

A SIMPLIFIED MODEL FOR EVALUATING THE RESPONSE OF THE CLIMATE SYSTEM TO THE INCREASE OF GREENHOUSE GASES INCLUDING THE SIMULATION OF THE GLOBAL CARBON CYCLE.

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Abstract

A simplified climate model which links a Box Advection Diffusion Model and a Global Carbon Cycle Model, has been set-up at DCMN of the University of PISA. The biosphere is represented by six ecosystems: tropical and temperate forests, grassland, land used for agriculture, urban areas, tundra and semi-desertic areas. In the vertical direction the model considers four fields: terrestrial surface, litter, humus and stable charcoal. The effect of varying various model parameters affecting oceanic circulation and biosphere is discussed. The analysis shows that, on a two centuries time frame starting from unperturbed 1860 equilibrium, the atmospheric CO₂ concentration, and ultimately climate, will be prevalently determined by energy policies.

1. Introduction

The aim of the research programme established some years ago, is the study of climate response to various energy scenarios.

As first, specific objective, a global climate model has been set-up coupling a Box Advection Diffusion Model (BADM) with a Global Carbon Cycle Model (GCCM). The model contains a simple parametrization which anticipates a warming-induced transient response of the Global Thermohaline Circulation (GTC). This instrument is useful for studying the role that the ocean and the biosphere play during climate transients on the decades to centuries time frame that is of interest to the greenhouse problem.

Section 2 presents the model itself, focusing on GCCM. Section 3 summarizes the results of a series of sensitivity calculations. Observations on the work already done conclude the paper.

2 The model

The main features of the climate model set-up at DCMN are presented below in figures 1 to 3. In particular, figures 1 and 2 indicate schematically the main reservoirs and the oceanic and biospheric subdivision of BADM and GCCM. An overview of the model is presented in fig. 3, which focuses on the links between BADM, GCCM, and the proposed parametrization for the response of the GTC to the global warming. The ₀ subscript indicates climatological mean unperturbed values.

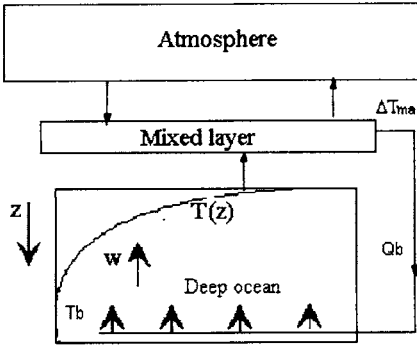


Figure 1 Main compartments and circulation scheme of BADM

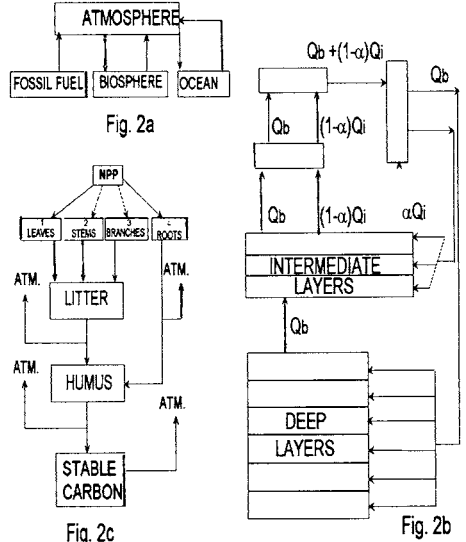


Figure 2 Main reservoirs and CO₂ fluxes in GCCM

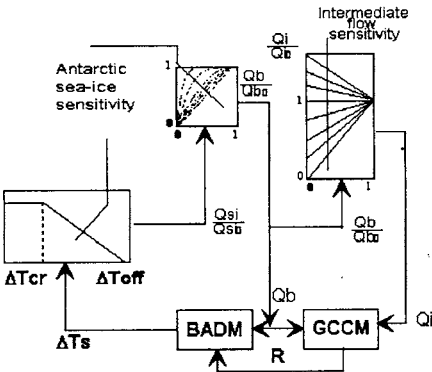


Figure 3 - Links between BADM, GCCM and GTC

2.1 The Box Advection Diffusion Model

The climatic model assumes that the surface temperature difference between the mixed layer and the atmosphere ΔT_{ma} does not appreciably vary during the transient; the reference value $\Delta T_{ma} = 4.8^\circ\text{C}$ is assumed. Based on this approximation and on the continuity of temperature across the mixed layer and the deep ocean interface, the model is reduced to the equation:

$$\frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial z^2} + w \frac{\partial T}{\partial z} \tag{1}$$

and the associated upper and lower boundary conditions (see [1] for details on BADM as well as for the parametrization for the AABW formation).

The heat diffusion in the interior of the ocean is parametrized in BADM by the so called deep ocean thermal diffusivity K [m²/s]. Due to the competing downward diffusion and upward advection of heat, the model predicts a steady-state exponential temperature profile in

2.2 The Global Carbon Cycle Model

The GCCM considers four main reservoirs: atmosphere, ocean, biosphere and fossil fuel (fig. 2a).

The atmospheric carbon content is driven by the flux of CO_2 emitted due to fossil fuel consumption ($F_{f,a}$), the net terrestrial biosphere output from both human disturbances (**DEFOR**) and Total Net Ecosystem Production (**TNEP**), and by $F_{m1,a}$, $F_{m2,a}$ which are the ocean-atmosphere fluxes respectively from Warm Surface Water (WSW) and to Cold Surface Water (CSW). These are calculated through the model of oceanic circulation shown in fig. 2b.

The relationship used is:

$$\frac{dN_a}{dt} = F_{f,a} + F_{m1,a} + F_{m2,a} + \text{DEFOR} + \text{TNEP} \quad (2)$$

In this paper, the attention is focused on the terrestrial biosphere (Fig. 2c) which is represented by six ecosystems: tropical forest, temperate forest, grasslands, agricultural areas, urban zones, tundra and semi-desert; vertically, the subdivision has been fixed in four dominions: the first is partitioned in leaves, branches, stems and roots; the other three are litter, humus and stable carbon in soil. The outflow from each component is equal to its content divided by its average life-span. The model accounts for anthropogenic impacts (forest cutting, burning and shifting agriculture), which allow to calculate DEFOR in eq. (2).

The driving input of the ecosystems is **NPP** (Net Primary Production), given by the difference between the annual assimilation of carbon and respirational losses. Global NPP is partitioned according to fixed distribution coefficients $\alpha_{j,k}$; j denotes the ecosystem number (1-6), k the vertical part number (1-4). The carbon originating from biomass and litter is not entirely channeled to the atmosphere, but a fraction ϵ_k is converted into long lasting charcoal.

Shifting agriculture practices can be mathematically represented by a time dependent exchange matrix \mathbf{a}_{ij} , denoting the gross annual transfer of land from ecosystem j to ecosystem i . The differential equations for the change of the carbon content are those suggested by Ketner [2].

Starting from the unperturbed climatological equilibrium, inputs to the model are provided in terms of CO_2 release to the GCCM atmosphere from fossil fuel reservoir. As illustrated in fig. 3 the coupling is firstly achieved by forcing BADM with a radiative perturbation term **R** calculated on the basis of the CO_2 level attained by the GCCM atmosphere. Then, the main output from BADM (referred to below as global mean surface temperature change ΔT_s), determines the response of the oceanic circulation both in BADM and in GCCM.

3. Values and ranges of the model parameters.

To the basic BADM parameters **K** and w_0 , are assigned the reference values first proposed by Hoffert et al. [3]: $6.34 \cdot 10^{-5} \text{ m}^2/\text{s}$ ($2000 \text{ m}^2/\text{y}$) and $1.27 \cdot 10^{-7} \text{ m/s}$ (4 m/y) respectively, giving a scale length **K/w₀** of **500 m**.

BADM was set-up by imposing a ramp radiative forcing $dR/dt=1.27 \cdot 10^{-9} \text{ W}/(\text{m}^2.\text{s})$, which falls in the range of interest of the greenhouse problem. The planetary albedo change is simply

estimated by assuming a climate sensitivity da/dT equal to $0.002/^\circ\text{C}$. With this feedback, the BADM sensitivity to a CO_2 doubling is approximately 3.4°C .

The GTC parametrization is focused on bottom water forming processes in Antarctica, with the possibility of a decrease of Q_b or, equivalently, of the model parameter w . The weakening of the bottom circulation was evaluated on the basis of different scenarios for the Antarctic sea-ice sensitivity, defined by the couple $\Delta T_{\text{cr}}, \Delta T_{\text{off}}$ (see [1] for details).

With regard to the intermediate circulation loop, the assumed lower and upper boundary for the unperturbed volumetric flow Q_{i0} are **35** and **140 Mm^3/s** , while the recirculation parameter α is allowed to vary in the range **1/3 to 1**. The sensitivity of the intermediate circulation, as defined by the model parameter **IFS**, is investigated assigning to **IFS** values from **-0.6 to 0.5**. The initial conditions are defined by the model equilibrium at an atmospheric CO_2 level of 285 ppmv in 1860.

The energy scenarios are the most important element in determining future CO_2 concentrations. Both the standard and high IIASA scenarios [4] were applied.

3.1 Main results of the sensitivity analyses.

The results of the sensitivity analyses are reported in [1]. They can be summarized as follows:

- BADM is quite insensitive to the values of K and w_0 provided the scale length K/w_0 of the unperturbed profile is maintained, as already observed by Harvey and Schneider [5];
- some differences in the atmospheric CO_2 build-up are observed when either doubling or halving the Q_i value; the model is almost insensitive to the intermediate circulation scheme (α parameter);
- a reduction in the global mean upwelling rate has a significant impact on the transient response, corresponding to a lag-time (as measured with respect to the no feedback response) of several years after 100-200 years of integration even in the GTC low-sensitivity scenario;
- this extra-lag time (additional with respect to the anticipated effect of the oceanic thermal inertia) develops progressively until the upwelling feedback is eventually exhausted; it ranges from approximately 5 to over 10 years, as far as years around 2000 are concerned in intermediate (I) and high (H) sensitivity cases respectively;
- the case of GTC full stop, although very crude, illustrates the intrinsic character of this feedback: its actual role is to delay the response without absorbing the perturbation;
- inherently in the model dynamics, the impact of the flow weakening increases with time: around year 2030, extra-lag times rise to approximately 15y in case I and 30y in case H. Q_b variations are on the whole of the order of -15% (I) and -27% (H);
- the model indicates an almost complete insensitivity of R to variations in GTC, when a 200 year time frame is considered; significant differences take a longer time to develop, up to approximately 25 ppmv after 400 years.

Referring to present years, the anticipated flow reductions and ΔT_s variations are overwhelmed by the current uncertainty about the basic BADM parameters K and w_0 .

With regard to the biosphere response, the results of sensitivity analyses for GCCM linked to BADM are listed in table 1.

Table 1

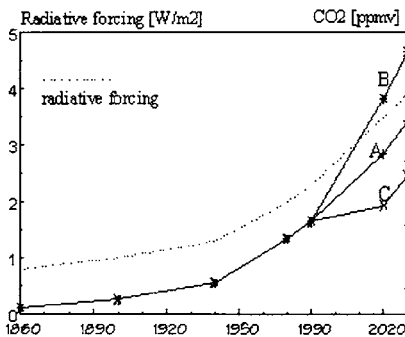
Sensitivity of the atmospheric CO₂ concentration (ppmv) to variations of main GCCM parameters or policy assumptions

	1990	2030
Oceanic diffusion coefficient doubled	-5,1	-14
Stop to deep water formation ($Q_b=0$)	+3,5	+12
NPP doubled	+0,8	-6,3
Life-span biomass doubled	+17	+36
Deforestation rate halved	-5,5	-15
Reforestation started in 1990 with $10^{11} \text{ m}^2/\text{y}$	0	-9,8
Stabilization of CO ₂ emissions to 1990 value	0	-28
High IIASA energy scenario	+0,1	+53

It is clear that the range in projected CO₂ concentrations due to energy scenarios is much larger than that due to parameter uncertainties.

The net effect of doubling the NPP is small because it involves not only the doubling of biomass but also the increase of CO₂ releases by deforestation.

Limiting the discussion to the time span of our interest (until 2030), a reference time history for the radiative forcing can be defined according to the case of unperturbed volumetric flows in GCCM, while fixing reference Q_{i0} and α values of $70 \text{ Mm}^3/\text{s}$ and 0.5. Figure 4a, shows the CO₂ atmospheric level (given by the fully coupled model of fig.3, with an intermediate sensitivity of GTC to the earth heating) and corresponding radiative forcing. The other curves of fig. 4a were obtained in a similar way, by considering the various policies outlined in table 1. The corresponding surface temperature responses are shown in fig. 4b. In 2020 the surface temperature increases differ of 0.3 degrees if one jumps from a policy of emission control and reforestation to the high IIASA scenario in energy consumption.

Fig. 4a Atmospheric CO₂ levels

- A) - reference atmospheric CO₂ level
- B) - high IIASA energy scenario

C) - CO₂ emission control + reforestation + deforestation rate halved (1990 values)

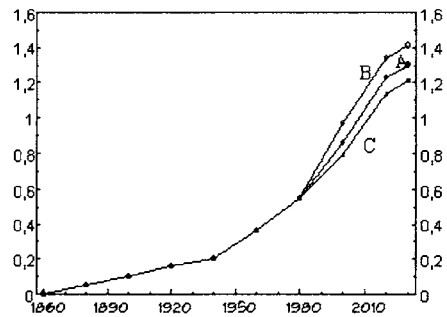


Fig. 4b Surface temperature change [°C]

Figure 4 Sensitivity of climate response to various policy scenarios

4. Concluding remarks

The model presented in section 2, although rather simple, is already an useful instrument for sensitivity analyses of climate changes related to various energy scenarios. In this respect, the following observation can be recalled:

- the low sensitivity of GCM to changes in the ocean circulation flows, at least in a century time scale and for the examined range of variation of the various parameters;
- the significant role of the GTC perturbation in delaying the climate response to the anthropogenic forcing, as pointed out also by several authors.
- the demonstration that the effect of environmental policy (reforestation) is fairly small (around - 10 ppmv in 2030); its effectiveness is very low, compared with that obtainable by changing the typology of energetic consumptions.

The DCMN model has some innovative features (coupling of BADM and GCM, explicit modeling of Antarctic Bottom Water formation), which should contribute to improve the reliability of simulated climate response. However, further improvements in the model are needed before the intended goals are reached.

Abbreviations

- **AABW**: Antarctic Bottom Water
- **BADM**: Box Advection Diffusion Model
- **CSW**: Cold Surface Water
- **DCMN**: Dipartimento Costruzioni Meccaniche e Nucleari
- **DEFOR**: Human disturbances to global carbon cycle
- **GCCM**: Global Carbon Cycle Model
- **GTC**: Global Thermohaline Circulation
- **IIASA**: International Institute of Applied System Analysis
- **IFS**: Intermediate Flow Sensitivity
- **NPP**: Net Primary Production of ecosystem
- **TNEP**: Total Net Ecosystem Production
- **WSW**: Warm Surface Water

Symbols

- **a**: earth mean surface albedo
- **a_{ij}**: rate of area transition from ecosystem j to i
- **F_{ca}**: Flux of carbon from fossil reservoir to atmosphere [Pg/y]
- **F_{m,1a}**: Flux of carbon from cold mixed layer to atmosphere [Pg/y]
- **F_{m,2a}**: Flux of carbon from warm mixed layer to atmosphere [Pg/y]
- **K**: ocean mean diffusivity [m²/s]
- **N_a**: Mass of carbon in atmosphere [Pg]
- **Q_b**: Deep water flux [Mm³/s]
- **Q_i**: Intermediate water flux [Mm³/s]
- **Q_{si}**: mean volumetric flow-rate of sea-ice formation [Mm³/s]
- **R**: Radiative forcing [W/m²]
- **t**: time [s]

- **w**: upwelling mean rate [m/s]
- **z**: vertical coordinate [m]
- **α**: coefficient of Qi partition between CSW and WSW
- **α_{jk}**: distribution coefficient of NPP
- **ΔT_{cr}**: value of ΔTs producing the start of GTC reduction [°C]
- **ΔT_{ma}**: Mean temperature difference between atmosphere and ocean surface water [°C]
- **ΔT_{off}**: value of ΔTs producing the stop of GTC [°C]
- **ΔT_s**: Temperature change of earth surface [°C]
- **ε_k**: Carbonization fraction of component k upon oxidation

References

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