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Evaluation of surface air temperature change due to the greenhouse gases increase with a statistical-dynamical model

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[1] A statistical-dynamical climate model is used for investigating the relative contribution of the changes in the radiation budget and surface air temperature due to the increase of the anthropogenic greenhouse gases predicted for 2100 on the basis of IPCC SRES A1FI (the highest greenhouse level scenario). Five experiments are performed considering the changes in concentrations of (1) CO_2, (2) CH_4, (3) N_2O, (4) tropospheric O_3, and (5) all the changes together. The results show that the mean global planetary absorbed solar radiation increases in response to the predicted conditions according to the scenario A1FI for year 2100 (A1FI-2100). This is due to the effect of O_3 absorptions. This increase leads to a decrease in the mean global planetary net thermal infrared radiation emitted to space by the Earth-atmosphere system to space and to an increase in mean global planetary net radiation. These changes are controlled mainly by the increase in CO_2 concentration. The changes in the radiation budget due to N_2O and CH_4 are small. The mean global surface air temperature response to the predicted conditions for A1FI-2100 was +0.59°C. The change in CO_2 concentration is responsible for an increase of +0.49°C. The higher increases occur in the polar regions: +2.15°C (at 85°S) and +1.55°C (at 85°N) in the case of the predicted conditions for A1FI-2100. Additional experiments indicate that the changes in surface air temperature are similar in the cases of the predicted conditions for A1FI-2100 and $4 \times CO_2$, $2 \times CO_2$ and $4 \times N_2O$, and in $2 \times N_2O$ and $4 \times CH_4$.

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1. Introduction

[2] An increase of 0.7°C in the mean annual global surface temperature has been observed in the last 100 years (http://www.globalchange.org/featall/2000spring2.htm). This has been attributed to the increase of greenhouse gases concentration due to anthropogenic use. Greenhouse gases have high transmissivity to solar radiation and high absorptivity to thermal infrared radiation. This implies in smaller planetary outgoing thermal infrared radiation flux to space and, consequently, warming of the climate system. The main greenhouse gases are water vapor, carbon dioxide (CO_2), ozone (O_3), nitrous oxide (N_2O) and methane (CH_4). Without the presence of these gases in the atmosphere the mean temperature of the Earth-atmosphere system would be 33°C lower [*Houghton et al.*, 1996]. The water vapor has been responsible for an increase of 20°C in the mean temperature. Among the anthropogenic gases CO_2 has more influence in the increase of mean temperature (7°C), followed by O_3 (2–3°C), N_2O (1.4°C), CH_4 (0.8°C) and the remainder gases (0.6°C) (http://rrz.uni_hambirg.de/klima2000/eng/eng_helf.html).

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[3] The concentration of all greenhouse gases has been increased because of anthropogenic cause since the beginning of the preindustrial era, except in the case of the water vapor and O_3 in the stratosphere. CH_4 showed higher increase of concentration, mainly from 1990. More than a half of the emission of CH_4 to the atmosphere is due to anthropogenic origin. According to IPCC Third Assessment Report (TAR) [*Houghton et al.*, 2001] the residence time of CO_2 (around 120 years) is higher compared to that of CH_4 (around 12 years). Anthropogenic CO_2 is released by both burning of fossil fuels and changes in land use. Burning of fossil fuels is responsible for 77% of the CO_2 emission to the atmosphere while in the case of change in land use, deforestation plays a principal role in the CO_2 emission, mainly in the tropical region [*Barnes*, 2004; *Schimel et al.*, 1996]. According to the IPCC TAR [*Houghton et al.*, 2001] and the Special Report on Emission Scenarios (SRES) [*Nakicenovic et al.*, 2000] the concentration of CO_2 in the scenario A1FI for year 2100 (hereafter called as A1FI-2100) will vary from 540 to 970 ppm while the concentration of CH_4 will

change between −190 to +1970 ppb relative to its year 2000 value. The values of the concentration of CO_2 and CH_4 for the year 2000 are 360 ppm and 1760 ppb, respectively [*Houghton et al.*, 2001].

[4] The radiative forcing of N_2O is lower than those of CO_2. According to the IPCC Assessments the term "radiative forcing" denotes an externally imposed perturbation in the radiative energy budget of the Earth's climate system, which may lead to changes in climate parameters (http://www.grida.no/climate/ipcc_tar/wg1/212.htm). Although the emission of tropospheric N_2O has increased at a lower rate than that of CH_4, its residence time is higher (around 114 years) [*Houghton et al.*, 2001]. The main anthropogenic sources of N_2O are from agriculture and industrial sources including adipic acid and nitric acid production [*Schimel et al.*, 1996]. The concentration of N_2O for the year 2000 is 316 ppb [*Houghton et al.*, 2001]. The concentration of O_3 in atmosphere greatly varies in time and space because of the interactions between the movements and chemical reactions in the atmosphere and its residence time is a few weeks. The increase of the O_3 in the troposphere is caused by photochemical processes and burning of fossil fuels and biomass [*Houghton et al.*, 1996]. It is estimated that the total amount of tropospheric O_3 has increased by 36% since 1750. The radiative forcing of O_3 for the year 2000 is around 0.38 Wm^{-2}. According to the TAR the maximum concentration of N_2O in A1F1-2100 will be +144 ppb above its year 2000 value and the tropospheric O_3 will increase by 62% relative to its year 2000 value [*Houghton et al.*, 2001].

[5] The impact of the increase of anthropogenic greenhouse gases concentration on climate can be projected using mathematical models that simulate future additions. In 1992, the IPCC released emission scenarios (IS92) to be used for driving general circulation models (GCMs) to develop future climate change scenarios. The IS92 were the first scenarios to provide estimates for the full set of greenhouse gases. These scenarios provided input to the IPCC Second Assessment Report (SAR). Projections of future climate from forcing IS92 scenarios experiments using several coupled atmosphere-ocean general circulation models (AOGCMs) were reported by *Kattemberg et al.* [1996]. The model calculations indicated an increase in global mean temperature relative to the present value of about 1° to 4.5°C by 2100 for a full range of IPCC scenarios. Because of the increase of the understanding of possible future greenhouse gas emissions and climate change in 1996 the IPCC developed a new set of emission scenarios (SRES), which provided input to the TAR. *Cubasch and Meehl* [2001] reported a large number of AOGCM climate simulations with various forcings scenarios from the SRES that provided estimates of possible future climate change [see *Albritton and Meira Filho*, 2001, box 6]. The models projected an increase in global mean temperature from 1.4°C to 5.8°C by 2100 for a full range of new emission scenarios. Temperature increases are higher than those in the SAR due partly to the increase of radiative forcing and primarily to the lower projected emissions in the SRES scenarios relative to the IS92 scenarios. In particular for the A1FI, the highest SRES greenhouse level scenario, which takes into account fossil fuel intensive energy emission sources, the temperature increase by 2100 is from 3.2°C to 5.7°C. Later studies have been devoted to investigate the uncertainty in the IPCC TAR temperature changes. Uncertainty in upper limits for temperature change by 2100 of less than 5°C were obtained by *Wigley and Raper* [2001] (1.7°–4.9°C), *Reilly et al.* [2001] (1.1°–4.5°C) and *Frame et al.* [2005] (1.4°C–4.1°C). In a recent IPCC Expert Meeting on Emission Scenarios there was a consensus that the range as given by IPCC remains large and recent studies have widened the range of uncertainty for climate sensitivity [*Hoogwijk*, 2005].

[6] In the model experiments reported at the SAR and TAR the IPCC scenarios took into account simultaneously the estimates of the future changes in the full set of greenhouse gases concentration. As pointed out by *Kattemberg et al.* [1996], the change in the radiative forcing since 1900 is approximately equivalent to that given by a 40% increase in CO_2. The equilibrium response to the trace gases and an equivalent increase in CO_2 are broadly similar. Since CO_2 is the main anthropogenic greenhouse gas, the equilibrium distribution of warming due to increases in CO_2 concentration has been discussed more extensively in the IPCCs reports. However, some differences in the pattern of changes may occur when changes in equivalent CO_2 are used instead of changes in the other trace gases [*Wang et al.*, 1992]. Thus the effect of the changes in the trace gases concentration on future climate deserves a detailed investigation. Earlier studies using simple models have examined the roles of individual gases on climate by doubling or quadrupling their atmospheric concentration. Radiative convective models (RCMs) were used for studying the effects of the changes in CH_4 and N_2O on the energy radiative budget [*Donner and Ramanathan*, 1980; *Wang et al.*, 1976] and the role of O_3 in the tropospheric-surface energy balance [*Ramanathan and Dickinson*, 1979; *Ramanathan*, 1976]. However, the relative importance of future changes on climate due to the main anthropogenic greenhouse gases must be investigated in more detail than has been done earlier using the recent IPCC scenarios. In particular, the projected future climate change from the more drastic SRES forcing scenario deserves to be examined.

[7] The objective of the present paper is to study the relative contributions of the changes in the radiation budget and surface air temperature caused by the increase of anthropogenic greenhouse gases concentration predicted for 2100 according to IPCC SRES A1FI (the highest greenhouse scenario). We propose to evaluate separately each of the four major greenhouse gases (CO_2, O_3, CH_4, and N_2O) in order to quantify their contribution to the future climate change. Such a study has not been done earlier. For this purpose, a zonally averaged statistical-dynamical model (SDM) with a detailed parameterization of the radiative processes is used. This kind of model is essentially mechanistic, being directed toward understanding the dependence of a particular mechanism on the other parameters of the problem. Thus a SDM is better suited for the present study. In GCMs, since many mechanisms are included simultaneously, the cause and effect relationship is not always possible to trace.

[8] In section 2 the SDM is presented and the numerical experiments concerning the effects of greenhouse gases are

shown in section 3. Section 4 contains the summary and conclusions.

2. Model and Experiments

2.1. Description of the Model

[9] The SDM used in this study is the same as that developed by *Moraes et al.* [2004]. The SDM is a latter version of the coupled biosphere-atmosphere climate model developed by *Varejão-Silva et al.* [1998] in which a detailed parameterization of the radiative processes [*Chou and Suarez*, 1994, 1999] which takes into account the effects of the main absorbing and emitting gases in the atmosphere is included. This allows us a detailed study of the radiative effects of greenhouse gases on climate.

[10] The model is a two-layer global primitive equation model in sigma-coordinate and includes parameterizations of friction, diabatic heating, and large-scale eddies. The energy fluxes such as solar radiation, thermal infrared radiation, sensible and latent heat fluxes, and subsurface flux are computed separately for the land fraction and the remaining part (covered by ocean-ice-snow) of the latitude belt. The parameterizations of the biosphere model based on BATS (Biosphere-Atmosphere Transfer Scheme) [*Zhang*, 1994] are used for the land fraction of the latitude belt. Detailed description of the coupled biosphere-atmosphere model is given by *Varejão-Silva et al.* [1998].

[11] The thermal infrared and solar radiation parameterization schemes used in the SDM are those developed by *Chou and Suarez* [1994] and *Chou and Suarez* [1999], respectively. In a recent version of the thermal radiation model, the surface emissivity in 10 spectral bands is considered. These schemes use several broadband parameterization schemes for thermal infrared and solar radiation to produce a computationally fast and accurate representation of radiation processes. Detailed description of the radiation schemes are given by *Chou and Suarez* [1994, 1999] and details of the input data for the radiation models and the coupling with the SDM are given by *Moraes et al.* [2004].

[12] The SDM has 10° latitude resolution and employs a latitudinal centered finite-differencing scheme. The strategy for running the SDM is the same as that given by *Moraes et al.* [2004]. The SDM is run in two steps. First, the original SDM of *Varejão-Silva et al.* [1998] is integrated without the inclusion of the biosphere parameterization using as initial condition an isothermal atmosphere (270 K) at rest. Explicit time integration was used with a time step of 30 min. The SDM is integrated for a six month period forced by mean annual conditions in order to obtain stationary solutions. In a second step, the SDM is run for a six month period including the effects of the biosphere and the new radiation models for obtaining new stationary solutions. Since the values of the 500 hPa temperature and the wind speed are necessary to run the biosphere-atmosphere coupled SDM they cannot be zero in the initial conditions. So, the mean annual zonally averaged simulation obtained earlier is used as an initial condition for running the coupled biosphere-atmosphere model. The new stationary solutions correspond to the simulation of the mean annual zonally averaged climate with the coupled biosphere-atmosphere SDM.

2.2. Numerical Experiments

[13] In the control experiment the actual concentration of the greenhouse gases used in the radiation models is obtained from the TAR, i.e., 360 ppm (CO_2), 1760 ppb (CH_4) and 316 ppb (N_2O) [*Houghton et al.*, 2001]. These values are for the year 2000. The vertical profiles of ozone mixing ratios are obtained from M.-D. Chou (personal communication, 2000). They are based on the optical properties of the atmosphere defined by *McClatchey et al.* [1972] and correspond to the standard atmosphere in tropical, middle and high latitudes. Results of *Moraes et al.* [2004] showed that the mean annual zonally averaged radiative fluxes and climate characteristics for the actual climate are well simulated by the SDM. These simulations will be compared with the results of the perturbed experiments.

[14] To study the relative contributions of the changes caused by the increase of the anthropogenic greenhouse gases concentration predicted for year 2100 the concentrations of the four major anthropogenic greenhouse gases are changed from their actual values (values for year 2000) to those from the more drastic IPCC SRES scenario for 2100 (A1FI-2100). Five experiments are carried out with the SDM considering the changes in the concentration of (1) CO_2, (experiment 1), (2) CH_4 (experiment 2), and (3) N_2O (experiment 3), (4) O_3 (experiment 4), and (5) CO_2, CH_4, N_2O and O_3 together (experiment 5). In experiments 1 to 3 the concentrations of CO_2, CH_4, and N_2O are changed from 360 ppm to 970 ppm, from 1760 ppb to 3730 ppb, and from 316 ppb to 460 ppb, respectively; in the case of the change in the concentration of tropospheric O_3 (experiment 4) the values given by *McClatchey et al.* [1972] are increased by 62%. In experiment 5 the changes in the concentration of CO_2, CH_4, N_2O and O_3 are taken into account simultaneously. Additional experiments considering the doubling and quadrupling of the actual concentration of CO_2, N_2O and CH_4 are also made.

[15] The strategy for running the SDM with the A1FI-2100 is the same as that in the control case.

3. Model Results

[16] In experiments 1–5 the climate changes are considered as the perturbed case minus the control experiment. Figures 1a–1c show the mean global planetary absorbed solar radiation, net thermal infrared radiation and net radiation, respectively. The changes (perturbed minus control) in these variables and the percentages of the changes in relation to the control case are presented in Table 1. As can be seen, in the case of the concentration of anthropogenic greenhouse gases predicted in A1FI-2100 (experiment 5) slight changes occur in the planetary absorbed solar radiation while for the net outgoing thermal infrared radiation the changes are higher. The increase in the CO_2 concentration in the atmosphere causes a reduction of 0.12 Wm^{-2} (0.05%) in the planetary absorbed solar radiation. The interaction between CO_2 and solar radiation provokes a slightly increase of planetary albedo (0.03%) (figure not shown). Since N_2O and CH_4 do not interact with solar radiation,

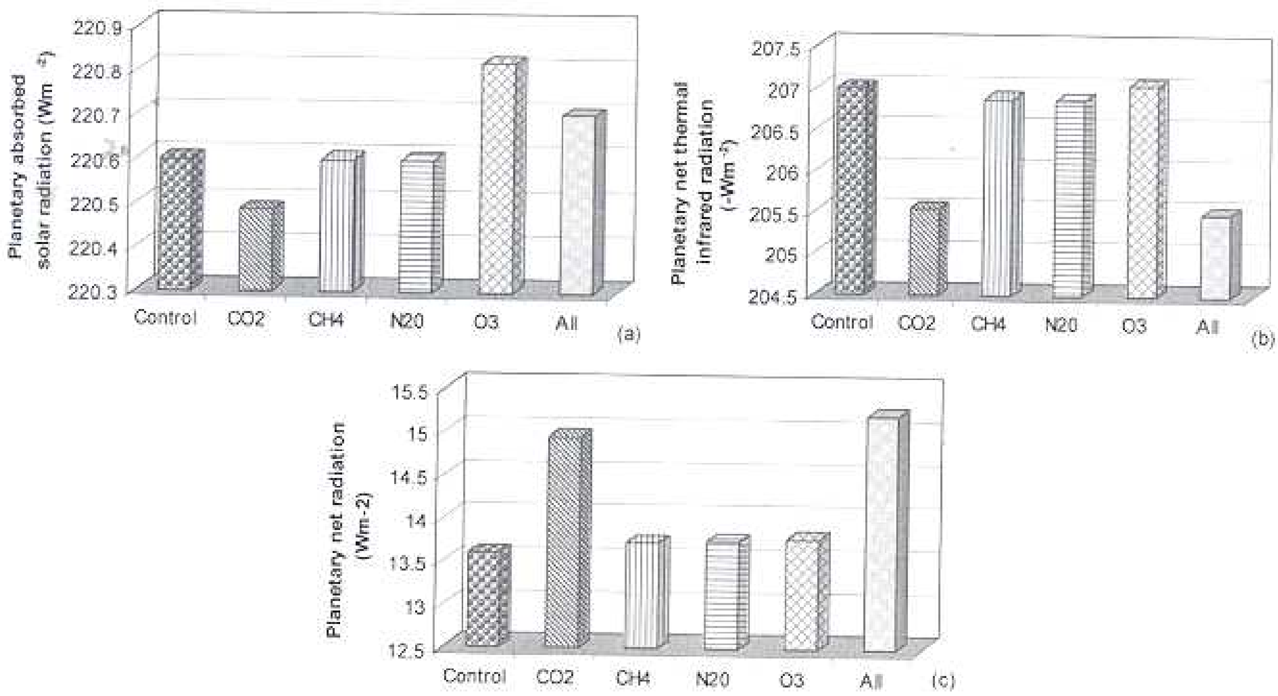

Figure 1. Mean global planetary (a) absorbed solar radiation, (b) net outgoing thermal infrared radiation, and (c) net radiation at the surface (Wm^{-2}). Shown are the values for experiments 1–5.

the change in their concentrations do not influence on the planetary absorbed solar radiation. However, the increase in the concentration of O_3 predicted in A1FI-2100 shows an opposite effect to that is verified in experiments 1, 2 and 3, i.e., there is an increase of 0.22 Wm^{-2} (0.10%) in the mean global planetary absorbed solar radiation. This may be due to the interactions between solar radiation and the tropospheric O_3, which has high absorption in the spectral bands where the emission of solar radiation is maximum. Thus the increase of tropospheric O_3 concentration causes larger storage of solar radiation in Earth-atmosphere system and a slight reduction in the mean global planetary albedo (0.04%) (figure not shown). Since the effect of the tropospheric O_3 is higher compared with the changes in the concentrations of the other three anthropogenic gases, there is an increase of 0.11 Wm^{-2} (0.05%) in the mean global planetary absorbed solar radiation.

[17] The increase of greenhouse gases concentration leads to a reduction in the net thermal infrared radiation emitted by the Earth-atmosphere system to space in the five experiments (Figure 1b). The increase of the concentration of CO_2, CH_4, O_3 and N_2O predicted in A1FI-2100 provokes a decrease of 1.51 Wm^{-2} (0.73%) in the mean global planetary net outgoing thermal infrared radiation. The change in CO_2 is responsible for a reduction of 1.45 Wm^{-2} (0.7%) while the changes in the other three anthropogenic gases are smaller: N_2O (−0.07%), CH_4 (−0.06%), and O_3 (+0.02%). Comparing experiments 1, 2, 3 and 4 it can be noted that among the anthropogenic gases CO_2 plays a major role in controlling the planetary net outgoing thermal infrared radiation.

[18] Because of the changes in planetary solar radiation and net outgoing thermal infrared radiation the planetary net radiation increases in the five experiments, as shown in Figure 1c and Table 1. An increase of 1.61 Wm^{-2} (11.9%) is noted when the concentration of the four anthropogenic greenhouse gases predicted in A1FI-2100 are taken into account together. The alteration in CO_2 concentration is responsible for an increase of 1.34 Wm^{-2} (9.84%) showing the important role of this gas in controlling the change of the planetary net radiation. As a consequence of the planetary radiation balance there is a warming of the

Table 1. Changes (Perturbed Minus Control) in the Mean Global Values of Planetary Absorbed Solar Radiation, Net Thermal Infrared Radiation, Net Radiation (Wm^{-2}) and Surface Air Temperature (°C) and the Percentages of the Changes in Relation to the Control Case Due to the Increase of Anthropogenic Greenhouse Gases for the A1FI-2100 Scenario[a]

	Mean Global Control Value	Changes for the A1FI-2100 Scenario				
		CO_2	CH_4	N_2O	O_3	All
Planetary absorbed solar radiation	220.6 Wm^{-2}	−0.12 (−0.05%)	0.00 (0.00%)	0.00 (0.00%)	+0.22 (+0.10%)	+0.11 (+0.05%)
Planetary net outgoing thermal infrared radiation	207.0 Wm^{-2}	−1.45 (−0.70%)	−0.12 (−0.06%)	−0.14 (−0.07%)	+0.05 (+0.02%)	−1.51 (−0.73%)
Planetary net radiation	13.6 Wm^{-2}	+1.34 (+9.84%)	+0.12 (+0.90%)	+0.14 (+1.04%)	+0.18 (+1.28%)	+1.61 (+11.9%)
Surface air temperature	282.12 K	+0.49 (+5.50%)	+0.04 (+0.43%)	+0.05 (+0.55)	+0.07 (+0.76%)	+0.59 (+6.60%)

[a]Also shown are the mean global values in the control experiment.

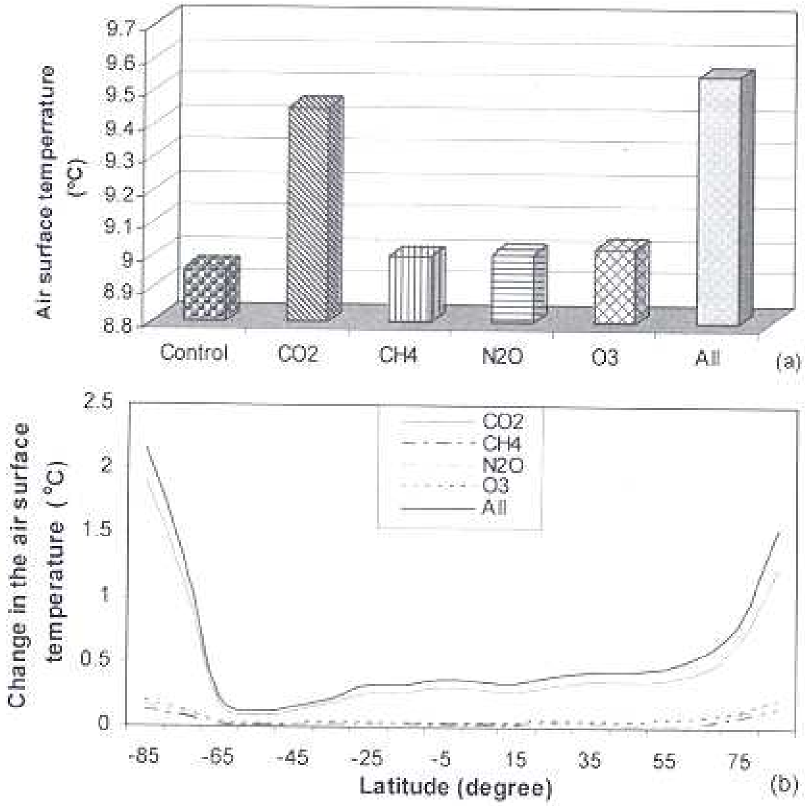

Figure 2. Increase of surface air temperature (°C): (a) mean global values and (b) latitudinal variation of the changes (perturbed minus control). Shown are the values of experiments 1–5.

Earth-atmosphere system. As shown in Figure 2a and Table 1 there is an increase of 0.59°C (6.6%) in the mean global surface air temperature in the case of the concentrations of CO_2, CH_4, O_3 and N_2O predicted in A1FI-2100. When only the change in the concentration of CO_2 is considered the increase is of 0.49°C (5.5%) while the changes due to O_3, N_2O, CH_4 and are responsible for an increase of 0.76%, 0.55% and 0.43% in relation to the control case, respectively. As shown in Figure 2b, the change in CO_2 concentration plays the major role in all the latitude belts compared with the other greenhouse gases. The change in the surface air temperature is higher in the polar regions, mainly in the Southern Hemisphere. As shown in Table 2 and Figure 2b, when all the changes in gas concentration are included the surface air temperature increases by 2.15°C (at 85°S) and 1.55°C (at 85°N). The changes in CO_2 are responsible for increases of 1.9°C (at 85°S) and 1.25°C (at 85°N).

[19] In addition to the five experiments concerning the effects of the change in the concentration of the anthropogenic greenhouse gases predicted in A1FI-2100, other experiments considering 2 × CO_2, 4 × CO_2, 2 × N_2O, 4 × N_2O, 2 × CH_4 and 4 × CH_4 are also made. The control experiment it the same as that in the previous case. Figure 3a and Table 3 show the mean global surface temperature for the doubling and quadrupling the actual concentrations of these greenhouse gases. The latitudinal changes (perturbed minus control) are shown in Figure 3b. As shown in Figure 3a and Table 3 the doubling of the amount of CO_2 concentration is responsible for an increase of 0.37°C in the mean global surface air temperature while in the case of the doubling of CH_4 and N_2O the increase is less than 0.1°C. The difference between the mean global surface air temperature in the cases 2 × CO_2 and 4 × N_2O is less than 0.1°C. The changes are also similar for 4 × CH_4 and 2 × N_2O experiments. The difference in the mean global surface air temperature between the 4 × CO_2 experiment and the experiment considering simultaneously the concentrations of CO_2, CH_4, N_2O and O_3 predicted in A1FI-2100 is less than 0.1°C, as seen in Table 3. From Figure 3b, in the polar regions the effect on the surface air temperature caused by the increase of the four anthropogenic greenhouse gases concentrations is similar as that in the case of 4 × CO_2. For the other latitude belts the increase is somewhat higher for 4 × CO_2.

[20] The results shown above indicated the relative importance of the changes and mechanisms involved due to the increase of anthropogenic greenhouse gases concentration in the atmosphere. Taking into account that the

Table 2. Changes in Surface Air Temperature (°C) in Polar Regions Due to the Increase of Anthropogenic Greenhouse Gases for the A1FI-2100 Scenario[a]

Experiment	ΔT at 85°S, °C	ΔT at 85°N, °C
CO_2	+1.90	+1.25
CH_4	+0.13	+0.16
N_2O	+0.17	+0.21
O_3	+0.20	+0.23
All	+2.15	+1.55

[a]Shown are the values at the latitude belts centered at 85°N (S) for the five experiments.

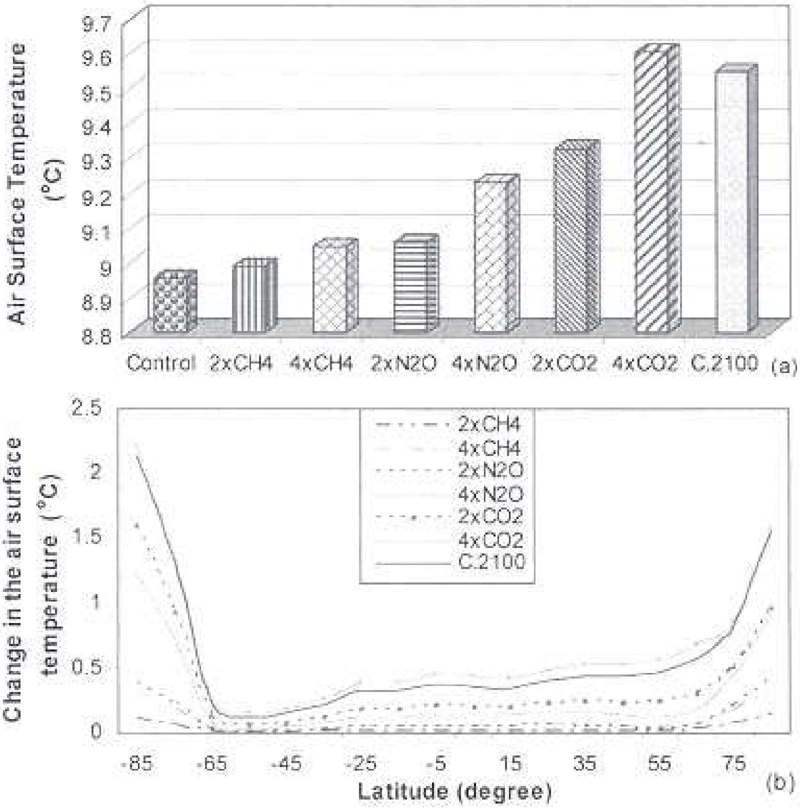

Figure 3. Increase of surface air temperature (°C) for: 2 × CO_2, 4 × CO_2, 2 × N_2O, 4 × N_2O, 2 × CH_4 and 4 × CH_4: (a) mean global values and (b) latitudinal variation of the changes (perturbed minus control). Shown are also the mean global values and the latitudinal variation of the changes corresponding to the concentrations of CO_2, CH_4, N_2O and O_3 for the A1FI-2100 scenario.

model results correspond to the simulation of a future scenario of climate change due the increase of anthropogenic greenhouse gases concentration the comparison between the model predictions and observed data is a difficult task. To our knowledge, for the first time in this study the effects of the increase of the main anthropogenic gases concentration predicted in A1FI-2100 are investigated all together using a SDM. Also, the relative importance of different gas concentration predicted in A1FI-2100 is examined which was not studied earlier even with GCMs. Comparing with the model results presented by the TAR, the SDM projects a lower increase of temperature for the A1FI scenario. The results of 2 × CO_2 and 4 × CO_2 experiments are consistent with the current evidence [*Mitchell*, 1989] and GCM studies, which show higher increase of the surface air temperature near the poles. The increase of the surface air temperature due to the doubling of CO_2 concentration in the present study (0.37°C) is less than that according to the SAR, which varies from 1.5°C to 4.5°C [*Kattemberg et al.*, 1996]. The change in surface air temperature in the SDM is also less than results of fifteen models presented in the TAR, which project an equilibrium temperature increase from 2°C to 5.1°C [*Cubasch and Meehl*, 2001]. However, it is similar to those obtained by *Lindzen* [1995, 1998] (0.3°C and 0.55°C, respectively).

[21] The lower values of temperature increase obtained with the SDM compared to the GCM results may be attributed to the differences between the models such as the resolution, the treatment of radiative processes and clouds, planetary boundary layer modeling and coupling of the surface to the atmosphere, treatment of snow and ice, etc. Also it should be born in mind that the SDM is a zonally averaged mean annual climate model and so a greater response can hardly be expected. As mentioned earlier, the SDM is essentially mechanistic, being directed toward understanding the dependence of a particular mechanism on other parameters of the problem. The change in surface air temperature in the SDM is in better agreement

Table 3. Increase of Surface Air Temperature (°C) for 2 × CO_2, 4 × CO_2, 2 × N_2O, 4 × N_2O, 2 × CH_4 and 4 × CH_4: Mean Global Values and Latitudinal Variation of the Changes[a]

Experiment	ΔT, °C	ΔT at 85°S, °C	ΔT at 85°N, °C
2 × CH_4	+0.04	+0.11	+0.14
4 × CH_4	+0.09	+0.33	+0.35
2 × N_2O	+0.10	+0.4	+0.42
4 × N_2O	+0.28	+1.23	+0.90
2 × CO_2	+0.37	+1.59	+0.96
4 × CO_2	+0.65	+2.22	+1.56
Change in the four greenhouse gases for A1FI-2100	+0.59	+2.15	+1.55

[a]Shown are the mean global values and the latitudinal variation of the changes corresponding to the concentrations of CO_2, CH_4, N_2O and O_3 for the A1FI-2100 scenario.

with results obtained with RCMs, where the increase of surface air temperature varies from +0.48°C to +4.2°C (see *Schlesinger and Mitchell* [1987, Table 1], which presents results of seventeen RCMs).

[22] The results presented above showed that the changes are in qualitative agreement with those obtained from more complex GCMs and simpler RCMs This indicates that the present SDM is a good complement to GCMs and can play important role in generalizing and confirming results of RCM simulations.

4. Summary and Conclusions

[23] In this paper the relative contributions of the changes in the radiation budget and surface air temperature caused by the increase of anthropogenic greenhouse gases concentration predicted for 2100 according to the more drastic IPCC SRES scenario (A1FI-2100) were investigated. For this purpose a coupled biosphere-atmosphere SDM with a detailed parameterization of solar radiation and thermal infrared radiation fluxes was used. This kind of model is directed toward understanding the dependence of a particular mechanism on the other parameters of the problem. The simulation of the mean annual zonally averaged climate was taken as the control experiment. In the control experiment the concentrations of greenhouse gases are for year 2000. Five experiments were made for studying the relative contributions of the effects of the increase of the four major anthropogenic greenhouse gases concentration: changes in (1) CO_2, (2) CH_4, (3) N_2O, (4) O_3, and (5) all the changes together. Additional experiments considering the doubling and quadrupling of CO_2, CH_4, and N_2O were also made.

[24] The results showed that when the concentrations of the four major anthropogenic greenhouse gases predicted in A1FI-2100 were taken into account slight changes occurred in planetary absorbed solar radiation while in the planetary net thermal infrared radiation the changes were higher. The change in CO_2 was responsible for a decrease of 0.05% in the planetary absorbed solar radiation and for a slight increase of the mean global planetary albedo occurred (0.03). However, the change in tropospheric O_3 concentration provoked an increase in planetary absorbed solar radiation (0.1%). This is due to the effect of O_3 absorptions, because it has high absorption in the spectral bands where the solar radiation emission is maximum. Since the effect of tropospheric O_3 was higher than that of CO_2, CH_4 and N_2O, there was an increase in the mean global planetary absorbed radiation (0.05%).

[25] Because of the increase of the opacity of the atmosphere the planetary net outgoing thermal infrared radiation decreased in the five experiments. As a consequence of the changes in planetary absorbed solar radiation and net thermal infrared radiation there was an increase of planetary net radiation. In the case of the concentrations of CO_2, CH_4, O_3 and N_2O predicted in A1FI-2100 there were a decrease of 0.73% in the mean global planetary thermal infrared radiation and an increase of 11.9% in the mean global planetary net radiation. Among the anthropogenic gases CO_2 played a major role in controlling the changes in the mean global planetary net outgoing thermal infrared radiation (−0.7%) and net radiation (+9.84%). The alterations in the concentrations of N_2O, CH_4 and O_3 were responsible for −0.07%, −0.06% and +0.02% in the mean global planetary net outgoing thermal infrared radiation and for +1.04%, +0.9% and +1.28% in the mean global planetary net radiation, respectively.

[26] The mean global surface air temperature response to the increase of the concentrations of CO_2, CH_4, O_3 and N_2O predicted in A1FI-2100 was +0.59°C (+6.6%). The change in the concentration of CO_2 was responsible for an increase of +0.49°C (+5.5%) while the changes due to the other greenhouse gases concentrations were smaller (less than +1%). The changes in surface air temperature due to CO_2 concentration are higher in the polar regions, mainly in the Southern Hemisphere. The additional experiments considering the doubling and quadrupling of the concentrations of CO_2, CH_4, and N_2O showed that the difference in mean global surface air temperature between $4 \times CO_2$ and in the case of the concentration of greenhouse gases predicted in A1FI-2100 was less than 0.1°C. In the polar regions the changes in surface air temperature were equivalent in these two cases while in the other latitudes the increase is somewhat higher for $4 \times CO_2$. The results also showed that the effects on the surface air temperature were similar in the cases $2 \times CO_2$ and $4 \times N_2O$, and in the cases $2 \times N_2O$ and $4 \times CH_4$.

[27] Since the model results correspond to a simulation of a future scenario of climatic change due to the increase of anthropogenic gases concentration in the atmosphere a comparison with observed data is difficult. For the first time a SDM was used to investigate the relative effects of changes in the main anthropogenic gases concentration predicted for 2100 (IPCC SRES A1FI scenario). Although the magnitude of changes is lower, the SDM gives credible predictions consistent with more complex and expensive GCM experiments. Also, the surface air temperature increase in the SDM is in good agreement with that obtained from earlier RCMs. This indicates that the SDM is valuable for estimating climate response to future changes in greenhouse gases concentration in the atmosphere.

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References

Albritton, D. L., and L. G. Meira Filho (2001), Technical summary of the working group I report, in *Climate Change 2001: The Scientific Basis*, edited by J. T. Houghton et al., pp. 21–83, Cambridge Univ. Press, New York.

Barnes, C. (2004), Air pollution, lecture notes, Environ. Sci., Univ. of Sydney, Sydney, Australia. (Available at http://www.usyd.edu.au/envsci/students/notes/air/airpol_notes.pdf)

Chou, M.-D., and M. J. Suarez (1994), An efficient thermal infrared radiation parameterization for use in general circulation models, in *Technical Report Series on Global Modeling and Data Assimilation, Tech. Memo. 104606*, vol. 3, 102 pp.

Chou, M.-D., and M. J. Suarez (1999), A solar radiation parameterization (CLIRAD-SW) for Atmospheric Studies, *NASA Tech. Memo., NASA/TM-1999-104606*, vol. 15, 42 pp.

Cubasch, U., and G. A. Meehl (2001), Projections of future climate change, in *Climate Change 2001: The Scientific Basis*, edited by J. T. Houghton et al., pp. 525–582, Cambridge Univ. Press, New York.

Donner, L., and V. Ramanathan (1980), Methane and nitrous oxide: Their effects on terrestrial climate, *J. Atmos. Sci.*, *37*, 119–124.

Frame, D. J., B. B. B. Booth, J. A. Kettleborough, D. A. Stainforth, J. M. Gregory, M. Collins, and M. R. Allen (2005), Constraining climate forecasts: The role of prior assumptions, *Geophys. Res. Lett.*, *32*, L09702, doi:10.1029/2004GL022241.

Hoogwijk, M. (2005), IPCC expert meeting on emission scenarios, meeting report, Intergovt. Panel on Clim. Change Tech. Support Unit Working Group III, Bilthoven, Netherlands. (Available at http://www.ipcc.ch/meet/washington.pdf)
Houghton, J. T., L. G. Meira Filho, B. A. Callender, N. Harris, A. Kattenberg, and K. Maskell (1996), *Climate Change 1995: The Science of Climate Change—Contribution of the Working Group I to the Second Assessment of the Intergovernamental Panel on Climate Change*, 572 pp., Cambridge Univ. Press, New York.
Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (Eds.) (2001), *Climate Change 2001: The Scientific Basis—Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, 881 pp., Cambridge Univ. Press, New York.
Kattemberg, A., F. Giorgi, H. Grassl, G. A. Meehl, J. F. B. Mitchell, R. J. Stouffer, T. Tokioka, A. J. Weaver, and T. M. L. Wigley (1996), Climate models—Projections of future climate, in *Climate Change 1996: The Science of Climate Change*, edited by J. T. Houghton et al., pp. 285–357, Cambridge Univ. Press, New York.
Lindzen, R. S. (1995), How cold would we get under CO_2-less sky, *Phys. Today*, *48*, 78–80.
Lindzen, R. S. (1998), Can increasing carbon dioxide cause climate change?, *Proc. Natl. Acad. Sci. U. S. A.*, *94*, 8335–8342.
McClatchey, R. A., R. W. Fenn, J. E. A. Selby, F. E. Voltz, and J. S. Garing (1972), Optical properties of the atmosphere, *Tech. Rep. AFCRL-72-0497*, 108 pp., Air Force Cambridge Res. Lab., Bedford, Mass.
Mitchell, J. F. B. (1989), The climatic effect and climate change, *Rev. Geophys.*, *27*, 115–139.
Moraes, E. C., S. H. Franchito, and V. B. Rao (2004), Effects of biomass burning in Amazonia on climate: A numerical experiment with a statistical-dynamical model, *J. Geophys. Res.*, *109*, D05109, doi:10.1029/2003JD003800.
Nakicenovic, N., et al. (2000), *Special Reports on Emissions Scenarios: A Special Report of Working Group III of the International Panel on Climate Change*, edited by N. Nakicenovic and R. Swart, 612 pp., Cambridge Univ. Press, New York.
Ramanathan, V. (1976), Radiative transfer within the Earth's troposphere and stratosphere: A simplified radiative convective model, *J. Atmos. Sci.*, *33*, 1330–1346.
Ramanathan, V., and R. E. Dickinson (1979), The role of stratospheric ozone in the zonal and seasonal radiative balance of the earth-troposphere system, *J. Atmos. Sci.*, *36*, 1084–1104.
Reilly, J., P. H. Stone, C. E. Forest, M. D. Webster, H. D. Jacoby, and R. G. Prinn (2001), Climate change: Uncertainty and climate change assessments, *Science*, *293*(5529), 430–433.
Schimel, D., D. Alves, I. Enting, and M. Heimann (1996), Radiative forcing of climate change, in *Climate Change 1995: The Science of Climate Change*, edited by J. T. Houghton et al., pp. 65–131, Cambridge Univ. Press, New York.
Schlesinger, M. E., and K. F. B. Mitchell (1987), Climate model simulations of the equilibrium climatic response to increased carbon dioxide, *Rev. Geophys.*, *25*, 760–798.
Varejão-Silva, M. A., S. H. Franchito, and V. B. Rao (1998), A coupled biosphere-atmosphere climate model suitable for use in climatic studies due to land surface alterations, *J. Clim.*, *11*, 1749–1767.
Wang, W.-C., Y. L. Yung, A. A. Lacis, T. Mo, and J. E. Hanssen (1976), Greenhouse effects due to man-made perturbations of trace gases, *Science*, *194*, 685–690.
Wang, W.-C., M. P. Dudek, and X.-Z. Liang (1992), Inadequacy of effective CO_2 as a proxy in assessing the regional climate change due to other radiatively active gases, *Geophys. Res. Lett.*, *19*, 1375–1378.
Wigley, T. M., and S. C. B. Raper (2001), Interpretation of high projections for global-mean warming, *Science*, *293*, 451–454.
Zhang, T. (1994), Sensitivity properties of a biosphere model based on BATS and a statistical-dynamical climate model, *J. Clim.*, *7*, 891–913.

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