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SENSITIVITY STUDIES ON THE CLIMATIC EFFECT OF AN INCREASE OF ATMOSPHERIC CO_2

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RESUMEN

Se llevan a cabo experimentos numéricos sobre la sensibilidad de un modelo termodinámico, con especial referencia al cálculo del efecto de una duplicación del CO_2 atmosférico. Se presentan estimaciones sobre el efecto de incluir en el modelo lo siguiente:

a) El cálculo de las anomalías de la temperatura superficial de los océanos mediante el uso de la conservación de energía térmica aplicada a la capa oceánica mezclada.

b) Parametrizaciones de la evaporación y la condensación de vapor de agua que no violan la conservación del vapor de agua.

c) La retroalimentación albedo-temperatura.

d) Una capa de nubes de extensión horizontal variable.

Se demuestra que cuando se incluyen en el modelo a), b) y c), la duplicación del CO_2 atmosférico produce un calentamiento promedio en el Hemisferio Norte de .9°C en la temperatura superficial oceánica, de 1.1°C en la temperatura superficial de los continentes, y un calentamiento promedio de la temperatura en la superficie de 1.0°C. Este calentamiento aumenta en 0.1°C ó 0.2°C cuando d) también se incluye; y disminuye en 0.2°C cuando el efecto de la retroalimentación albedo-temperatura se suprime, y en 0.7°C cuando a) se suprime y temperaturas oceánicas normales se usan en los cálculos. Además, cuando b) no se satisface, y el calor perdido por evaporación en la superficie y el calor ganado por condensación de vapor de agua en las nubes se parametrizan como en experimentos anteriores, entonces el calentamiento calculado en la superficie decrece 0.4°C.

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ABSTRACT

Numerical experiments on the sensitivity of a thermodynamic model, with special reference to the climatic effect of a doubling of the atmospheric CO_2, are carried out. Estimates are presented on the separate effect of including in the model the following:

a) The computation of the surface ocean temperature anomalies by the use of the conservation of thermal energy applied to the ocean mixed layer.

b) Simple parameterizations of evaporation and condensation of water vapor that do not violate the conservation of water vapor.

c) The albedo-temperature feedback.

d) A cloud layer of variable horizontal extent.

It is shown that when a), b) and c) are included in the model, the doubling of the atmospheric CO_2 produces an average warming in the Northern Hemisphere, of .9°C in the surface ocean temperature, of 1.1°C in the continental ground temperature; and an average surface temperature warming of 1.0°C. This warming increases by 0.1°C or 0.2°C when d) is also included; and decreases by 0.2°C when the albedo-temperature feedback effect is suppressed, and by 0.7°C when a) is suppressed and normal surface ocean temperatures are used in the computations. Furthermore when b) is not satisfied and the parameterizations of the heat lost by evaporation at the surface and the heat gained by condensation of water vapor in the clouds are parameterized as in previous experiments, the computed surface warming decreases by 0.4°C.

1. INTRODUCTION

In previous numerical experiments on the climatic effect of an increase of the atmospheric CO_2 (Adem and Garduño, 1982), we have used a thermodynamic climate model with parameterizations for the heat lost by evaporation at the surface and the heat gained by condensation of water vapor at the cloud described in a recent paper (Adem, 1982). Such parameterizations were originally developed for monthly prediction, and as pointed out by Adem (1965) they violate the conservation of water vapor in the atmosphere. To adapt the model for long term integrations it seems essential to satisfy this conservation law.

The purpose of this paper is to introduce in the model simple parameterizations for the heating functions which do not violate the conservation of water vapor in the atmosphere, in order to evaluate its importance. Furthermore sensitivity studies on the climatic effect of an increase of the atmospheric CO_2, are carried out, with the new version of the model, to evaluate the importance of cloudiness, and heating different from radiation, as well as the effect of the inclusion of an ocean mixed layer and the albedo-temperature feedback.

INCORPORATION OF THE CONSERVATION OF WATER VAPOR IN THE MODEL

The heat lost by evaporation at the surface (G_3) and the heat gained by condensation of water vapor at the clouds (G_5) are expressed by formulas of the type

$$G_3 = G_{3N} + G_3DN \tag{1}$$

$$G_5 = G_{5N} + G_5DN \tag{2}$$

where G_{3N} and G_{5N} are prescribed seasonal climatological normal values; and G_3DN and G_5DN the corresponding anomalies to be computed internally in the model.

The conservation of water vapor in an atmospheric column of unit area requires that

$$G_3 - G_5 = LE \tag{3}$$

where L is the heat of vaporization and E includes the horizontal transport and the storage of water vapor terms. In a previous paper (Adem, 1968) a complete study using (3) has been carried out on the parameterization of $G_3 - G_5$ for use in a thermodynamic model. In this paper we will use a simpler approach.

Substituting (1) and (2) in (3)

$$(G_{3N} - G_{5N}) + (G_3DN - G_5DN) = L(E_N + EDN) \tag{4}$$

where we have written E as the sum of a normal value E_N and an anomaly EDN.

Equation (3) is assumed to be valid for the normal values, therefore

$$G_{3N} - G_{5N} = LE_N \tag{5}$$

Substracting (5) from (4)

$$G_3DN - G_5DN = LEDN$$

we shall assume that

$$G_3DN = G_5DN$$

This assumption implies that the anomaly of the transport and storage of water vapor is taken as zero. However, since G_{3N} and G_{5N} are prescribed so that (5) is satisfied, the normal value of the transport and storage (E_N) is retained. Therefore we are satisfying the equation of conservation of water vapor under the assumption that $E_N \gg EDN$.

2. THE EFFECT OF CLOUDINESS AND HEATING DIFFERENT FROM RADIATION

In previous computations we have used the following parameterizations:

$$
\begin{aligned}
G_2 &= G_{2N} + G_2DN \\
G_3 &= G_{3N} + G_3DN \\
G_5 &= G_{5N} + G_5DN \\
\epsilon &= \epsilon_N + \epsilon DN
\end{aligned}
\tag{6}
$$

where G_2, G_3, G_5 and ϵ are the sensible heat given off from the surface to the atmosphere, the heat lost by evaporation, the heat gained by condensation of water vapor in the clouds and the horizontal extent of cloudiness respectively; G_{2N}, G_{3N}, G_{5N} and ϵ_N are the corresponding normal values; and G_2DN, G_3DN, G_5DN and ϵDN the corresponding departures from those values. The detailed expressions of G_2DN, G_3DN, G_5DN and ϵDN are given in several previous papers (Adem, 1965, 1982). They were originally derived by Clapp *et al* (1965).

In the numerical experiments presented in this section we have used the most recent version of the thermodynamic model described by Adem (1982), with the modifications in the parameterizations of the heating functions and cloudiness pertinent to each of the experiments. This version of the model has already been applied to compute the climatic effect of an increase of the atmospheric CO_2 by Adem and Garduño (1982).

In this section we shall carry out 5 numerical experiments to determine the sensitivity of the model to the parameterizations used for G_2, G_3, G_5 and ϵ. A summary of the parameterizations used in each experiment is given in table 1 and a description of the experiments and results is given below.

Experiment 1

We use the parameterizations of G_2, G_3, G_5 and ϵ described by Adem (1982) and utilized in previous computations. The results of this experiment has been presented in detail in a previous paper (Adem and Garduño, 1982). In this case the annual average increase of the surface temperature due to a doubling of the atmospheric CO_2 is of 0.7°C.

Experiment 2

In this second experiment we use the same parameterizations as in the previous one, but prescribe a zero anomaly of cloudiness ($\epsilon DN = 0$), so that the interacting effect of this anomaly is suppressed. In this case the computed average annual surface temperature is 0.6°C instead of the 0.7°C of experiment 1, in which an anomaly of the horizontal extend of cloudiness is generated internally in the model. In this experiment, as well as in experiment 1, the atmospheric water vapor is not conserved.

Table 1

Experiments on the effect of cloudiness and heating different from radiation on the warming due to a doubling of the atmospheric CO_2

Experiment	G_2	G_3	G_5	ϵ	Average value of T_sDN(°C)	
1	$G_{2N} + G_2DN$	$G_{3N} + G_3DN$	$G_{5N} + G_5DN$	$\epsilon_N + \epsilon DN$	0.7	Water vapor is not conserved
2	$G_{2N} + G_2DN$	$G_{3N} + G_3DN$	$G_{5N} + G_5DN$	ϵ_N	0.6	
3	$G_{2N} + G_2DN$	$G_{3N} + 2G_2DN$	$G_{5N} + 2G_2DN$	ϵ_N	1.0	Water vapor is conserved
4	$G_{2N} + G_2DN$	G_{3N}	G_{5N}	ϵ_N	1.1	
5	G_{2N}	G_{3N}	G_{5N}	ϵ_N	1.4	

Experiment 3

We use the Bowen Ratio approach to parameterize the anomaly of the heat lost by evaporation G_3DN, which is taken as equal to twice the anomaly of sensible heat given off from the surface to the atmosphere ($G_3DN = 2G_2DN$).

In this experiment the anomaly of heat of condensation is taken as equal to the anomaly of evaporation ($G_5DN = G_3DN$), so that according to the study carried out in the previous section the atmospheric water vapor is conserved. Furthermore, as in experiment 2 the anomaly of cloudiness is taken as zero.

The results of this experiment are given in detail in section 3. For the purpose of this study we give only the annual average warming of the surface temperature in the Northern Hemisphere, which is equal to 1.0°C.

Experiment 4

We take the anomalies of G_3, G_5 and ϵ equal to zero, so that, besides radiation, the only heating anomaly included is that of sensible heat given off from the surface to the atmosphere. Therefore this model does not include the hydrological cycle. In this case the annual average of the warming of surface temperature is equal to 1.1°C.

Experiment 5

In this experiment we take zero anomalies of G_2, G_3, G_5 and ϵ. Therefore, we include only the interactions due to heating by radiation. In this case the computed annual average of the increase of surface temperature is equal to 1.4°C.

Discussion of results and conclusions

Table 1 shows the summary of the heating functions used in each experiment as well as the corresponding computed average increase in surface temperature.

Fig. 1 shows the annual cycle of the surface temperature increase. The abscissa is the time in months and the ordinate the increase in °C. Each curve is labelled with the corresponding number of the experiment to the left and with the annual average to the right.

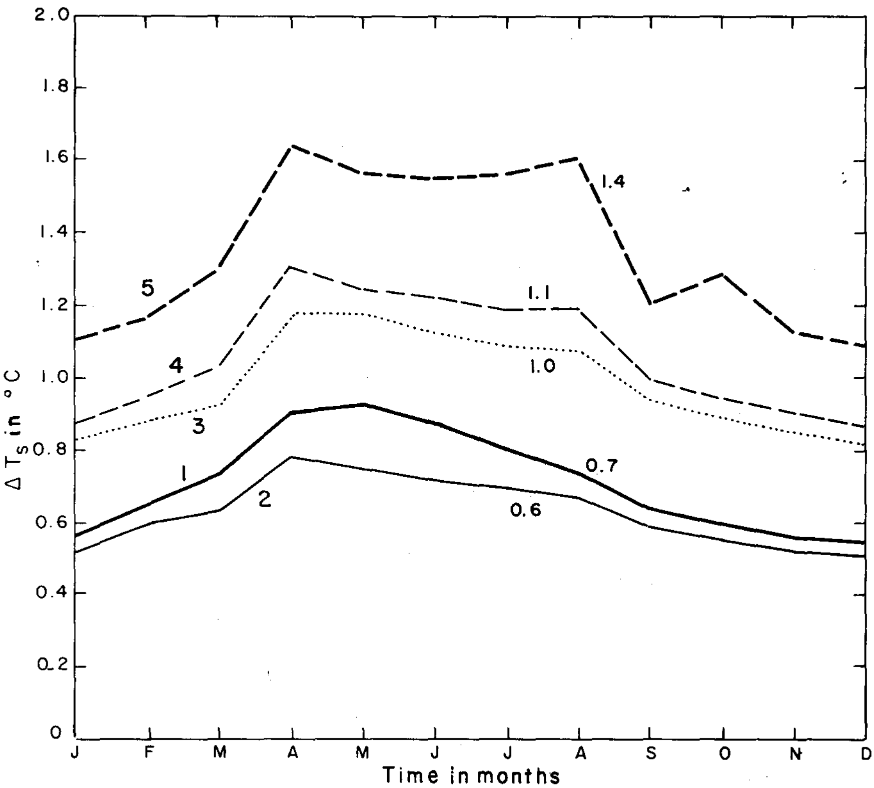

Fig. 1. Northern Hemisphere surface temperature increase due to a doubling of the atmospheric CO_2. The abscissa is the time in months and the ordinate the increase in °C. Each curve is labelled with the corresponding number of the experiment to the left and with the annual average to the right. The characteristics of each experiment are described in the text and summarized in Table 1.

Comparison of the results of experiment 1 and 2 shows that the interaction due to the anomalies of cloudiness increase the computed annual surface temperature anomaly by 0.1°C. Furthermore, comparison of curves 1 and 2 of Fig. 1, shows that the maximum increase due to cloud anomalies occurs in spring and summer where the difference of these two curves show values as large as 0.2°C.

Comparison of the results of experiment 3 with 2 shows that the inclusion of the conservation of water vapor in the atmosphere increases the anomaly by 0.4°C, from 0.6 to 1.0°C.

In the model used in experiment 3, in which the water vapor is conserved we have used a Bowen Ratio approach to parameterize G_3 which is a crude parameterization. To determine how critically the results depend on the interactions of the anomalies of G_2, G_3 and G_5 we have carried out experiments 4 and 5. Furthermore we repeat experiment 3 with different values of Bowen Ratio. The results for all these experiments are shown in Fig. 2, where the ordinate is the mean annual increase of surface temperature and where the abscissa is the anomaly of $G_2 + G_3$ used in the experiment, which due to the use of a Bowen Ratio is expressed as b G_2DN, where b is a parameter. The values of b are shown in the abscissa.

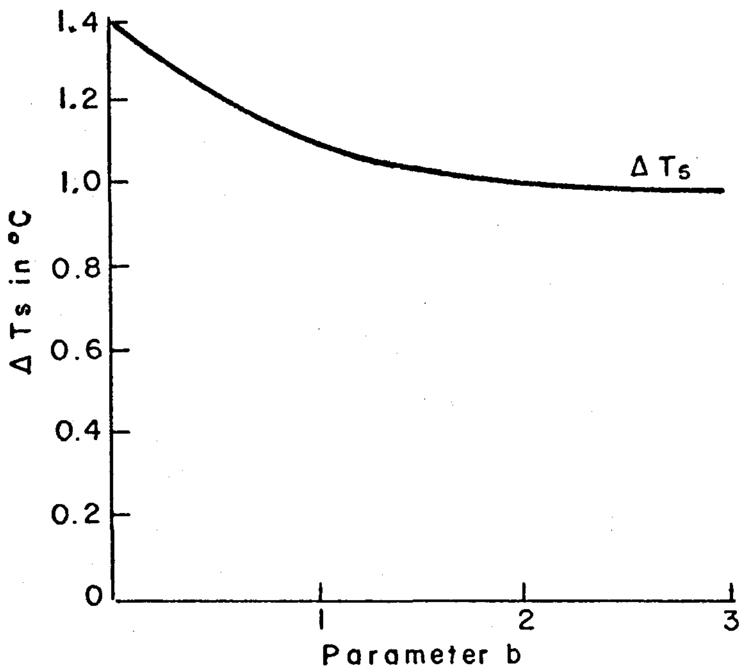

Fig. 2. The annual increase of surface temperature in the Northern Hemisphere due to a doubling of the atmospheric CO_2. Due to the use of a Bowen ratio the anomaly of $G_2 + G_3$ used in some of the experiments is expressed as b G_2DN, where b is shown in the abscissa.

The value zero in the abscissa corresponds to experiment 5, the value 1 to experiment 4 and the value 3 to experiment 3. The value 2 corresponds to an experiment as 3 but with $G_3 DN = G_2 DN$.

Fig. 2 shows that the maximum value (1.4°C) is obtained in the model when the anomalies of the heating different from radiation is zero, and that, as the anomaly of $G_2 + G_3$ increases the solution decreases asymptotically towards the value of experiment 3, which is equal to 1.0°C. Therefore the solution in experiment 3 does not depend critically on the detailed value of the Bowen Ratio.

3. EFFECT OF THE OCEAN MIXED LAYER AND THE COMPUTED OCEAN TEMPERATURE ANOMALIES

The model used in these numerical experiments includes a fully mixed upper layer of the ocean to which the conservation of thermal energy is applied in the form

$$H_s \rho_s C_s \frac{\partial T_s}{\partial t} = E_s - G_2 - G_3$$

where H_s is the depth of the layer, ρ_s is the density, C_s the specific heat, T_s the surface temperature and E_s the heating by short and long wave radiation, G_2 and G_3 are the sensible heat given off to the atmosphere and the heat lost by evaporation at the surface. This equation of conservation of thermal energy, together with the other equations of the model, allows the computation of the surface ocean temperature and the surface continental ground temperature, besides the mean tropospheric temperature and other variables, as described by Adem (1982).

In this section we will investigate the effect of the depth of ocean layer (H_s) in the solution. In these experiments we will use the version of the model which conserves the water vapor in the atmosphere and which uses a Bowen Ratio for the parameterization of G_3 as was used in experiment 3 of section 2.

Figures 3 and 4 show respectively the computed surface temperature anomalies and mean tropospheric anomalies for January (A) and July (B). In this case we have used a depth of the ocean layer of 100 m (H_s = 100 m). Comparison of A and B shows that the gradient from the equator to the pole is stronger in summer than in winter and that the largest anomalies are in the polar regions in the summer.

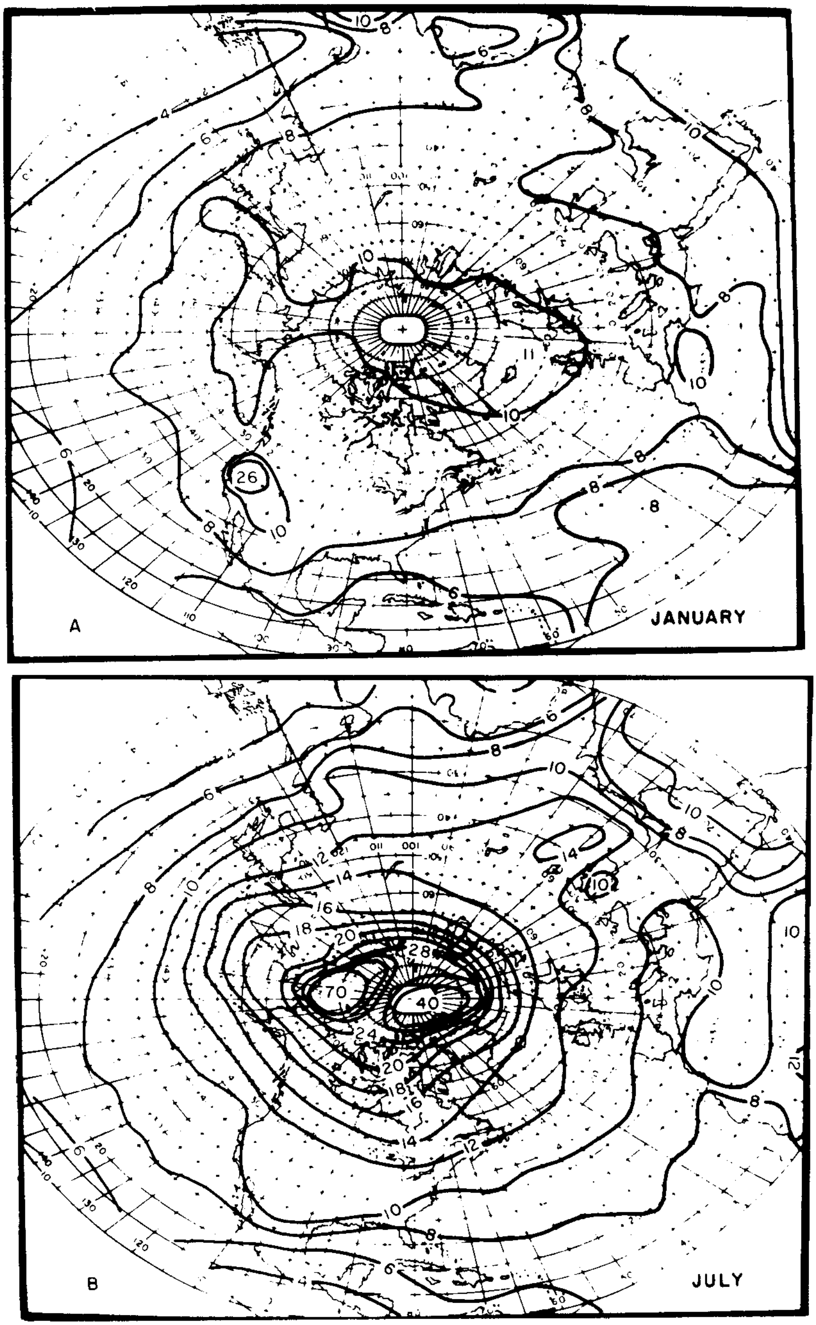

Fig. 3. Computed surface warming due to a doubling of the atmospheric CO_2: for January (A) and July (B), in tenths of ^{o}C.

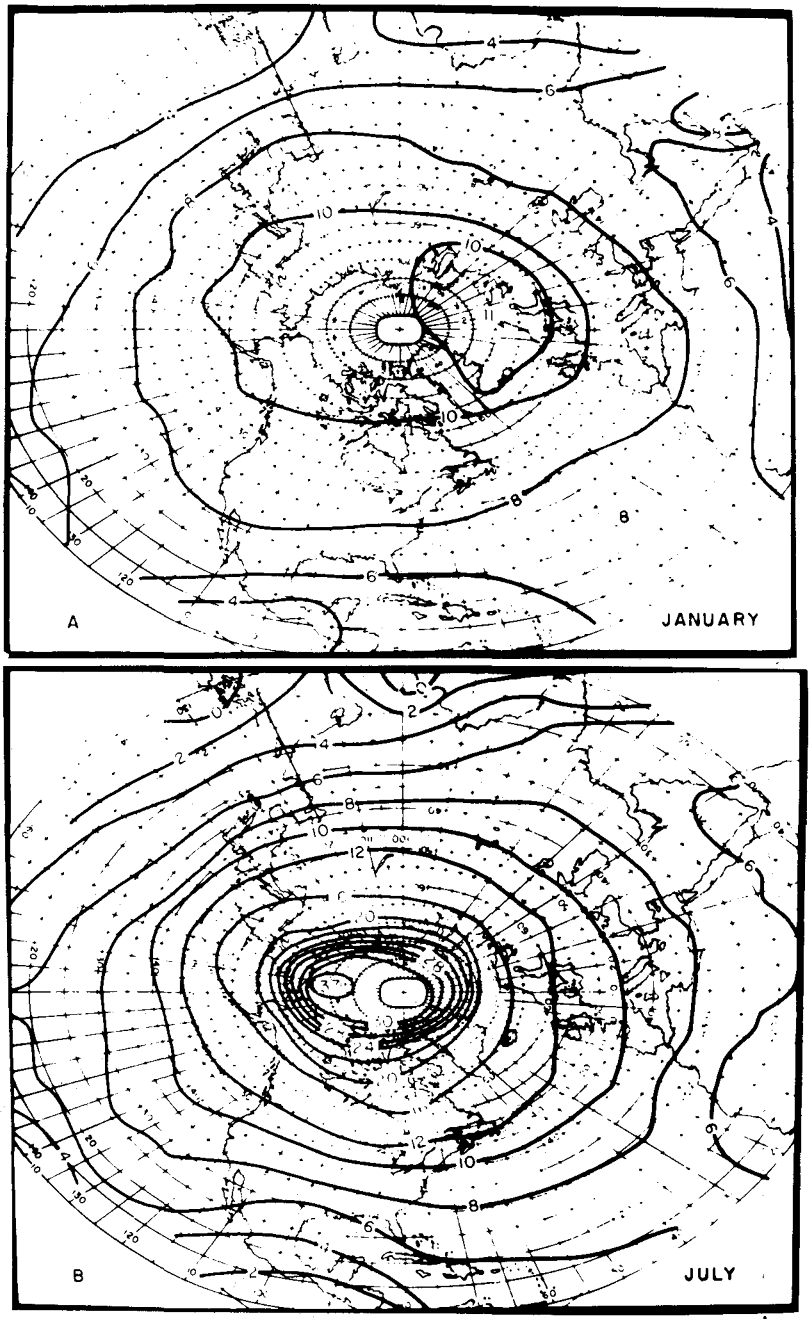

Fig. 4. Computed mean tropospheric temperature warming due to a doubling of the atmospheric CO_2: for January (A) and July (B), in tenths of ^{o}C.

Fig. 5 shows the zonally averaged seasonal values for the surface temperature anomaly. For all the seasons there is a general increase from lower to higher latitudes. The largest values occur in the pole. This solution is similar to the case of experiment 1 of section 2 which was discussed in detail in a previous paper (Adem and Garduño, 1982), except that in the present computation, which corresponds to experiment 3, larger values are obtained with an annual mean surface temperature anomaly of 1.0°C instead of 0.7°C.

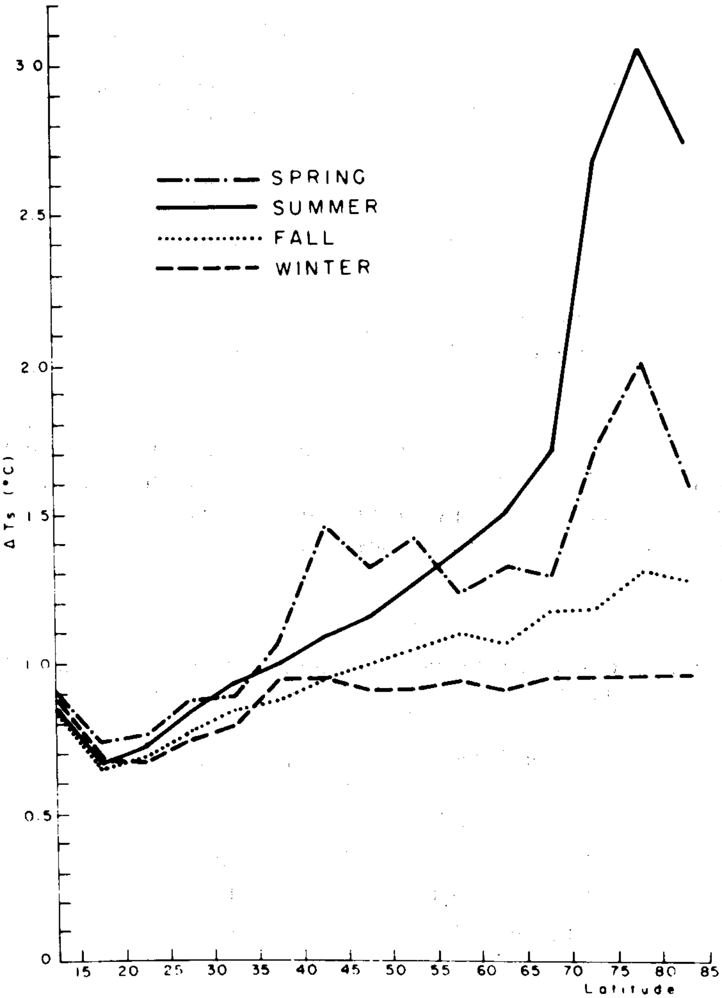

Fig. 5. Zonally averaged values of the surface temperature warming due to a doubling of the atmospheric CO_2 for the four seasons of the year, in °C.

To determine the importance of the ocean mixed layer, we have estimated the average temperature increase in the oceanic and continental regions separately. Table 2 shows the mean surface temperature increase for each season of the year. The first column shows the mean values for the surface ocean temperature, the second column, the mean ground temperature in the continents and the third column, the mean values for the total region of integration, including oceans and continents. This table shows that the largest increases occur in the continents with a maximum value in spring of 1.2°C. The values in the ocean have a maximum in summer equal to 1.0°C.

Table 2

Average surface temperature warming (°C) due to a doubling of the atmospheric CO_2, in the Northern Hemisphere

Season	Ocean	Continent	Total
Winter	0.8	1.0	0.9
Spring	0.9	1.2	1.0
Summer	1.0	1.1	1.0
Autumn	0.8	1.0	0.9

Table 3 is similar to table 2 but refers to the mean tropospheric temperature increases. In this case the values are also larger over the continents than over the oceans with the maximum values also in spring over continents and in the summer over oceanic regions. The average values are about 0.2°C smaller than the surface temperature.

Table 3

Average mean tropospheric temperature warming (°C) due to a doubling of the atmospheric CO_2, in the Northern Hemisphere

Season	Ocean	Continent	Total
Winter	0.7	0.8	0.7
Spring	0.7	1.0	0.8
Summer	0.8	0.9	0.8
Autumn	0.6	0.8	0.7

In this experiment we have used a depth of the ocean mixed layer of 100 m. In order to determine the effect of the depth of this layer we have carried out 2 more experiments, using the same model. In one case we use a depth of 25 m and in the other we use an infinite depth, which in the model is equivalent to using zero ocean temperature anomalies and prescribing the normal observed ocean temperatures.

The results of the computations are shown as monthly averages. Figures 6 and 7 show the hemispheric averages for the mean tropospheric temperature and the surface temperature increases respectively. The dashed, solid and dotted lines correspond respectively to the depths 25 m, 100 m, and ∞. Comparison of these curves shows that the solution with prescribed normal SST (zero anomalies) yields much lower temperatures than the solution when the ocean temperature anomalies are computed by the use of a mixed ocean layer.

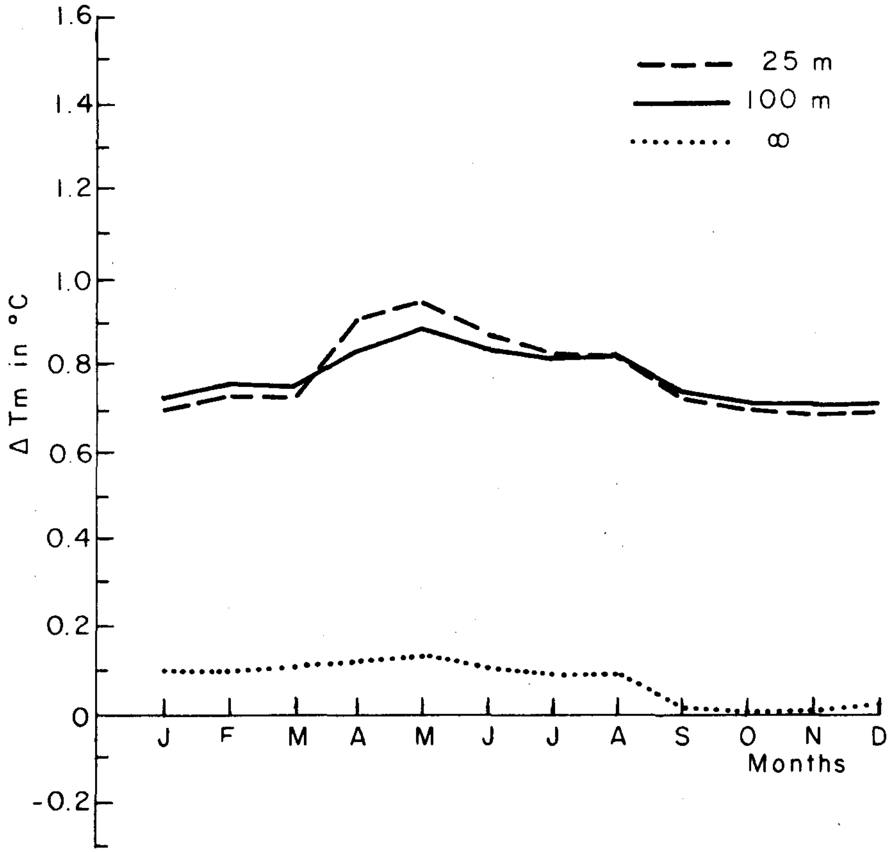

Fig. 6. Hemispheric average of the computed mean tropospheric temperature warming due to a doubling of the atmospheric CO_2, computed with a model that has an ocean mixed layer of 100 m (continuous line) and 25 m (dashed line); and with a model in which present ocean temperatures are prescribed (dotted line). The abscissa is the time in months, and the ordinate the temperature warming in Celsius degrees.

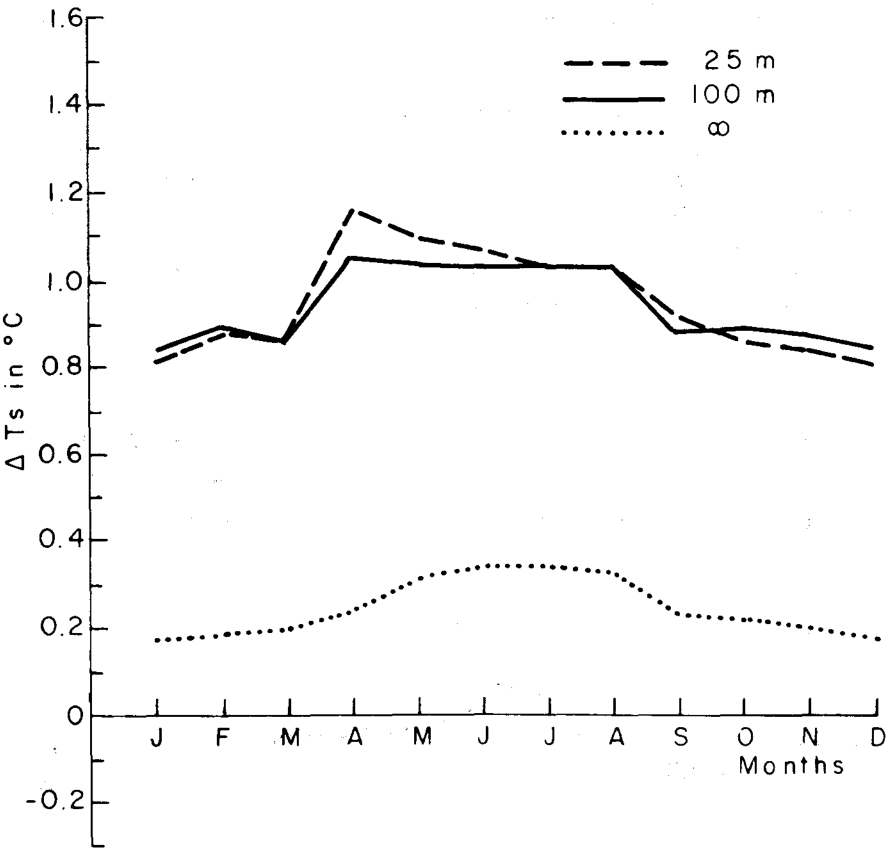

Fig. 7. Hemispheric average of the computed surface temperature warming due to a doubling of the atmospheric CO_2, computed with a model that has an ocean mixed layer of 100 m (continuous line) and 25 m (dashed line); and with a model in which present ocean temperatures are prescribed and kept fixed (dotted line). The abscissa is the time in months, and the ordinate the temperature warming in Celsius degrees.

Table 4 shows a comparison of the annual temperature increase for a model in which a mixed later of 100 m depth is used to compute the sea surface temperature anomalies and one in which normal sea surface temperatures (zero anomalies) are prescribed. The first column (ΔT_{so}) is the average ocean temperature increase, the second (ΔT_{sc}), the average surface (ground) temperature increase in continents and the third column (ΔT_s) the average surface temperature increase over the whole region of integration. In the forth, fifth and sixth columns are the mean tropospheric temperature increases over oceans (ΔT_{mo}), continents (ΔT_{mc}) and the total region of integration (ΔT_m). The first line of the table shows the values for a model that uses a mixed layer to compute the ocean temperature; and the second line shows the values when the ocean temperature anomalies are prescribed and equal to zero.

Table 4

Annual temperature increases, in the Northern Hemisphere, due to a doubling of the atmospheric CO_2. First line: computed with a model in which an ocean mixed layer is used to compute the ocean temperature. Second line: when prescribed normal surface ocean temperatures are used

Model	Annual temperature increase (°C)					
	ΔT_{so}	ΔT_{sc}	ΔT_s	ΔT_{mo}	ΔT_{mc}	ΔT_m
With mixed layer	0.9	1.1	1.0	0.7	0.9	0.8
With prescribed normal SST	0	0.5	0.3	0.1	0.3	0.1

A comparison of the values of this table shows that the use of a mixed layer has generated an anomaly of 0.9°C in the oceans. This anomaly (ΔT_{so}) has had such interactions in the solution that the corresponding computed temperature anomalies shown in the table, have increased in a substantial way, compared with the case in which the ocean temperature anomalies are kept fixed and equal to zero: the continental ground temperature (ΔT_{sc}) from 0.5 to 1.1°C; the tropospheric temperature over oceans (ΔT_{mo}) from 0.1 to 0.7°C, and over continents (ΔT_{mc}) from 0.3 to 0.9°C; the annual averages for the total region of integration increase from 0.1 to 0.8°C for the mean tropospheric temperature (ΔT_m) and from 0.3 to 1.0°C for the surface temperature (ΔT_s). The influence of the ocean anomaly is felt not only over the oceans but also in a very strong way over and in the continents, showing the efficiency of the model in transporting thermal energy vertically as well as horizontally.

The case of an ocean mixed layer of 25 m has little variations with respect to the case of 100 m. There are only seasonal changes smaller than 0.1°C. The anomalies for the case 25 m are slightly larger in summer and spring and smaller in winter and autumn than the case of 100 m. The annual averages are the same for both cases. However in other cases, especially when the forcing function changes sign throughout the year, the seasonal effect due to the depth of the mixed layer in the solution can be important (Adem, 1984).

4. EFFECT OF THE ALBEDO-TEMPERATURE FEEDBACK

In the model used in these experiments the snow-ice boundary is carried out as a variable by assuming that it coincides with the 0°C computed surface isotherm. This is accomplished by an adjusting process between surface albedo and surface temperature by which at each grid point an albedo for snow-ice cover is assigned when the computed surface temperature is lower (or equal) than 0°C, and an albedo for no snow-ice in the ground is assigned, when the surface temperature is larger than 0°C, as is described by Adem (1982). This adjusting process converges rapidly due to the snow-ice temperature feedback.

In order to determine the sensitivity of the solution to the snow-ice temperature feedback we carry out an experiment in which we prevent the melting of snow-ice cover. This can be done by using a value lower than 0°C for the isotherm to which the snow-ice boundary is coupled. For this purpose a numerical experiment was carried out using −2°C as isotherm instead of 0°C. The results are shown in Fig. 8, where the ordinate is the average increase of surface temperature and the abscissa is the time of the year in months. The dashed line is the solution when we use an isotherm of −2°C and the solid line the solution of the present model, in which we use an isotherm of 0°C. Comparison of the two curves shows a considerable difference due to the increased melting of snow and ice. The largest differences are in spring and summer which are the times of the year when the melting mainly occurs.

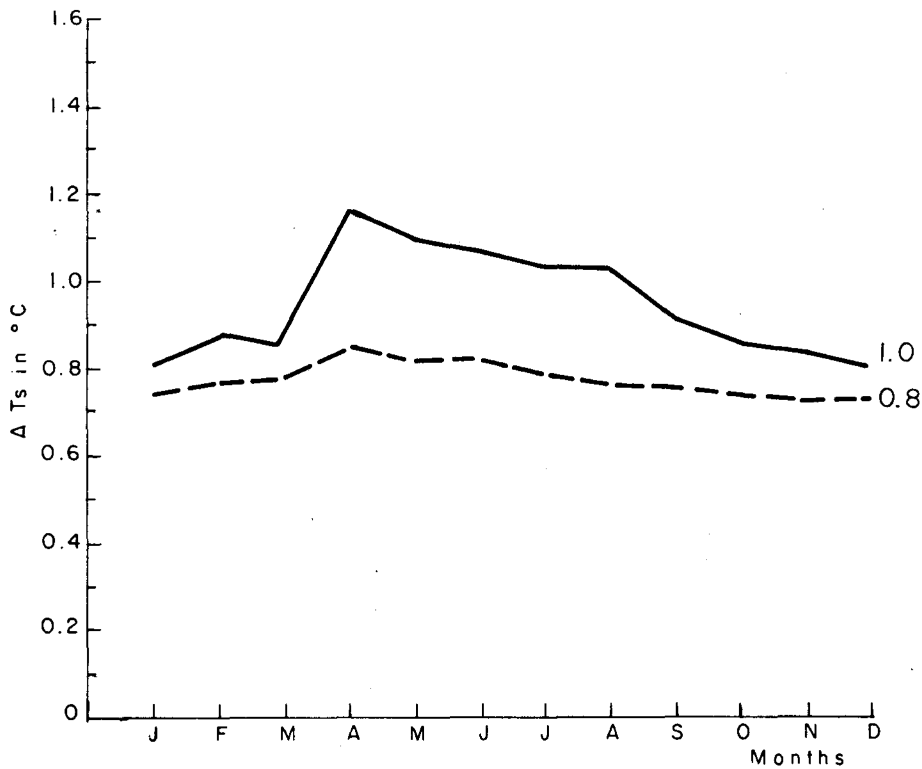

Fig. 8. Northern Hemisphere surface temperature increase due to a doubling of the atmospheric CO_2, with the effect of the albedo-temperature feedback (continuous line) and without such effect included (dashed line). The abscissa is the time in months, and the ordinate the surface temperature increase in Celsius degrees.

In the $-2^{o}C$ isotherm case practically no melting occurred. Therefore, the difference between the two solutions can be considered the main contribution of the albedo-temperature feedback. The annual average of this difference is $0.2^{o}C$, which is 20% of the total surface temperature increase.

Fig. 9 shows the zonally averaged values of surface temperature for the two cases: the dashed line corresponds to the $-2^{o}C$ isotherm case and the solid line to the $0^{o}C$ isotherm case. A comparison of these two curves shows that the effect of the

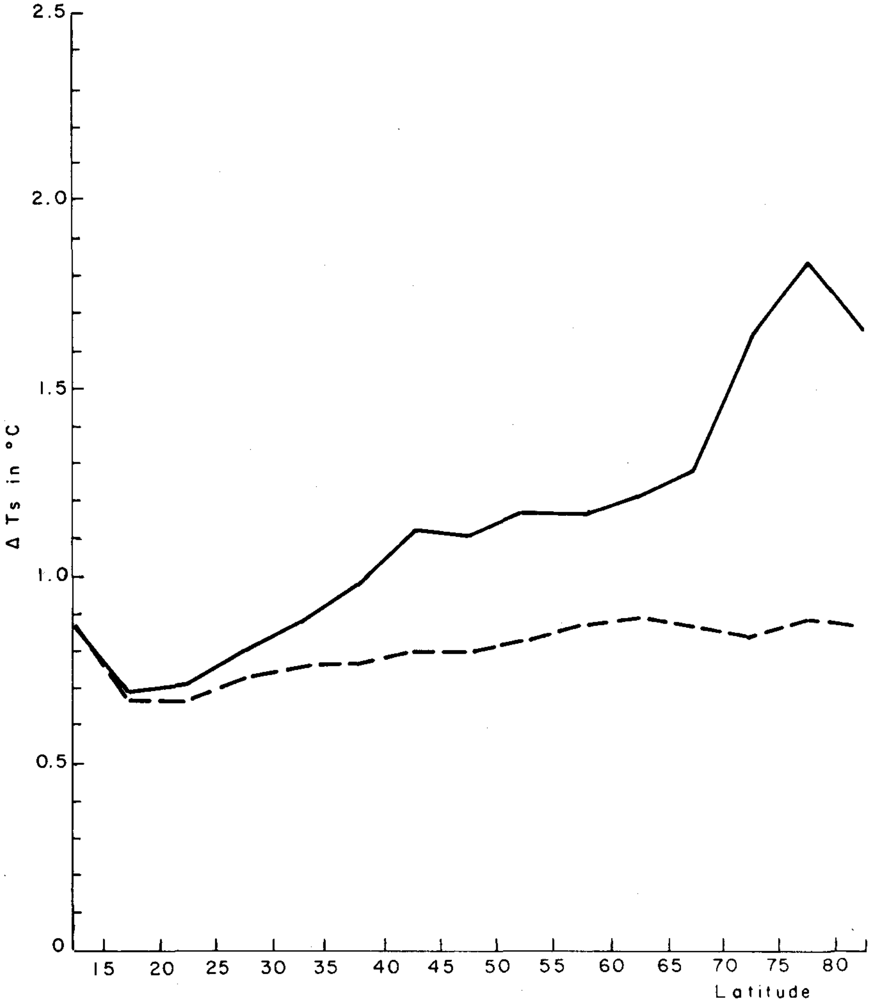

Fig. 9. Zonally averaged annual values of the surface temperature increase due to a doubling of the atmospheric CO_2, with the effect of the albedo-temperature feedback (continuous line) and without such effect included (dashed line).

albedo-temperature feedback increases from lower to higher latitudes with the maximum in the pole and with two secondary maxima in middle latitudes. The large effect in the pole is due to melting of snow and ice in summer and spring and the maxima in middle latitude to melting in spring.

5. CONCLUSIONS AND SUGGESTIONS FOR POSSIBLE IMPROVEMENT IN THE RESULTS

From a comparison of the results of experiments 2 and 3 we conclude that the incorporation of conservation of water vapor in the thermodynamic model increases substantially the computed anomaly of surface temperature due to a doubling of the atmospheric CO_2. Experiment 3 shows that in this case we obtain an average value of 1.0^oC in the Northern Hemisphere. In this experiment the effect of the cloud anomaly has been neglected. It is suggested by the comparison of experiments 1 and 2, that the inclusion of that anomaly would increase the computed surface temperature anomaly to 1.1 or 1.2^oC. However, this value is still smaller than those computed with general circulation models, which yield a value of about 2^oC (Manabe and Stouffer, 1980) and even larger values (Augustsson and Ramanathan, 1977; Watts, 1978, among others). Reference to the results of a variety of authors and models has been given in a previous paper and will not be repeated here (Adem and Garduño, 1982).

Improvement in our results could be obtained by improving the parameterization of the heating functions, especially radiation, as well as the parameterization of cloudiness. The ocean mixed layer and the albedo temperature feedback play an important role in the climatic effect of an increase of CO_2, and therefore an improvement in the way how they are incorporated in the model should also improve the results.

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