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An examination of some feedback mechanisms in the carbon dioxide climate problem

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ABSTRACT

A radiative convective equilibrium model has been used both alone and in conjunction with a mixed-layer oceanic model to explore the consequences of some possible secondary climatic responses resulting from a precursor CO_2-induced warming. Calculations were performed for both standard (300 p.p.m.) and doubled CO_2 amounts. This permitted several feedback mechanisms to be examined and quantified. For example, a 10% increase in existing low cloud amount (0.302 to 0.332) was found to completely compensate for the surface and tropospheric warming caused by doubling the CO_2 amount. A similar compensation was obtained by increasing low cloud albedo from 0.69 to 0.74. A combination of these two perturbations required such small individual increases that it raised the question whether general circulation models with self-predicting cloud properties would be able to attain sufficient accuracy to realistically evaluate such subtleties in an assessment of the CO_2 climate problem. An interesting aspect of the temperature compensation associated with the cloud amount and albedo increases was that this compensation did not extend to the stratosphere, which experienced a general cooling. The potential climatic consequences of this cooling are discussed. The impact of surface wind changes over the ocean attributable to a CO_2 warming was also considered and shown to affect both the sea surface temperature and mixed-layer depth noticeably. A number of potential feedback mechanisms associated with such wind changes were identified, and served to stress the need to take more recognition of the ocean's role in assessing the CO_2 problem. The possibility of an increase in the number of hurricanes and other severe tropical storms resulting from a general warming of the low latitude oceans from a CO_2 increase was noted.

1. Introduction

Continued concern is being expressed by the scientific community, Williams (1978), National Academy of Sciences (1977), regarding the potential impact on climate of the rising carbon dioxide content of the atmosphere. This anthropogenically created increase is attributed to the burning of fossil fuels and the clearing of forests. Various studies with one-dimensional models, for example Manabe and Wetherald (1967), Augustsson and Ramanathan (1977), Hunt and Wells (1979), indicate that a doubling of the atmospheric carbon dioxide content from a nominal value of 300 p.p.m. to 600 p.p.m. would result in a global mean warming of 2–3 K. See Schneider (1975) for a summary of the various calculations. A more elaborate three-dimensional model investigation by Manabe and Wetherald (1975) suggested that such a warming would produce a near surface temperature increase at high latitudes of possibly 10 K. While appreciating the limitations of current models for adequate assessment of the true impact of this carbon dioxide problem, there appears to be a growing consensus that possibly wide-ranging climatic changes (not necessarily all deleterious, Kellogg, 1978) could occur.

Given this view it is obvious that all aspects of the CO_2 problem need to be closely assessed. In this regard the identification of potential feedback mechanisms (positive or negative) is clearly crucial. The purpose of the current paper is to attempt to quantify by means of the one-dimensional radiative convective model used by Hunt and Wells (1979) the consequences of some possible *secondary* climatic responses induced by a precursor CO_2

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increase. While the magnitudes of the responses considered here have been kept as realistic as possible such responses have not been observed in the atmosphere to date, hence to a certain extent it is the model sensitivity which is in fact being assessed. In any case, for climatic assessment purposes it is desirable to ascertain the accuracy to which model features, such as cloud amount, need to be specified or computed if a variation in such a feature provides a negative feedback to the CO_2-induced warming. Thus this work extends previous studies by Manabe and Wetherald (1967) and Reck (1978) into the sensitivity of radiative convective models to parameter variations. Their work was primarily concerned with such variations for standard (300 p.p.m.) CO_2 amounts; here the possibility of non-linear responses associated with doubled CO_2 amounts is examined. Other non-linearities resulting from the alteration of two model parameters simultaneously are also considered.

2. Model description

The model in its simplest form was a variant of the fixed relative humidity, one-dimensional radiative convective equilibrium model of Manabe and Wetherald (1967). It differed from their model in having a different vertical structure; tropospheric lapse rates set by the moist adiabatic lapse rate rather than using a specified value of 6.5 km^{-1}; and surface heat fluxes determined by bulk aerodynamic formulae, with a constant anemometer velocity of 7.5 m s^{-1} and a fixed drag coefficient of 0.0015. The model was also run in a more realistic mode with the underlying land surface replaced by a one-dimensional 30 level mixed-layer ocean model. Further details of the model formulation are given in Hunt and Wells (1979), and Table 1.

Table 1. *Principal model parameters*

Cloud values	Low	Middle	High
Height (km)	2.7–1.7	4.1	10.0
Amount	0.302	0.079	0.181
Albedo	0.69	0.48	0.21
Absorptivity	0.035	0.02	0.005

Fixed relative humidity. Temperature distribution constrained to moist adiabatic lapse rate. 18 atmospheric levels, 0–37.5 km. 30 oceanic levels, 0–300 m. Anemometer velocity, 7.5 m s^{-1}. Drag coefficient, 0.0015.

All results are for annually averaged conditions at 35° latitude, and are considered to be fairly representative of the global mean for reasons discussed previously by Hunt and Wells (1979). Only two CO_2 mixing ratios are employed, a "Standard" value of 300 p.p.m. and a doubled value of 600 p.p.m.

3. Results

3.1. *Use of fixed relative humidity profile*

Table 2 compares, for the land only version of the model, the surface temperature increases calculated with the current model with those of Manabe and Wetherald (1967) resulting from a doubling of the atmospheric CO_2 content. Values are given for both fixed relative and absolute humidity profiles. The non-trivial differences between the two sets of temperature increases arise primarily in the specifications of the lapse rates used in the convection code. Results similar to those computed here have been obtained by Rowntree and Walker (1978) using a penetrative convection scheme. Although clearly shown by Manabe and Wetherald it is not sufficiently

Table 2. *Surface temperatures computed with radiative convective models*

	1 × CO_2, fixed rel. humidity	2 × CO_2, fixed rel. humidity	Temperature difference	1 × CO_2, fixed abs. humidity	2 × CO_2, fixed abs. humidity	Temperature difference
Current model	293.41	295.23	1.82	295.17	295.86	0.69
Manabe and Wetherald (1967)	288.39	290.75	2.36	291.05	292.38	1.33

The differences in the absolute temperatures between the two models are not significant as the absolute temperature varies with adjustable model parameters such as the anemometer velocity, see below.

appreciated that the *total* CO_2-induced warming has a very large contribution from the increased water vapour content of the atmosphere associated with the *primary* CO_2 warming. For the current model the majority of the surface temperature increase (1.82–0.69 = 1.13 K), can be attributed to increased absorption by solar radiation (0.29 K) and long-wave radiation (0.84 K) by atmospheric water vapour. It is the omission of this water vapour feedback which is responsible for the small surface temperature increase recently obtained by Idso (1980) for a doubling of the CO_2 amount.

This strong positive feedback mechanism highlights the need for accurate specification of the evaporation rate, and surface sensible heat flux, in general circulation models to be used in climatic assessments of CO_2 increases. The use of fixed relative humidity in the one-dimensional models is apparently reasonably justified by the general circulation model results of Manabe and Wetherald (1975), although temperature variations caused by changes in relative humidity are non-trivial according to Rowntree and Walker (1978).

3.2. *Influence of cloud amount*

Clouds are a notoriously difficult atmospheric property to deal with adequately in models. Since cloud prediction schemes in general circulation models are related to the computed atmospheric water vapour content (Gates and Schlesinger, 1977; Kasahara and Washington, 1971), it is possible that a variation in cloud amount or type could result from a CO_2-induced warming. Presumably similar cloud changes are also to be expected in the actual atmosphere, although this is not necessarily a universally held viewpoint, see for example Cess (1976). Incidentally the desirability of predicting model clouds is an added reason for requiring an accurate prescription of the boundary layer mechanisms in large-scale models, as noted in the previous sub-section. Current cloud prediction schemes appear to be capable of only crudely forecasting the gross character of synoptic cloud distributions, see Figs. 29 and 30 of Gates and Schlesinger (1977). Nevertheless it is useful to have some quantitative estimate concerning the sensitivity of surface temperature to cloud amount variations, as this defines the accuracy to which cloud cover will need to be predicted in a model assessment of the CO_2 climatic impact.

In the current model all cloud properties are based on zonal mean observations (see Table 1 and Manabe and Strickler (1964) for details of the cloud formulation), thus permitting simple variations to be made. The model has three cloud layers. Previously Manabe and Wetherald (1967) have demonstrated for the standard CO_2 atmospheric content that varying cloud amounts can have a substantial impact on surface temperatures. Table 3 summarizes some results for the current land model for both normal and enhanced cloud cover for two CO_2 amounts. Calculations were performed for an arbitrary 10% cloud increase for each of the three cloud layers independently. In the actual atmosphere it is unlikely that the cloud layers are independent but this is a convenient model artifact. The cooling of the surface caused by increased low and middle cloud amounts in Table 3 is to be expected, the surface warming for high clouds is more difficult to explain but basically arises from such clouds occurring in regions of low temperature, where their ability to influence the outgoing long-wave radiation is reduced. Table 3 reveals that variations to the thick, low cloud layer are more important than those to the middle and high cloud layers, hence only the former is considered subsequently. Results for the low cloud layer are given in Table 4 for the coupled atmos-

Table 3. *Surface temperature variations with cloud cover for the land only model at 35° latitude*

Cloud	Control	+10% low cloud	+10% mid cloud	+10% high cloud
$1 \times CO_2$	293.41	291.73	293.22	293.77
Temperature change		−1.68	−0.19	+0.36
$2 \times CO_2$	295.23	293.42	295.0	295.60
Temperature change		−1.81	−0.23	+0.37

Table 4. *Surface temperature and mixed-layer depth variations with cloud cover for the coupled atmospheric–oceanic model at 35° latitude*

	Control	+10% low cloud
1 × CO_2, temperature, K	293.62	291.74
1 × CO_2, mixed-layer depth, m	211.9	243.3
2 × CO_2, temperature, K	295.43	293.61
2 × CO_2, mixed-layer depth, m	200.1	220.0

pheric oceanic model. Although slight differences occur in the surface temperatures for the two versions of the model, Tables 3 and 4 confirm that essentially the same results are obtained for CO_2 and low cloud amount variations over land or sea. The annual mean ocean mixed-layer depth variations in Table 4 have to be interpreted carefully, as seasonal integrations (see below) show that actual differences tend to be confined to the late winter–early spring transition period.

More importantly Tables 3 and 4 indicate that a 10% increase in low cloud cover (0.302 to 0.332) is sufficient to entirely compensate for the CO_2-induced surface temperature rise! This apparent cancellation of cloud and CO_2 effects is rather more subtle than the tables suggest. Temperature profiles for these two situations shown in Fig. 1 reveal that while the surface and tropospheric temperatures were essentially identical, marked differences existed in the stratospheric temperatures. These differences imply a somewhat altered stratospheric calculation. This could change the tropospheric–stratospheric dynamical coupling, see Hunt (1978), and thereby indirectly influence the tropospheric circulation. Some support for this mechanistic linkage affecting the troposphere has been obtained in experiments by the author with a general circulation model designed to assess a stratospherically initiated sun weather mechanism. Thus it would seem premature to assume that because mutual compensation could arise between some CO_2-induced atmospheric perturbation, such as a cloud cover variation, and the CO_2-generated surface temperature rise that this simply resolves the CO_2 problem. The atmosphere is too inherently non-linear for such simplistic solutions to exist.

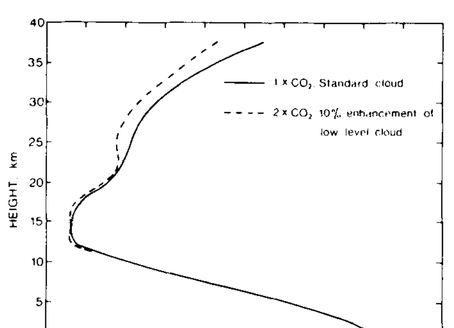

Fig. 1. Annual mean temperature profiles at 35° latitude for standard and perturbed conditions. Radiative convective equilibrium model with land surface.

The possibility that a cloud amount increase could be simultaneously associated with an enhancement in cloud albedo was also investigated. While details of cloud albedo only variations are given in the next sub-section it is noted here that the combined cloud amount and albedo perturbations produce a non-linear response from the surface temperature. The individual surface coolings for a doubled CO_2 situation for low-level cloud amount and albedo increases were respectively 1.81 K and 5.89 K. This total cooling of 7.70 K should be compared with a cooling of 8.63 K when the cloud amount and albedo increases were incorporated simultaneously. More importantly it was found that a 5% low cloud amount increase (0.302 to 0.317) together with a low cloud albedo enhancement (0.69 to 0.72) could reproduce the result shown in Fig. 1. Such small variations in cloud properties would not only be difficult to measure, *but would require model parameterizations quite beyond the current state of the art if this order of accuracy was required to be achieved in a general circulation model.* It should also be recalled that while only zonal mean quantities for a single latitude are being considered here, a general circulation model has to reproduce synoptic variations over a range of latitudes thus considerably enhancing the difficulties.

3.3. *Influence of cloud albedo and absorptivity*

If the cloud type changed as a result of a CO_2-induced atmospheric warming then cloud albedo and absorptivity could also change. Furthermore cloud albedo can increase according to Twomey (1977) if the number density of cloud condensation nuclei in the atmosphere increases. Such an effect could result from the expected higher use of coal as a source of energy in the future. Twomey's Fig. 3 was used to estimate albedo increases resulting from a rise in cloud condensation nuclei from 30 to 1000 cm^{-3}. The latter value corresponds to the upper limit over continents, but this would represent a very large increase in pollution if it occurred globally as implicitly assumed here. For low, middle and high clouds the albedo changes, respectively, were: 0.69 to 0.87, 0.48 to 0.73 and 0.21 to 0.44.

Table 5 summarizes surface temperature variations for the land model for the two CO_2 cases produced by the above cloud albedo increases. Clearly cloud albedo increases are a very strong negative feedback influence on surface temperature, particularly for low clouds. In fact it was found that a much smaller albedo increase for the low clouds, 0.69 to 0.74, was sufficient to counter the CO_2-induced surface temperature rise. This is a much more modest, and therefore more possible, albedo change. Nevertheless, as was found for the cloud amount compensation situation discussed in the previous sub-section, the stratospheric temperatures still differed and the temperature profiles were almost identical to those in Fig. 1. Thus the same reservations concerning a stratospheric-induced impact on the troposphere still apply.

Note that in Table 5 the temperature changes are slightly different for the two CO_2 mixing ratios indicating a small non-linearity in the atmospheric response in the double CO_2 case. Such non-linearities might be expected to be larger in the real atmosphere where physical mechanisms omitted from the model are operative.

In Table 6 results for low cloud albedo variations based on the coupled atmospheric-oceanic model are listed. The temperature decreases caused by the albedo increase from 0.69 to 0.87 are quite similar to those for the land model for both CO_2 amounts, with the additional degree of freedom associated with a variable mixed-layer presumably accounting for any differences. The mixed-layer depth increases are much larger than for the cloud amount perturbation runs in Table 4, because the temperature changes were much larger for the albedo runs. In fact the sensitivity of the mixed layer to cloud albedo variations is rather surprising, and emphasizes the importance of including the oceans in any assessment of geophysical perturbations, in contrast to the current fashion of concentrating such assessments on land only cases.

Table 6. *Surface temperature and mixed-layer depth variations with albedo increase of low cloud for the coupled atmospheric–oceanic model at 35° latitude*

	Control	Low cloud
1 × CO_2, temperature, K	293.62	286.99
1 × CO_2, mixed-layer depth, m	211.9	290.0
2 × CO_2, temperature, K	295.43	289.37
2 × CO_2, mixed-layer depth, m	200.1	290.0

Finally the importance of cloud absorptivity was considered by doubling the magnitude of this quantity in the land model for the three cloud decks individually. The surface temperature was found to vary by about 0.1 K hence this parameter appears to be of negligible importance.

3.4. *Cloud height variations*

The use of fixed cloud top height as opposed to fixed cloud top temperature in models is presently a matter of debate, see Reck (1979). It is not the intention here to enter this debate, but to provide a further estimate of the sensitivity of the response to cloud height variations. All that was examined with the present model was the effect on

Table 5. *Surface temperature variations with cloud albedo increases given in text for the land only model at 35° latitude*

	Control	Low cloud	Mid cloud	High cloud
1 × CO_2	293.41	287.22	291.59	288.67
Temperature change		−6.19	−1.82	−4.74
2 × CO_2	295.23	289.34	293.33	290.69
Temperature change		−5.89	−1.90	−4.54

the surface temperature of slightly increasing the cloud height, as this is a possible reaction in the real atmosphere to an enhanced hydrologic cycle induced by a CO_2 warming. The results are summarized in Table 7 for the two selected CO_2 amounts.

Raising the cloud height warmed the surface as a warmer lower atmosphere was required to compensate for the reduced cloud emission to space, attributable to the higher, and colder, location of the cloud. This result is in agreement with Reck (1979). There was a small variation in sensitivity with CO_2 amount, particularly for the low, thick cloud which is clearly the most important of the three cloud layers. This is also the cloud layer which might be most affected by an enhanced hydrologic cycle.

The important point for the present study is that an increased cloud height caused by a CO_2 warming acts as a positive feedback mechanism, thereby exacerbating the CO_2 problem.

3.5. *Perturbations in wind at the anemometer level*

Only a limited number of physical effects in the real atmosphere can be examined via radiative convective models. One of considerable importance is the exchange of energy between the atmosphere and surface, the sensitivity of which can be partially evaluated by varying the anemometer velocity in the present model, see Hunt and Wells (1979) for details of the formulation. A decrease in the intensity of the surface wind might arise from a CO_2 atmospheric warming, as Manabe and Wetherald (1975) obtained a reduction in the latitudinal temperature gradient and hence in overall baroclinicity in their general circulation experiment. As the results given here indicate such an effect would raise the surface temperature and thus constitute an additional positive feedback mechanism.

Fig. 2 illustrates the change in surface temperature as the anemometer velocity was varied from 2 to 10 m s^{-1} for the two CO_2 amounts. The standard velocity used in the model was 7.5 m s^{-1}. The temperatures for the coupled atmospheric–oceanic model were within 0.25 K of those given in Fig. 2. The figure shows that there was a strong variation of surface temperature with anemometer velocity, with the effect of doubling CO_2 being essentially a linear perturbation. A similar linearity was noted when the CO_2 amount, anemometer velocity and low-level cloud amount were varied simultaneously.

A number of other important consequences are associated with a reduction in the anemometer velocity. By reducing the evaporation rate the atmospheric water vapour and cloud amounts could be altered and presumably their associated radiative transfer properties. In addition, in the ocean it was found that the mixed-layer depth varied quite markedly with anemometer velocity, Fig. 3, and a shallower mixed layer might be produced by a CO_2-induced decrease in anemometer velocity. Such a decrease would alter the stability properties of the ocean and might have

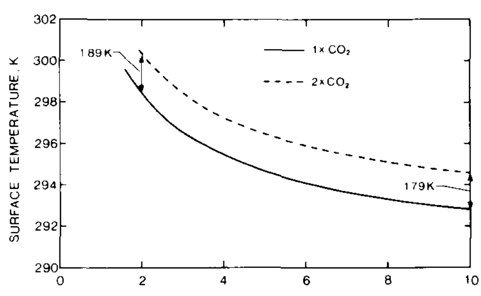

Fig. 2. Variation of the surface temperature at 35° latitude as a function of surface wind. Results are virtually identical for land or coupled atmospheric–oceanic model.

Table 7. *Surface temperature variations induced by cloud height variations for land only model at 35° latitude*

	Control	Low cloud raised 0.4 km	Mid cloud raised 0.5 km	High cloud raised 0.5 km
1 × CO_2	293.41	294.08	293.53	293.39
Temperature change		0.67	0.12	−0.02
2 × CO_2	295.23	295.77	295.34	295.27
Temperature change		0.54	0.11	+0.04

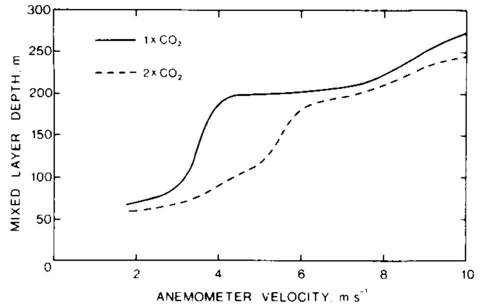

Fig. 3. The influence of the surface wind intensity on the mixed layer depth at 35° latitude in the coupled atmospheric–oceanic model.

biological as well as climatological implications. As regards the latter the polewards oceanic transport of heat, which is a crucial climatic factor (Oort and Vonder Haar, 1976), is strongly influenced by the surface wind intensity according to the model results of Bryan and Lewis (1979). Thus if less heat were transported away from the tropical source region by oceanic currents, a warmer tropics and cooler high latitudes would be expected. This would constitute a negative feedback mechanism countering the reduced latitudinal temperature gradient obtained by Manabe and Wetherald (1975). A potentially disturbing aspect of any general tropical ocean warming is the possibility, all other factors being the same, that more hurricanes and other intense tropical storms might be generated, particularly at higher latitudes than now, with all their well-known damage-producing abilities.

Another aspect of less intense surface winds is that they would reduce the transfer rate of CO_2 into the oceans, where currently about 50% of anthropogenically produced CO_2 is thought to accumulate, Bolin (1979). If this happened it would constitute a positive feedback factor to the CO_2 growth rate in the atmosphere, and therefore to the CO_2 climate problem. Although suitable coupled climate–CO_2 mass balance models have still to be developed, the analysis of actual CO_2 observations by Bacastow (1977) is supportive of this interpretation.

All the above features are strongly influenced by the atmosphere–surface interaction, which again emphasizes the importance of improving the boundary layer parameterization used in models.

Although much of this sub-section is speculative, particularly concerning the magnitude of any anemometer wind reduction, it does emphasize the broader perspective that is obtained when examining the CO_2 problem with a coupled atmospheric–oceanic model. Since oceans constitute 70% of the Earth's surface it is trite to state that such a model is the more realistic one to use in this problem. The use of a one-dimensional mixed-layer ocean model has obvious limitations, but at least the qualitative aspect of the results should be indicative of the response of the real world. Since the role of the oceans in the CO_2 problem may turn out to be more important than that of the atmosphere in determining the final climatic effects, it is clear that an evaluation using a coupled atmospheric–oceanic general circulation model is urgently needed.

3.6. *The influence of other possible perturbing mechanisms*

In addition to the perturbations discussed above other possibilities involving ozone, particulates, relative humidity etc. can be explored. A number of these have been considered by Manabe and Wetherald (1967) and Reck (1978), usually for the standard CO_2 amount. In particular the implications of a CO_2 increase on the ozone distributions have been examined in some detail by Groves and Tuck (1979). A broader perspective highlighting the need to evaluate other gases involved in the atmospheric greenhouse effect has been urged by Kondratyev and Bunakova (1978). The only additional mechanism which will be mentioned here is that of surface albedo, which has a particularly strong feedback potential as first demonstrated by Manabe and Wetherald (1967). It is possible that regional variations in precipitation induced by increasing CO_2 could alter albedoes over land by affecting the vegetative cover. Even though the global area involved is likely to be small compared with the extent of the oceans, a bioclimatological feedback exists which ultimately should be considered in general circulation model experiments, see for example Cess (1978).

4. Seasonal variations with the coupled model

Seasonal variations of the one-dimensional model system can be explored to some effect with the coupled atmospheric–oceanic model as demonstrated by Hunt and Wells (1979). Only two perturbations, involving a reduced anemometer velocity and an increase in cloud cover, will be considered here for the standard and double CO_2 amounts in order to expand on results given in sub-sections 3.2 and 3.5. The results were generated by marching the coupled model forward with a time step of 8 h allowing for the variation of the solar input with time.

Figs. 4 and 5 illustrate respectively the sea surface temperature and mixed-layer depth seasonal variations for the two CO_2 amounts for standard and halved anemometer velocities. As discussed in Hunt and Wells (1979) the basic distributions in these figures provide a reasonable simulation of observations, and essentially represent a response to the seasonal input of solar radiation. Some interannual variability is apparent in the figures which is thought to arise from non-linear effects, as the simulations were equilibrated having been run out for the order of 120

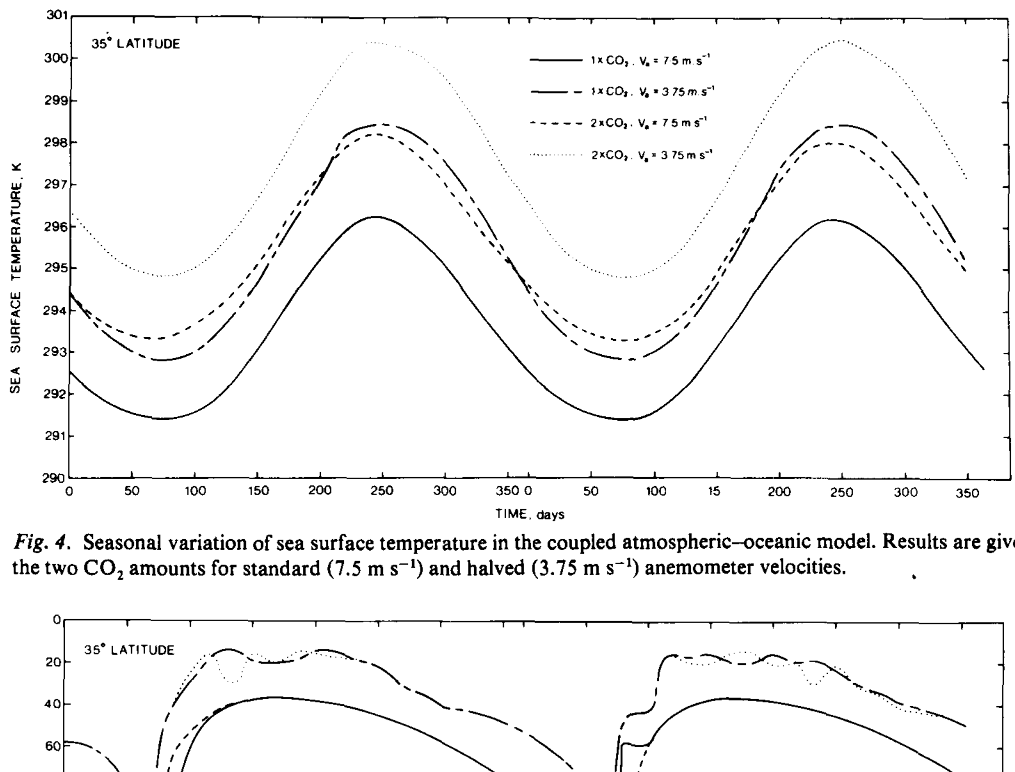

Fig. 4. Seasonal variation of sea surface temperature in the coupled atmospheric–oceanic model. Results are given for the two CO_2 amounts for standard (7.5 m s^{-1}) and halved (3.75 m s^{-1}) anemometer velocities.

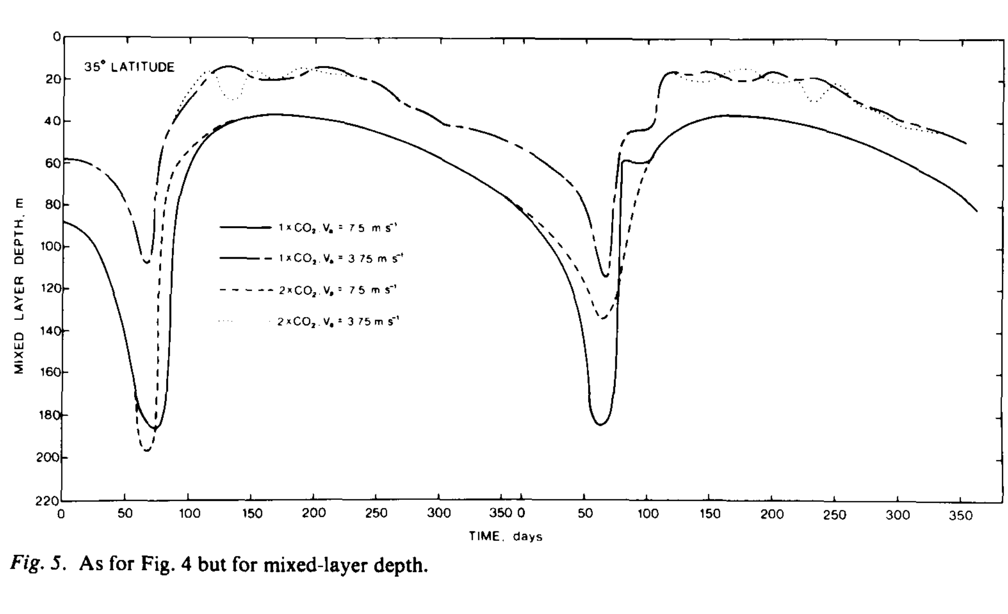

Fig. 5. As for Fig. 4 but for mixed-layer depth.

years. A slight seasonal variation occurs in the temperature differences between the runs but the mean differences are well represented by the annually averaged results in Fig. 2. The sensitivity of the sea surface temperature to the magnitude of the anemometer velocity is highlighted in Fig. 4, where a halving of this velocity is seen to have an equivalent effect to doubling the CO_2 amount. The mixed-layer depth variations, Fig. 5, between the different experiments vary with anemometer velocity rather than CO_2 amount, see also Fig. 3, and serve to illustrate the importance of the magnitude of the surface wind to this critical ocean parameter.

The final results are shown in Fig. 6 where the impact of a 10% increase in low cloud amount was explored using the seasonal model. The sea surface temperature differences in this figure are very similar to the annual mean values given in Table 4 and, in particular, confirm extremely well that a 10% low cloud increase is able to compensate for a doubling of the CO_2 content as regards the surface temperature. The corresponding mixed-layer depth seasonal variations are not presented, as apart from differences which occurred in the late winter–early spring transition, these depths were virtually identical to those of the control model for the remainder of the year.

While the seasonal runs have adequately confirmed the annual mean runs for the cases concerned here, it is important to note that the former are the more realistic simulations and have the greater information content, despite the economy gained by only considering annual mean situations. In the actual atmosphere, of course, the snow albedo feedback at high latitudes is an important aspect of seasonal variability.

5. Conclusions

This study has examined some physical processes which have a role as potential feedback mechanisms in any CO_2-induced climatic change. The list is by no means exhaustive but the results emphasize the subtleties of many of the mechanisms which could be activated, thereby highlighting the extremely difficult task that is involved in assessing the CO_2 problem. If cloud variations are induced by a CO_2 warming then they could constitute a very important feedback mechanism. The sensitivity of the model to cloud variations was found to be very high, implying a need for great accuracy in model generated cloud properities of general circulation models used in CO_2 experi-

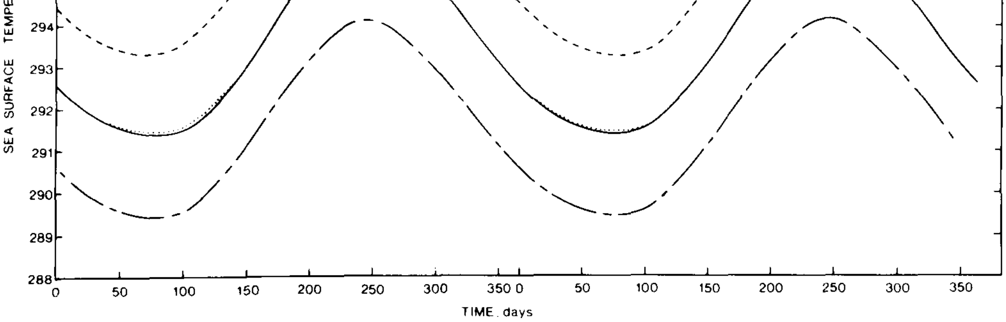

Fig. 6. Seasonal variation of sea surface temperature in the coupled atmospheric–oceanic model. Results are given for the two CO_2 amounts for standard cloud cover and for low cloud amount increased by 10%.

ments. Whether such accuracy is, or will be, attainable remains an unknown factor at this time. The ability of cloud variations to compensate for CO_2-induced temperature changes in the troposphere, but not the stratosphere, emphasizes the need for a careful assessment of the potential of stratospheric perturbations to influence the tropospheric circulation.

The role of the oceans in the CO_2 climatic problem is suggested to be more important than that of the atmosphere, and requiring more attention than it is currently receiving. In particular the sensitivity of the oceans to variations in intensity of the surface winds was noted, with possible consequences to the sea surface temperature, oceanic heat fluxes and CO_2 transfer across the atmospheric oceanic interface. Perhaps foremost amongst the oceanic effects is the possibility that a general warming of the tropical oceans could result in an enhanced frequency of hurricanes and other tropical storms, or their occurrence at higher latitudes, all other factors remaining constant. Requisite studies of hurricane frequencies for low-latitude regions where inter-annual sea surface temperature enhancements have occurred periodically do not appear to have been made.

Finally it must be realized that although a number of feedback mechanisms have been examined or identified, their impact on the *ultimate* influence of CO_2 on climate cannot be assessed with the current model. The required assessment can only be made by developing appropriate general circulation models. In the meantime nothing is achieved by disparaging the performance of existing models because they lack some possible feedback mechanisms, as this paper has endeavoured to illustrate such mechanisms have probably equal potential to exacerbate the CO_2 climate problem as they do to ameliorate it.

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ПРОВЕРКА НЕКОТОРЫХ МЕХАНИЗМОВ ОБРАТНЫХ СВЯЗЕЙ В ПРОБЛЕМЕ ВЛИЯНИЯ УГЛЕКИСЛОГО ГАЗА НА КЛИМАТ

Модель радиационно-конвективного равновесия как сама по себе, так и в сочетании с моделью перемешанного слоя океана, используется для объяснения следствий некоторых возможных вторичных климатических откликов, предшествующих потеплению, вызываемому CO_2. Расчеты производились как для стандартного (300 p.p.m.), так и для удвоенного количества CO_2. Это позволило проверить и количественно определить некоторые механизмы обратных связей. Например найдено, что увеличение на 10% существующего количества низких облаков полностью компенсирует нагрев поверхности и тропосферы, вызываемый удвоением количества CO_2. Подобная компенсация была получена увеличением альбедо низких облаков от 0,69 до 0,74. Комбинация этих двух возмущений требовала столь малых индивидуальных увеличений, что возник вопрос, в состоянии ли модели общей циркуляции с собственным предсказыванием свойств облаков достигнуть достаточной точности для реалистической оценки таких тонких различий в решении проблемы влияния CO_2 на климат. Интересный аспект температурной компенсации, связанной с увеличением количества и альбедо облаков, состоял в том, что эта компенсация не распространялась на стратосферу, которая испытывала общее охлаждение. Обсуждаются потенциальные климатические следствия этого охлаждения, также рассматривалось влияние изменений ветра у поверхности над океаном, приписываемых нагреванию из-за увеличения CO_2, и показано, что оно заметно воздействует как на температуру поверхности моря, так и на глубину перемешанного слоя. Ряд потенциальных механизмов обратных связей, связанных с такими изменениями ветра, был идентифицирован и послужил поводом подчеркнуть необходимость уделять болшее внимание роли океана в оценки проблемы CO_2. Отмечается возможность увеличения числа ураганов и других сильных тропических штормов из-за общего нагревания океанов в низких широтах при увеличении содержания CO_2.