0.5), (200, 0.05), (400, -0.1), (600, -0.08), (800, -0.02), (1000, 0.05), (1200, 0.1), (1400, 0.15),
(1600, 0.2)
dev_cost_per_hect_97 = GRAPH(pot_arable_land_86/pot_arable_land_tot_84)
(0.00, 100000), (0.1, 7400), (0.2, 5200), (0.3, 3500), (0.4, 2400), (0.5, 1500), (0.6, 750), (0.7, 300), (0.8,
150), (0.9, 75.0), (1.00, 50.0)
Education_Index = GRAPH(GDP_per_capita_2)
(0.00, 0.00), (1000, 0.81), (2000, 0.88), (3000, 0.92), (4000, 0.95), (5000, 0.98), (6000, 0.99), (7000,
1.00)
fam_resp_to_soc_norm_41 = GRAPH(fam_income_expect_42)
(-0.2, 0.5), (-0.1, 0.6), (0.00, 0.7), (0.1, 0.85), (0.2, 1.00)
fecundity_mult_34 = GRAPH(life_expectancy_19)
(0.00, 0.00), (10.0, 0.2), (20.0, 0.4), (30.0, 0.6), (40.0, 0.7), (50.0, 0.75), (60.0, 0.79), (70.0, 0.84), (80.0,
0.87)
fert_cont_eff_table_45 = GRAPH(fert_cont_facil_pc_46)
(0.00, 0.75), (0.5, 0.85), (1.00, 0.9), (1.50, 0.95), (2.00, 0.98), (2.50, 0.99), (3.00, 1.00)

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fr_inp_al_land_dev_108 = GRAPH(marg_prod_land_dev_109/marg_prod_agr_inp_110)
 (0.00, 0.00), (0.25, 0.05), (0.5, 0.15), (0.75, 0.3), (1.00, 0.5), (1.25, 0.7), (1.50, 0.85), (1.75, 0.95), (2.00, 1.00)

fr_pop_urban_26 = GRAPH(population_1)
 (0.00, 0.00), (2e+009, 0.2), (4e+009, 0.4), (6e+009, 0.5), (8e+009, 0.58), (1e+010, 0.65), (1.2e+010, 0.72), (1.4e+010, 0.78), (1.6e+010, 0.8)

fr_serv_al_fert_cont_48 = GRAPH(need_for_fert_cont_44)
 (0.00, 0.00), (2.00, 0.005), (4.00, 0.015), (6.00, 0.025), (8.00, 0.03), (10.0, 0.035)

GDP_per_capita_2 = GRAPH(ind_out_pc_49)
 (0.00, 120), (200, 600), (400, 1200), (600, 1800), (800, 2500), (1000, 3200)

Histpop = GRAPH(TIME)
 (1900, 1.59), (1920, 1.81), (1940, 2.25), (1960, 3.00), (1980, 0.00), (2000, 0.00), (2020, 0.00), (2040, 0.00), (2060, 0.00), (2080, 0.00), (2100, 0.00)

hlth_serv_al_pc_21 = GRAPH(serv_out_pc_71)
 (0.00, 0.00), (250, 20.0), (500, 50.0), (750, 95.0), (1000, 140), (1250, 175), (1500, 200), (1750, 220), (2000, 230)

ind_cap_out_ratio_2_ICOR2T = GRAPH(s_nr_res_use_fact_131)
 (0.00, 3.75), (0.1, 3.60), (0.2, 3.47), (0.3, 3.36), (0.4, 3.25), (0.5, 3.16), (0.6, 3.10), (0.7, 3.06), (0.8, 3.02), (0.9, 3.01), (1.00, 3.00)

jobs_per_hect_79 = GRAPH(agr_inp_per_hect_101)
 (2.00, 2.00), (6.00, 0.5), (10.0, 0.4), (14.0, 0.3), (18.0, 0.27), (22.0, 0.24), (26.0, 0.2), (30.0, 0.2)

jobs_per_ind_cap_unit_75 = GRAPH(ind_out_pc_49)
 (50.0, 0.00037), (200, 0.00018), (350, 0.00012), (500, 9e-005), (650, 7e-005), (800, 6e-005)

jobs_per_serv_cap_unit_77 = GRAPH(serv_out_pc_71)
 (50.0, 0.0011), (200, 0.0006), (350, 0.00035), (500, 0.0002), (650, 0.00015), (800, 0.00015)

land_fert_degr_rt_122 = GRAPH(ppoll_index_143)
 (0.00, 0.00), (10.0, 0.1), (20.0, 0.3), (30.0, 0.5)

land_fert_regen_time_125 = GRAPH(p_fr_inp_for_land_maint_126)
 (0.00, 20.0), (0.02, 13.0), (0.04, 8.00), (0.06, 4.00), (0.08, 2.00), (0.1, 2.00)

land_yield_mlt_cap_102 = GRAPH(agr_inp_per_hect_101)
 (0.00, 1.00), (40.0, 3.00), (80.0, 4.50), (120, 5.00), (160, 5.30), (200, 5.60), (240, 5.90), (280, 6.10), (320, 6.35), (360, 6.60), (400, 6.90), (440, 7.20), (480, 7.40), (520, 7.60), (560, 7.80), (600, 8.00), (640, 8.20), (680, 8.40), (720, 8.60), (760, 8.80), (800, 9.00), (840, 9.20), (880, 9.40), (920, 9.60), (960, 9.80), (1000, 10.0)

lifet_mlt_food_20 = GRAPH(food_pc_88/subsist_food_pc_127)
 (0.00, 0.00), (1.00, 1.00), (2.00, 1.43), (3.00, 1.50), (4.00, 1.50), (5.00, 1.50)

lifet_mlt_hlth_serv_1_24 = GRAPH(eff_hlth_serv_pc_22)
 (0.00, 1.00), (20.0, 1.10), (40.0, 1.40), (60.0, 1.60), (80.0, 1.70), (100, 1.80)

lifet_mlt_hlth_serv_2_25 = GRAPH(eff_hlth_serv_pc_22)
 (0.00, 1.00), (20.0, 1.50), (40.0, 1.90), (60.0, 2.00), (80.0, 2.00), (100, 2.00)

lifet_mlt_ppoll_29 = GRAPH(ppoll_index_143)
 (0.00, 1.00), (10.0, 0.99), (20.0, 0.97), (30.0, 0.95), (40.0, 0.9), (50.0, 0.85), (60.0, 0.75), (70.0, 0.65), (80.0, 0.55), (90.0, 0.4), (100, 0.2)

Life_Expectancy_Index = GRAPH(life_expectancy_19)
 (25.0, 0.00), (35.0, 0.16), (45.0, 0.33), (55.0, 0.5), (65.0, 0.67), (75.0, 0.84), (85.0, 1.00)

marg_land_yield_mlt_cap_111 = GRAPH(agr_inp_per_hect_101)
 (0.00, 0.075), (40.0, 0.03), (80.0, 0.015), (120, 0.011), (160, 0.009), (200, 0.008), (240, 0.007), (280, 0.006), (320, 0.005), (360, 0.005), (400, 0.005), (440, 0.005), (480, 0.005), (520, 0.005), (560, 0.005), (600, 0.005)

mortal_0_to_14_4 = GRAPH(life_expectancy_19)
 (20.0, 0.0567), (30.0, 0.0366), (40.0, 0.0243), (50.0, 0.0155), (60.0, 0.0082), (70.0, 0.0023), (80.0, 0.001)

mortal_15_to_44_8 = GRAPH(life_expectancy_19)

(20.0, 0.0266), (30.0, 0.0171), (40.0, 0.011), (50.0, 0.0065), (60.0, 0.004), (70.0, 0.0016), (80.0, 0.0008)
 mortal_45_to_64_12 = GRAPH(life_expectancy_19)
 (20.0, 0.0562), (30.0, 0.0373), (40.0, 0.0252), (50.0, 0.0171), (60.0, 0.0118), (70.0, 0.0083), (80.0, 0.006)
 mortal_65_plus_16 = GRAPH(life_expectancy_19)
 (20.0, 0.13), (30.0, 0.11), (40.0, 0.09), (50.0, 0.07), (60.0, 0.06), (70.0, 0.05), (80.0, 0.04)
 pc_res_use_mlt_132 = GRAPH(ind_out_pc_49)
 (0.00, 0.00), (200, 0.85), (400, 2.60), (600, 3.40), (800, 3.80), (1000, 4.10), (1200, 4.40), (1400, 4.70), (1600, 5.00)
 ppoll_tech_mult_icor_COPM = GRAPH(s_ppoll_gen_fact_138)
 (0.00, 1.25), (0.1, 1.20), (0.2, 1.15), (0.3, 1.11), (0.4, 1.08), (0.5, 1.05), (0.6, 1.03), (0.7, 1.02), (0.8, 1.01), (0.9, 1.00), (1.00, 1.00)
 p_fioa_cons_var_59 = GRAPH(ind_out_pc_49/ind_out_pc_des_59)
 (0.00, 0.3), (0.2, 0.32), (0.4, 0.34), (0.6, 0.36), (0.8, 0.38), (1.00, 0.43), (1.20, 0.73), (1.40, 0.77), (1.60, 0.81), (1.80, 0.82), (2.00, 0.83)
 p_fr_cap_al_obt_res_1_135 = GRAPH(nr_res_fr_remain_133)
 (0.00, 1.00), (0.1, 0.9), (0.2, 0.7), (0.3, 0.5), (0.4, 0.2), (0.5, 0.1), (0.6, 0.05), (0.7, 0.05), (0.8, 0.05), (0.9, 0.05), (1.00, 0.05)
 p_fr_cap_al_obt_res_2_136 = GRAPH(nr_res_fr_remain_133)
 (0.00, 1.00), (0.1, 0.2), (0.2, 0.1), (0.3, 0.05), (0.4, 0.05), (0.5, 0.05), (0.6, 0.05), (0.7, 0.05), (0.8, 0.05), (0.9, 0.05), (1.00, 0.05)
 p_fr_inp_for_land_maint_126 = GRAPH(perc_food_ratio_128)
 (0.00, 0.00), (1.00, 0.04), (2.00, 0.07), (3.00, 0.09), (4.00, 0.1)
 p_fr_io_al_agr_1_94 = GRAPH(food_pc_88/s_indic_food_pc_89)
 (0.00, 0.4), (0.5, 0.2), (1.00, 0.1), (1.50, 0.025), (2.00, 0.00), (2.50, 0.00)
 p_fr_io_al_agr_2_95 = GRAPH(food_pc_88/s_indic_food_pc_89)
 (0.00, 0.4), (0.5, 0.2), (1.00, 0.1), (1.50, 0.025), (2.00, 0.00), (2.50, 0.00)
 p_fr_io_al_serv_1_64 = GRAPH(serv_out_pc_71/s_indic_serv_pc_60)
 (0.00, 0.3), (0.5, 0.2), (1.00, 0.1), (1.50, 0.05), (2.00, 0.00)
 p_fr_io_al_serv_2_65 = GRAPH(serv_out_pc_71/s_indic_serv_pc_60)
 (0.00, 0.3), (0.5, 0.2), (1.00, 0.1), (1.50, 0.05), (2.00, 0.00)
 p_indic_food_pc_1_90 = GRAPH(ind_out_pc_49)
 (0.00, 230), (200, 480), (400, 690), (600, 850), (800, 970), (1000, 1070), (1200, 1150), (1400, 1210), (1600, 1250)
 p_indic_food_pc_2_91 = GRAPH(ind_out_pc_49)
 (0.00, 230), (200, 480), (400, 690), (600, 850), (800, 970), (1000, 1070), (1200, 1150), (1400, 1210), (1600, 1250)
 p_indic_serv_pc_1_61 = GRAPH(ind_out_pc_49)
 (0.00, 40.0), (200, 300), (400, 640), (600, 1000), (800, 1220), (1000, 1450), (1200, 1650), (1400, 1800), (1600, 2000)
 p_indic_serv_pc_2_62 = GRAPH(ind_out_pc_49)
 (0.00, 40.0), (200, 300), (400, 640), (600, 1000), (800, 1220), (1000, 1450), (1200, 1650), (1400, 1800), (1600, 2000)
 p_land_life_mlt_yield_1_114 = GRAPH(land_yield_103/inherent_land_fert_124)
 (0.00, 1.20), (1.00, 1.00), (2.00, 0.63), (3.00, 0.36), (4.00, 0.16), (5.00, 0.055), (6.00, 0.04), (7.00, 0.025), (8.00, 0.015), (9.00, 0.01)
 p_land_life_mlt_yield_2_115 = GRAPH(land_yield_103/inherent_land_fert_124)
 (0.00, 1.20), (1.00, 1.00), (2.00, 0.63), (3.00, 0.36), (4.00, 0.29), (5.00, 0.26), (6.00, 0.24), (7.00, 0.22), (8.00, 0.21), (9.00, 0.2)
 p_ppoll_tech_chg_mlt_POLGFM = GRAPH(1-ppoll_index_143/des_ppoll_index_DPOLX)
 (-1.00, 0.00), (0.00, 0.00)
 p_res_tech_chg_mlt_NRCM = GRAPH(1-nr_res_use_rate_130/des_res_use_rt_DNRUR)
 (-1.00, 0.00), (0.00, 0.00)

p_yield_mlt_air_poll_1_106 = GRAPH(industrial_output_50/ind_out_in_1970_107)
(0.00, 1.00), (10.0, 1.00), (20.0, 0.7), (30.0, 0.4)

p_yield_mlt_air_poll_2_107 = GRAPH(industrial_output_50/ind_out_in_1970_107)
(0.00, 1.00), (10.0, 1.00), (20.0, 0.98), (30.0, 0.95)

p_yield_tech_chg_mlt_LYCM = GRAPH(des_food_ratio_DFR-food_ratio_127)
(0.00, 0.00), (1.00, 0.00)

soc_fam_size_norm_39 = GRAPH(del_ind_out_pc_40)
(0.00, 1.25), (200, 0.94), (400, 0.715), (600, 0.59), (800, 0.5)

urb_ind_land_pc_117 = GRAPH(ind_out_pc_49)
(0.00, 0.005), (200, 0.008), (400, 0.015), (600, 0.025), (800, 0.04), (1000, 0.055), (1200, 0.07), (1400,
0.08), (1600, 0.09)

yield_tech_mult_icor_COYM = GRAPH(s_land_yield_fact_104) (1.00, 1.00), (1.20, 1.05), (1.40, 1.12),
(1.60, 1.25), (1.80, 1.35), (2.00, 1.50)
