THE RELIABILITY OF AN ENERGY BALANCE MODEL IN SIMULATING CLIMATIC RESPONSES DUE TO INCREASES IN CARBON DIOXIDE LEVELS

BY

CHRISTOPHER ROBIN CULVER

A Research Paper

Submitted to the Department of Geography

in Fulfillment of the Requirements

of Geography 4C6

McMaster University

April 1989

ABSTRACT

A relatively simple climatic model based on the energy balance has been used to examine the climatic responses due to increases in carbon dioxide (CO_2). Simulations concerning the CO_2 concentration, the cloud fraction and the ocean's mixed-layer depth were all performed using an IBM-PC personal computer. The results were intended to provide a better understanding of the processes involved in an EBM, as well as the importance of this type of model in simulating climatic responses. There were four main areas of study within the research centred around both a decrease and an increase in CO_2 concentration, changes in the cloud fraction and the influence of the ocean's mixed-layer.

The role of the oceans in the climate system is still somewhat of a mystery to most scientists, in terms of its affect on a CO_2 enhanced climate. Changes in the cloud fraction serve either to enhance or suppress the effect of CO_2 on the surface temperature of the planet. This is dependant on whether the amount of cloud is reduced or increased. The focus of the study is based on the changes in carbon dioxide concentration levels. Simulations confirm, that when CO_2 is reduced, the surface temperature will decrease as well. When CO is halved, the temperature decrease is 2.51 °C. In contrast, when CO_2 is doubled the surface temperature rose by 2.91 °C. Thus, causing the present day climate of the model to warm drastically.

The reliability of the results proved to be difficult to assess. The model tends to overestimate decreases in temperature when CO_2 is reduced in content. However, Burt's model does seem to accurately represent increases in temperature for $2xCO_2$ .The simulation results fall within a range defined by the results of selected radiative convective models (RCM). Nevertheless, there is a need for increased research in the area of effects, produced by other parameters on a CO_2 enhanced climate.

ACKNOWLEDGEMENTS

I would like to acknowledge the advice and guidance provided to me by Dr. J.A. Davies. His help in defining not only the research topic, but its scope as well, was very much appreciated. I would also like to thank the Department of Geography for the opportunity to carry out this research in the field of Radiation Climatology.

In addition, I would like to recognize the support of my parents, as well as all of my fellow classmates. It has allowed me to strive for excellence, in the completion of this research paper.

I would especially like to recognize Dr. J.E. Burt (University of Wisconsin) for the design of this Energy Balance Model. For without his contribution, this particular piece of research could never have been completed.

BACHELOR THESIS (1989)
(Physical Geography)

MCMASTER UNIVERSITY
Hamilton, Ontario

TITLE: THE RELIABILITY OF AN ENERGY BALANCE MODEL IN SIMULATING CLIMATIC RESPONSES DUE TO INCREASES IN CARBON DIOXIDE LEVELS

AUTHOR: CHRIS CULVER, B.A. (MCMASTER UNIVERSITY)

SUPERVISOR: DR. JOHN A. DAVIES

NUMBER OF PAGES: 43, xxxii

TABLE OF CONTENTS

TABLE OF CONTENTS

CHAPTER I

INTRODUCTION

The use of climatic models has contributed to the growth of physical climatology in the past, and appears to be the researcher's tool of the future as well. These models allow for the simulation, all be it imperfect, of our present day climate and the processes involved in this system. In the early stages of modelling, the basic goal was to try to simulate this "simple" system. However, over time the researcher soon learned that this atmospheric system was not simple at all, but on the contrary very complex.

A. RESEARCH GOALS

1. PAST RESEARCH

Energy balance models were the first attempt at simulating the Earth-Atmosphere system. Sellers (1969) used a relatively simple climatic model (EBM) based on the energy balance. This model was used to perform a series of numerical experiments. Specific information concerning the processes involved in changing climates were obtained as a result. In 1974, Sellers then chose to focus his attention on the effect of carbon dioxide variations on the results of a simple energy balance model. The model used in these simulations was a more efficient version of his previous one.

Lian and Cess (1976) were involved in similar climatic work as well. They were studying the importance of energy balance models in simulating climatic changes. Thompson and Schneider (1979) and Gal-Chen and Schneider (1976) used an energy balance model to perform climatic simulations, however these did tend to emphasize seasonal experiments, rather than experiments designed to reach an equilibrium state. Most of the temperature results used to test the reliability of the test model are from simulations designed to reach equilibrium.

2. THESIS

The purpose of this research paper is to examine the reliability of a relatively simple climatic model with respect to a carbon dioxide (CO_2) induced atmosphere. The research examines how average global surface temperatures change as a result of the influence of CO_2 in the atmospheric system. However, there are important factors which interact with carbon dioxide in the Earth-Atmosphere, and they are also examined. The details of the research are outlined later in this chapter. Such factors as the cloud fraction and the ocean's mixed-layer can also contribute to carbon dioxide effects on climate. It is the goal of this research to provide a better understanding of two specific areas; the processes involved in energy balance models and the importance of relatively simple models in simulating responses to CO_2-induced climatic changes.

3. RESEARCH DESIGN

The design of this research is based on two main areas of examination. The first centres around the collection of temperature data from the test model. In this case the test model is a zero-dimensional energy balance model by Burt (1984). Through a series of simulations, the test model will produce temperature data for an everchanging climate. The parameters within the model which are of prime importance are the carbon dioxide concentration, the cloud fraction and the ocean's mixed-layer depth.

Dickinson (1982) performed a study on the increase in carbon dioxide concentration in the atmosphere and its relationship to other parameters. His experiments focused attention on the increase in carbon dioxide and the effects of interactions with other variables. The combined effects of CO_2 , the cloud fraction and the ocean's mixed-layer are very important when examining an everchanging climate. Watts (1980) and Hunt (1981) also emphasize this point concerning carbon dioxide and related feedbacks in their research as well.

The collection of past research temperature data is the final step before the model can be assessed for reliability. The main material of interest are the results, specifically the temperature results from the simulations for carbon dioxide increases. These simulations are from radiative convective models (RCM). These models tend to be more sophisticated because they usually involve more atmospheric feedbacks, as well as the dynamic process of convection. However, they still produce results which are comparable to those produced in the simulations in this research. Ramanathan and Coakley (1978) reviewed a series of results from radiative convective models, and their responses to increases in carbon dioxide concentrations. Augustsson and Ramanathan (1977), and Watts (1980) also contribute important information concerning CO_2-induced temperature changes in RCM simulations.

CHAPTER II

RESEARCH METHODS

The research involved in this paper centres around a series of simulations using the test model. These are computer simulations which will be executed using an IBM personal computer. The software is known as EBM0.EXE, which is an executable file. The model parameters under examination in this research are the carbon dioxide concentration, the cloud fraction and the ocean's mixed-layer. There are other parameters involved, but these parameters remain constant at their standard values. When all of the necessary simulations have been completed, the results will be compared to RCM temperature results, in order to come to a subjective conclusion concerning the reliability of the model; in simulating responses to increases in CO_2.

A. ENERGY BALANCE MODELS

1. BACKGROUND

Energy balance models are the simplest of the atmospheric simulation type models. These models enable the researcher to calculate the rate of change of the surface temperature of a planet. A set of parameters are used to calculate the equations which underly the basic radiation components. The solar and longwave components allow for the calculation of the rate of temperature change to take place. Each of these components are computed for both cloudy and clear sky conditions, before they are combined to form the total radiation component.

2. BURT'S EBM DESIGN

The design of J.E. Burt's zero-dimensional energy balance model is based on the premise that the rate of change of surface temperature is indeed proportional to the difference between the solar and the longwave radiation components (Burt, 1984). The test model produces a set of climate data for each individual simulation. A simulation can involve all standard values for the parameters, an individual parameter change or even a change in several model parameter values. There are two different sets of parameters. The first is a set which controls the boundaries of the simulation. This includes the initial temperature, the duration of the simulation in years, and the time step involved. The second set of parameters control the actual output of data from a simulation. These parameters affect the temperature results and are discussed in detail later in this chapter.

3. MODEL PARAMETERS

Once the first prompt appears on the screen, it is necessary to set the time scale for the simulations. For this research, it was decided that a time period of 50 years would be used. This is considered to be an accurate period of time for a model atmosphere to reach equilibrium. This period of time allows for all of the atmospheric constituents to react to any perturbation, and again reach a steady state equilibrium. In addition to setting the length of the time period, the step or skipping of output years can also be set. In this case the step is set at a two year interval. This allows the user to identify the more dramatic changes in temperature, while at the same time eliminating some of the repetative data for years after the model atmosphere has actually reached an equilibrium state.

The next step is the option of setting a base temperature. This base temperature is used in order to keep the magnitude of all of the temperature results in perspective. The model has the ability to create its own equilibrium temperature of 15.38 °C when all of the parameters are set to their standard values. This temperature in turn can be used as a base temperature. However, it was decided that a base temperature of 15.00 °C would be just as acceptable, and this would allow for calculations of temperature changes to be more readily obtained.

From this, the user's attention turns to the table of parameters. These parameters all have current and standard values listed, as well as the percentage change from the standard value (Figure 1). The main parameters which are of concern for this research are the CO_2 concentration, the cloud fraction and the equivalent mixed ocean depth. The carbon dioxide concentration level for the model has a standard value of 320 parts per million (ppm). This is the approximate value for the present day level of CO_2 in the atmosphere. The cloud fraction is that portion of the sky covered by clouds and has a standard value of 0.54. The equivalent mixed ocean depth is the depth of the layer of water directly below the surface. The standard value for this parameter is a depth of 75 metres. These are the key model parameters and their standard values which are under examination in this study.

4. RESEARCH SIMULATIONS

For this research, there will be a set of 6 main experiments. Within each of these experiments, there will be a number of simulations performed. Each simulation produces a table of climate data (Figure 2). This table contains the year, the temperature, the change in temperature over time, the solar and longwave radiation components, the total cloud, the total albedo and the number of steps in each yearly calculation of the simulation. The column of interest for this research is the temperature column. This column shows the changes in temperature as the model atmosphere attempts to reach equilibrium.

The first experiment involves the testing of a hypothesis. This is a test to see if a decrease in carbon dioxide concentration can have the same magnitude of influence on a model atmosphere, as that of an increase in CO_2 . However, in this case the influence should not be to increase temperature, but rather to decrease the temperature of the planet. This is done by running three simulations with different CO_2 concentration levels. One is the standard value, while the other two are values of 240 and 160 ppm. If decreasing carbon dioxide in the atmosphere leads to a decrease in temperature, it will become quite evident within the output.

The contrasting approach to the first experiment is the focus of the second. This experiment is one of the most widely examined in terms of climatic modelling because of its world wide importance. The increase of carbon dioxide in an atmosphere should lead directly to an increase in temperature. It is important to note that for both of these experiments that all other parameters are held constant at their standard values. This experiment involves a total of 17 simulations. There is a simulation for each different carbon dioxide concentration level within a range of 320 to 640 ppm. However, the interval of CO_2 levels is 20 ppm in order to highlight the temperature changes more readily. As indicated, the standard value for CO_2 is 320 ppm, while the doubling point is of course 640 ppm. The doubling point is the critical value of carbon dioxide in terms of temperature changes in the near future.

Thirdly, this research centres around the effect of cloud cover in addition to carbon dioxide in a model atmosphere. The interaction or feedback between these two parameters could be very important in terms of altering future temperatures. This section consists of three experiments, each with six simulations. The cloud fraction is set at three different values, while the CO_2 concentration is allowed to increase at a step of 60 ppm from 320 ppm to the doubling point. The values for the cloud fraction experiments are its standard value of 0.54, as well as values of 0.49 and 0.59. This attempts to examine the influence of both an increase, and a decrease in the cloud fraction; while carbon dioxide is increasing at the same time.

The last experiment involves the importance of the ocean's mixed-layer. In order to fully examine the impact of this parameter, a series of 10 simulations were performed. Each simulation involved a different value for the mixed-layer depth of the ocean. The range of values used was between the standard value of 75 and a maximum of 275 metres. For each depth, the CO_2 concentration was set at the present day level (320 ppm), and at the doubling point of carbon dioxide (640 ppm). This was done in order to examine not only the influence of the mixed-layer on the present day CO_2-induced climate, but also on the climate of the future when the CO_2 level has doubled.

B. BURT'S MODEL STRUCTURE AND EQUATIONS

1. SURFACE TEMPERATURE

The model is based around the idea that the rate of change of surface temperature (dT/dt) is indeed proportional to the difference between both the absorbed and the emitted radiation. The heat capacity of the planet is very important, and this controls the constant of proportionality. The heat capacity controls how the planet responds to changes in the radiation balance at the surface. In Burt's model, the heat capacity is defined in terms of the depth of the ocean's mixed-layer. This layer is assumed to be well-mixed, and freely exchanging energy with the atmosphere above. Therefore, in the following equation, the depth of the ocean's mixed-layer in metres can be seen as the parameter h. The equation is as follows

$$dT/dt = (S-F)/(0.19h) \qquad [1]$$

where S is the absorbed solar radiation and F is the longwave radiation emitted to space. Both of these parameters are expressed in Watts per square metre. The rate of change of the surface temperature (dT/dt) is measured in degrees Celcius per year. Both the solar and the longwave terms can be expressed as functions of the cloud parameter.

2. THE OCEAN'S MIXED-LAYER PARAMETER

As previously mentioned, the ocean's mixed-layer parameter controls the heat capacity in the model. The mixed-layer is the layer or depth of ocean water which is directly below the surface. This layer is assumed to be well mixed at any given time. This layer can be considered the equivalent of the troposphere, in terms of mixing within the ocean. This parameter has a standard value of 75 metres, but this is actually a very conservative estimate of the ocean's true mixed-layer depth.

3. SOLAR RADIATION

As stated above, the solar component can be calculated separately for both the clear and cloudy fractions of the planet. Therefore, the equation is as follows

$$S = S_c + S_o \qquad [2]$$

where S is the total absorbed solar radiation in Watts per square metre. As well, S_c and S_o are the absorbed solar for each of the cloudy and the clear portions of the atmosphere, respectively.

Turning attention towards the calculation of solar radiation for the cloudy fraction of the atmosphere, the important parameters are the actual cloud fraction, and the albedo of the cloudy fraction of the sky. Thus, the amount of solar radiation absorbed by the cloudy fraction is

$$S_c = (s/4)n(1-a_c) \qquad [3]$$

where s is the solar constant in Watts per square metre. Cloud fraction is expressed as n, but this is also a calculated value which will be explained in a later section. Similar to the cloud fraction term, is the albedo parameter for the cloudy fraction. The value for a_c will also be explained in a later section.

Using the symbols that were defined earlier, the equation for the absorbed solar for the clear portion of the sky is

$$S_o = (s/4)(1-n)(1-a_o) \qquad [4]$$

where s is again the solar constant. This time the clear fraction is calculated by subtracting n from a value of 1 (1-n). The albedo a_o is of the surface and of the clear atmosphere together.

4. THE CLOUD FRACTION PARAMETER

The fraction of the planet covered by clouds is the equivalent of the "normal" cloud amount n^*, plus any change in cloudiness produced by changes in temperature, n'. Thus, the resulting equation is

$$n = n^{*} + n' \quad [5]$$

The temperature-induced change is proportional to the decrease of temperature from standard conditions. This results in the calculation of n' by way of the following

$$n' = (T-T^{*})n_{T} \quad [6]$$

where T is the actual current temperature in degrees Celcius. The equilibrium temperature T^{*} when under standard conditions, and n_{T} is the strength of the temperature-cloud feedback.

5. THE ALBEDO PARAMETER

Like the cloud fraction parameter, the albedo of the planet is defined as the sum of the "normal" value and a resultant of a temperature-induced change due to a decrease in temperature. Albedo is calculated using equations for both the cloudy and the clear portions of the atmosphere. Therefore, the following equation for the cloudy portion is

$$a_{c} = a_{c}^{*} + (T-T^{*})a_{T} \quad [7]$$

where a_c^* is the "normal" cloudy sky fraction albedo and a_c' is the temperature-induced factor written as $(T-T^*)a_T$. This part of the equation contains the current temperature T, the equilibrium temperature under standard conditions T^*, and the temperature-albedo feedback, a_T.

There is also an albedo equation for the clear portion of the atmosphere. This is once again the sum of the unperturbed value, and the temperature-induced change resulting in the following

$$a_o = a_o^* + (T-T^*)a_T \qquad [8]$$

where a_o^* is the "normal" clear sky fraction albedo and a_*' is the temperature-induced factor written as $(T-T^*)a_T$.

6. LONGWAVE RADIATION

As indicated earlier, the longwave radiation component can also be divided into two separate expressions. There are separate calculations for both the cloudy, and the clear portions of the atmosphere.

$$F = F_c + F_o \qquad [9]$$

The longwave component F consists of both the cloudy portion calculation F_c , and the calculation for the clear portion of the sky as well, F_o. In order to calculate the longwave radiation emitted to space, it is first necessary to make a series of assumptions.

It is assumed that clouds are completely black to emission of longwave radiation from the surface. This should create the situation where the cloudy portion clouds are the only source of radiation to space. There is a further assumption that the clouds radiate at a rate that is proportional to the surface emission. Thus, cloud emission is some constant f_c times the surface emission F_s. Surface emission is itself computed from surface temperature values under the assumption that the surface also emits as a blackbody.

Of the radiation emitted to space by the clouds, some fraction e, is absorbed by the atmosphere above the clouds. The resulting fraction is e_c subtracted from the value 1 $(1-e_c)$, which escap=es to space.

$$F_C = n(1-e_C)f_C F_S RCO_2 \qquad [10]$$

In this equation, n is again the cloud fraction, e_c, f_c and F_s have already been previously defined. The only parameter left to be defined is RCO_2. This is the factor which accounts for varying carbon dioxide concentrations in the atmosphere. The components of this factor will be outlined in the next section.

As stated above, the surface is considered to be a blackbody emitting at a rate proportional to T^4. The variable T^4 is the temperature of the surface of the planet in degrees Kelvin to the power of four. Of that portion which is emitted, the atmosphere absorbs a fraction e, allowing the remainder $(1-e_o)$ to escape to space. It is assumed that the clear atmosphere emits radiation at a rate proportional to the surface emission. The carbon dioxide factor again modifies the longwave radiation flux. The result is

$$F_o = (1-n)[(1-e_o)+f_o]F_s RCO_2 \qquad [11]$$

where f_o is the clear atmospheric emission and F_s is once more the surface emission.

7. THE CO_2 CONCENTRATION PARAMETER

The carbon dioxide parameter is the centre of this entire research. The effects that CO_2 have on climate are of prime importance in this particular study. In Burt's model, the carbon dioxide factor is handled in the following manner. Both of the longwave radiation fluxes are modified by the factor RCO_2. This factor accounts for varying carbon dioxide concentrations in the atmosphere. This factor is a function of both the CO_2 concentration, and a parameter known as FCO_2 . The FCO_2 parameter expresses the relative importance of carbon dioxide to longwave radiation. The standard value for this parameter is 1.0, such that each doubling of carbon dioxide concentration leads to a temperature increase of approximately 2.5 °C. However, this affect can be greatly enhanced when other parameters are combined with an increase in CO_2.

CHAPTER III

DISCUSSION OF RESULTS

As previously mentioned, this research is based around a small set of climatic experiments. These experiments, containing several individual simulations, were performed to learn more about how an atmosphere responds to CO-induced perturbations. The results of all of the simulations using the test model will be discussed in detail in the succeeding sections.

A. MODEL SIMULATIONS

1. DECREASING CO_2 CONCENTRATIONS

The first experiment involved the investigation into an intriguiung question. If the assumption is made, based on simulation evidence, that an increase in carbon dioxide leads to an increase in surface temperature, then ultimately a decrease in CO_2 should lead to a decrease in temperature. Therefore, this was the main aim of the first experiment. There were three simulations involved in order to test this hypothesis. The carbon dioxide concentration level was set at its standard value of 320 ppm, as well as at levels of 240 and 160 ppm. The model was then set into its simulation mode, producing three sets of different results (Table 1).

The carbon dioxide concentration is at its standard level of 320 ppm, and all other parameters are held constant as well. The output of temperature data for the 50 year equilibrium period shows the following. The temperature starts at 15.00°C, and at the end of 50 years it had reached a temperature of 15.38°C. However, the actual temperatures are not really important, due to the use of a base temperature. The important element in the output is that there was a temperature increase of 0.38 °C. When all conditions for the model are standard, the CO_2 level is sufficient to raise the temperature of the surface. This scenario is a model representation of the present day climate where the atmosphere is slightly enhanced by carbon dioxide.

The carbon dioxide concentration level was then decreased by 80 ppm to a level of 240 ppm. This was the first step in the investigation into whether a decrease in CO_2 leads directly to a decrease in surface temperature. Again, starting at the base temperature of 15.00°C, the simulation proceeded to equilibrium. However, this time the temperature did not increase slightly, but actually decreased. The final temperature for year fifty was 14.23 °C. This indicated that for a concentration of 240 ppm, the temperature decreased 0.77°C. To be sure that this was the trend expected, the concentration level was again decreased.

Finally, the CO_2 concentration was set at a value which was half of the present day value. The level was set at 160 ppm, and the trend held true. The final output temperature in this case was a value of 12.49 °C. This was a dramatic decrease in temperature. Using the base temperature, it was calculated that there was an actual temperature decrease of 2.51 °C. Thus, indicating that as the concentration decreases, the temperature decreases at almost an exponential rate. The temperature profiles for all three simulations can be seen in Figure 3.

2. INCREASING CO_2 CONCENTRATIONS

The main experiment in this research was to examine the effects on surface temperature, as the carbon dioxide increases to its doubling point. Therefore, this experiment contains a series of simulations where the CO_2 level gradually increases from the present day level. The simulations begin with the CO_2 level set at 320 ppm, and all other parameters are at their standard values. The concentration is allowed to slowly increase at an interval of 20 ppm (Table 2abc).

The results for a concentration of 320 ppm have already been discussed. The results indicated that this value raises the surface temperature slightly by 0.38°C from the base temperature. The trend that should appear is that as CO_2 increases, the temperature should also increase. This trend does occur as the temperature increases slightly for every increase in the carbon dioxide concentration. If the midpoint between the present day equivalent and the doubling point of CO_2 is examined, the results indicate an increase of 1.91°C. If we recall the magnitude of the temperature decrease for the midpoint between 320 and 160 ppm, the decrease was only 0.77°C(240 ppm). This indicates that the response of the model atmosphere is even more dramatic for large increases in carbon dioxide in terms of temperature changes.

When the doubling point of carbon dioxide is reached, the result is very clear. If the concentration is doubled to a level of 640 ppm, the temperature is increased from the base temperature to a temperature of 17.91°C. This is an overall increase of 2.91°C in surface temperature. The doubling of the CO_2 level has caused the atmosphere to respond by increasing the surface temperature in order to maintain equilibrium. The temperature trends are very dramatic, and illustrate the profound impact of CO_2 on the temperature of the surface (Figure 4).

3. THE CLOUD FRACTION

The importance of the cloud fraction was the next set of experiments. This involved the examination of different cloud fraction values for an atmosphere with increasing carbon dioxide. The three cloud fraction values were 0.49, 0.54 and 0.59. These indicate the percentage or fraction of the sky considered to be covered by clouds. For each experimental value, simulations were run for increases in carbon dioxide. These simulations began with the standard value and proceeded to the doubling point. The output data from the simulations can be seen in appendix B (Tables 3-5).

The first experiment made use of a cloud fraction value of 0.49. The CO_2 concentration was allowed to increase from 320 to 640 ppm, while all other parameters were held constant. The simulation data shows that for a concentration of 320 ppm, the temperature increases 2.69 °C. This change in cloud fraction has produced a temperature increase almost equivalent to the effect of doubling the amount of CO_2 on the present day atmosphere. When the carbon dioxide concentration is doubled to a value of 640 ppm, the temperature increase is an incredible 5.20 °C. This is almost a doubling of the increase in temperature for when CO_2 is 320 ppm. This results in creating a larger net radiation flux. The difference between S and F in equation 1 is now larger, creating an increase in temperature.

When the value for the cloud fraction is returned to its standard value, the results are quite different. The temperature is still increasing as a result of carbon dioxide, but the magnitude of the increase is approximately 40% smaller. The cloud fraction creates results that have already been displayed in the previous section. However, this time the important element is not the CO_2, but the cloud fraction itself. The standard value creates only an increase of 2.91 °C for a doubling of CO_2. The difference between the two radiation components has now decreased, in turn causing the temperature to also decrease.

The last of the cloud fraction experiments was based on an increase in clouds in the sky. The cloud fraction was raised to a value of 0.59. This caused a dramatic change in the temperature results, which had previously been seen. The temperature actually decreased for a CO_2 value of 320 ppm. The decrease was in the magnitude of 2.03 °C. This was completely opposite to all other cloud fraction findings. When CO_2 was doubled, the temperature only increased 0.52 °C. In fact, the temperature only began to increase when the carbon dioxide concentration reached a level of 560 ppm. Befor this point, the temperature was always less than the base temperature of 15.00 °C. This indicates that when the cloudiness increases to 0.59, the CO_2 concentration must be at least 560 ppm to offset the clouds influence on the temperature regime. The increase in clouds has caused the amount of longwave radiation emitted to space decrease, leading to an increase in surface temperature as the atmosphere attempts to reach equilibrium. The temperature profiles for the three cloud fraction values for a CO_2-induced atmosphere, are illustrated in appendix C (Figures 5-10).

4. THE OCEAN'S MIXED-LAYER DEPTH

The last of the experiments was done to investigate the influence of the ocean's mixed-layer on a CO_2-induced atmosphere. This involved ten simulations, 2 for each specific mixed-layer depth. The depths used were 75, 125, 175, 225 and 275 metres. For each depth the carbon dioxide concentration was set at the standard value, as well as the $2xCO_2$ level (Table 6ab). This was done to try and examine how the ocean reacts to the present climate, and a CO_2 enhanced climate.

The best way to examine the output, is to look at each carbon dioxide concentration for all of the depths. The standard value is still 320 ppm for CO_2, and the depths range from 75 to 275 metres. The depth of the mixed-layer seems to have absolutley no effect on the model atmosphere, until the depth reaches the maximum value of 275 m. At this point, the ocean causes the system to take a long period of time before it regains equilibrium. There are indications that the oceanic system is attempting to try and stay in equilibrium at a depth of 175 m. However, the model system does maintain equilibrium within the fifty year time period. At the maximum depth, the temperature actually decreases 0.01°C by the time equilibrium is reached (Figure 11).

The simulations for the $2xCO_2$ concentration level were very similar to that of the standard value. There were no changes in the equilibrium temperature for any of the depths, except for the maximum of 275 m. The temperature seemed to decrease only slightly in magnitude from previous $2xCO_2$ experiments. The equilibrium temperature varied between 17.91 and 17.89°C for the four shallower depths. When the mixed-layer was extended to a depth of 275 metres, the temperature for the model atmosphere still increased, but to a smaller magnitude. The equilibrium temperature this time was only 17.85°C. This value was 0.04°C less than the normal temperature for an atmosphere which experienced a doubling of carbon dioxide. The temperature trends illustrate this decrease in the CO_2 influence on the surface temperature (Figure 12).

B. RADIATIVE CONVECTIVE MODEL RESEARCH

1. BACKGROUND ON RCM'S

Radiative Convective Models are somewhat different from the simpler energy balance models. These models are one-dimensional, this being in the vertical direction. They involve numerous feedback mechanisms as well as the process of convection. This dynamic process is important to the mixing of the atmosphere. It is also important in determining the surface temperature of the planet. RCM's produce temperature results for what is called the skin temperature of the planet. This can be considered the equivalent of the global surface temperature calculated by an energy balance model.

There are four areas of results which must be addressed. These of course are decreases and increases in carbon dioxide, changes in the cloud fraction and the influence of the ocean's mixed-layer. Results produced by radiative convective models will be examined in these three areas. It is from this research, that a judgement of reliability concerning the test model can be concluded.

The results obtained for comparison are from a selected group of radiative convective models. These models were chosen based on their sound research, and not for their specific findings. These models all produce a range of temperature results, due to feedback and convection processes.

2. DECREASING THE CO_2 CONCENTRATION

There have also been experiments done to examine the relationship between a decreasing carbon dioxide concentration level and the surface temperature response. These experiments concentrate on a $1/2xCO_2$ scenario, where the level of carbon dioxide would be 50% of the present day level (Table 7). Manabe and Wetherald (1967) performed this simulation along with the $2xCO_2$ scenario. They used two different types of RCM's which produced average surface temperature decreases of 1.25 and 2.28 °C. In another study by Sellers (1974), he used his revised version of a previous climatic model. From the results of the simulations performed concerning decreases in carbon dioxide, he produced a value of 1.64 °C. This result indicates that there would be a decrease in temperature, if the level of CO_2 was cut by half.

3. INCREASING THE CO_2 CONCENTRATION

The following models all completed simulations concerned with a doubling of CO_2 in the atmosphere. Thus, this will be the main focus when examining the temperature results produced by the test model. Manabe and Wetherald (1967), used their RCM to calculate the surface temperature effect of a doubling scenario. Premised on the thermal equilibrium of the atmosphere, the model produced this result. For a doubling of carbon dioxide within the atmosphere, the temperature change at the surface would fall within a range of 1.33 to 2.92 °C. In addition, Manabe (1971) again attempted to answer this question. The result this time was a single value of 1.9 °C. The other models calculated the temperature for a $2xCO_2$ scenario to be within a range of 0.69 to 3.2 at maximum. The specific results for Hunt (1981), Hansen et al. (1981) and others can be seen in table 8 (Appendix D). The main conclusion that can be drawn from these results is that there is a wide range. This is partly the result of convection on the model atmosphere, but mostly because each of these models are attempting to simulate the system differently. Not all of the RCM's use all of the same processes, and feedbacks as the others. After all, these are models which are attempting to simulate a part of reality in an imperfect way.

3. CLOUD FRACTION CONCLUSIONS

In terms of examing results for cloud effects on

CO_2-induced atmospheres, the past research is somewhat thin. However, Dickinson (1982) was able to come to some conclusions based on his analysis of RCM's. He concluded that clouds do not only serve to trap radiation, but also to effect the albedo of the system. A decrease in cloud cover directly decreases the reflectivity of the planet. This in turn increases the amount of radiation initially received at the surface of the planet. Dickinson suggested that if the cloud fraction increased by only 1%, the absorbed solar would increase, while the longwave radiation component would actually decrease in magnitude. This would result in the warming of the climate as the system would increase the surface temperature to remain at equilibrium. At this point in time, it is not known to what extent cloudiness might be able to change climate, if the change in cloud cover was much larger.

4. THE ROLE OF THE OCEANS

The oceans comprise about 70% of the earth's surface and provide an even larger fraction of the total water evaporated into the atmosphere (Dickinson, 1982). In the climate system, the ocean is the lower boundary, where energy, heat and moisture are exchanged with the atmosphere. In terms of the oceans influence on temperature, the conclusions seem to be weak. There aren't any real concrete conclusions concerning the magnitude of the influence of the mixed-layer. However, it has been suggested that there is a delay of about several decades concerning a CO_2-climate change. The mixed-layer has the capacity to store large amounts of heat, and this tends to slow down the dramatic effect of a carbon dioxide induced atmosphere. At present, there are attempts being made in order to examine the thermal adjustment of the ocean (Dickinson, 1982), but these require much more sophisticated models known as general circulation models (GCM).

C. RELIABILITY OF BURT'S EBM

1. ASSESSMENT OF RELIABILITY

The test model has been used to perform a series of major experiments concerning the influence of carbon dioxide. Some of the experiments focused only on CO_2, while others examined the combined effects of CO_2 and other parameters. The results for all of the simulations have been documented. In addition, past research material using radiative convective models (RCM) has also been detailed in reference to the model experiments. However, only two of the four sections can be assessed, and these sections will decide the question of model reliability.

The results for decreasing the standard value of carbon dioxide to half for the test model tend to be slightly larger than those for selected RCM's. Recall, that the values for specific RCM's fell within a range of 1.25 to 2.58°C , for a decrease in temperature. The value obtained from the simulations was 2.51°C. This is a larger decrease in temperature than most other models predict. This could be the result of only limited feedback processes within the model. It may not be able to accurately simulate climatic conditions which existed in past history. Therefore, based on limited past research into the $1/2xCO_2$ climate scenario, the reliability of the model is slightly weak. It has the tendency to over compensate in terms of decreasing surface temperature, when CO_2 is halved.

The second area to be assessed for accuracy are the temperature results produced from the simulations involving increases in CO_2 . The main focal point is the simulation result for a doubling of carbon dioxide. The results compiled from past research for selected models produced a range of values. However, the range for increases in surface temperature can be defined as between 0.69 to 3.5°C. This is a wide range, but the results are for several different RCMs. The test model experiment produced an increased temperature value of 2.91°C. This value does fall within the upper limit of this "acceptable" range. Thus, it can be concluded with a certain degree of accuracy that the test model is reliable in simulating increases in surface temperature for a doubling of CO_2.

CHAPTER IV

CONCLUSIONS

The goal of this research was to provide a better understanding of both the processes involved in EBM's, as well as the importance of these relatively simple models in simulating responses to increases in carbon dioxide within the atmosphere. Through the use of computer simulation and past research, hopefully these goals have been acheived.

A. SUMMARY OF SIMULATION RESULTS

The results of the simulations produced four main conclusions concerning increases in CO_2 in the earth-atmosphere system. These were 1) that a decrease in the level of CO_2 in the atmosphere will lead to a decrease in the surface temperature of the planet, 2) by increasing carbon dioxide to the doubling point, the surface temperature can be raised 2.91 °C. Thirdly, 3) the cloud fraction can enhance or depress the effects of carbon dioxide, depending on whether the cloud fraction is decreased or increased and 4) that the ocean's mixed-layer does not alter a CO_2-induced climate, unless the depth is sufficient to store a large amount of heat created by an increase in temperature. These are the general conclusions from the set of simulations performed for this research.

B. RCM RESEARCH SUMMARY

The results summarized in tables 7 and 8, indicate that many researchers are obtaining surface temperature results within the same range. The data concerning the $1/2xCO_2$ scenario fall within a range of 1.25 and 2.28 °C, for a decrease in temperature. In terms of the $2xCO_2$ experiments, the range of values is slightly larger. There is a minimum of 0.69 and a maximum temperature increase of 3.5 °C. This is a wide range, but the results are all obtained using different radiative convective models (RCM) with variations in the amount of atmospheric processes involved.

C. RELIABILITY OF THE MODEL

The reliability of the test model was only investigated based on two of the four experiments. This was the result of a lack of concrete research in the areas concerned with the influences of other parameters in affecting changes within a CO_2-induced atmosphere. However, the reliability was still assessed, and the basic conclusion is that the model is accurate in its ability to simulate increases in carbon dioxide in the atmosphere. In contrast, it tends to simulate decreases in CO_2 within the atmosphere with less accuracy. The surface temperature results fall within the range defined by selected RCM's examined for increases in CO_2. Unfortunately, the value for the $1/2xCO_2$ experiment was slighty larger than the maximum range value for decreases in surface temperature. Therefore, the general assessment is that Burt's model is quite reliable in simulating increases in CO_2 , and this is important because this is the direction of continuing research in climatic modelling.

D. GENERAL ASSESSMENT OF THE STUDY

This research was able to cleary fulfill its first goal. That being, to provide a better understanding of the processes involved in energy balance models (EBM). However, in order to truly complete the second aim, it is necessary to further research the importance of other parameters in affecting a CO_2-induced atmosphere. When this is done, only then can a true assessment of reliability be performed on any type of climatic model, and not just the simpler energy based types. Thus, Burt's model does provide a method of simulating responses to climatic changes due to increase in carbon dioxide with a reasonable amount of accuracy.

APPENDIX A

NOTATION FOR ALL EQUATIONS

NOTATION FOR ALL EQUATIONS

dT/dt	Rate of change of temperature ($^\circ C yr^{-1}$)
S	Absorbed solar radiation (Wm^{-2})
S_c	Absorbed solar radiation by cloudy portion (Wm^{-2})
S_o	Absorbed solar radiation by clear portion (Wm^{-2})
F	Emitted longwave radiation (Wm^{-2})
F_c	Emitted longwave radiation by cloudy portion (Wm^{-2})
F_o	Emitted longwave radiation by clear portion (Wm^{-2})
n	Cloud fraction
n^*	Normal cloud amount
n'	Cloudiness produced by temperature change
n_T	Temperature-cloud feedback
T	Current temperature ($^\circ C$)
T^*	Equilibrium temperature ($^\circ C$)
a_c	Cloud sky fraction albedo
a_c^*	Normal cloud sky fraction albedo
a_c'	Temperature-induced albedo factor for cloudy sky
a_o	Clear sky fraction albedo
a_o^*	Normal clear sky fraction albedo
a_o'	Temperature-induced albedo factor for clear sky
a_T	Temperature-albedo feedback
e_c	Longwave absoption above the clouds
e_o	Longwave absorption of clear atmosphere
f_c	Cloud emisssion of longwave radiation (Wm^{-2})
f_o	Clear atmosphere emission of longwave (Wm^{-2})
F_s	Surface emission (Wm^{-2})
h	Depth of ocean's mixed-layer (m)
s	Solar constant (Wm^{-2})
RCO_2	Carbon dioxide concentration factor

APPENDIX B

MODEL DESIGN AND SIMULATION DATA

LIST OF TABLES

YEAR	T1	T2	T3
0.00	15.00	15.00	15.00
2.00	15.16	14.67	13.93
4.00	15.26	14.48	13.32
6.00	15.31	14.37	12.97
8.00	15.34	14.31	12.77
10.00	15.36	14.27	12.65
12.00	15.37	14.25	12.59
14.00	15.37	14.24	12.55
16.00	15.38	14.23	12.52
18.00	15.38	14.23	12.51
20.00	15.38	14.23	12.50
22.00	15.38	14.23	12.50
24.00	15.38	14.23	12.50
26.00	15.38	14.23	12.50
28.00	15.38	14.23	12.50
30.00	15.38	14.23	12.50
32.00	15.38	14.23	12.49
34.00	15.38	14.23	12.49
36.00	15.38	14.23	12.49
38.00	15.38	14.23	12.49
40.00	15.38	14.23	12.49
42.00	15.38	14.23	12.49
44.00	15.38	14.23	12.49
46.00	15.38	14.23	12.49
48.00	15.38	14.23	12.49
50.00	15.38	14.23	12.49

TABLE 1. Temperatures resulting from decreases in carbon dioxide concentrations for a 50 year equilibrium period. Concentrations are 320 ppm(T1), 240 ppm(T2) and 160 ppm(T3) carbon cioxide.

YEAR	C1	C2	C3	C4	C5	C6
0.00	15.00	15.00	15.00	15.00	15.00	15.00
2.00	15.16	15.26	15.36	15.44	15.53	15.60
4.00	15.26	15.41	15.56	15.70	15.83	15.95
6.00	15.31	15.50	15.68	15.85	16.00	16.15
8.00	15.34	15.55	15.75	15.93	16.10	16.27
10.00	15.36	15.58	15.79	15.98	16.16	16.33
12.00	15.37	15.60	15.81	16.01	16.19	16.37
14.00	15.37	15.61	15.82	16.02	16.21	16.39
16.00	15.38	15.61	15.83	16.03	16.22	16.40
18.00	15.38	15.61	15.83	16.04	16.23	16.41
20.00	15.38	15.62	15.84	16.04	16.23	16.41
22.00	15.38	15.62	15.84	16.04	16.24	16.42
24.00	15.38	15.62	15.84	16.04	16.24	16.42
26.00	15.38	15.62	15.84	16.04	16.24	16.42
28.00	15.38	15.62	15.84	16.04	16.24	16.42
30.00	15.38	15.62	15.84	16.04	16.24	16.42
32.00	15.38	15.62	15.84	16.04	16.24	16.42
34.00	15.38	15.62	15.84	16.04	16.24	16.42
36.00	15.38	15.62	15.84	16.04	16.24	16.42
38.00	15.38	15.62	15.84	16.04	16.24	16.42
40.00	15.38	15.62	15.84	16.04	16.24	16.42
42.00	15.38	15.62	15.84	16.04	16.24	16.42
44.00	15.38	15.62	15.84	16.04	16.24	16.42
46.00	15.38	15.62	15.84	16.04	16.24	16.42
48.00	15.38	15.62	15.84	16.04	16.24	16.42
50.00	15.38	15.62	15.84	16.04	16.24	16.42

TABLE 2a. Temperatures resulting from increases in carbon dioxide concentrations for a 50 year equilibrium period. Concentrations range from 320 ppm (C1) to 420 ppm(C6) with an interval of 20 ppm carbon dioxide.

x

YEAR	C7	C8	C9	C10	C11	C12
0.00	15.00	15.00	15.00	15.00	15.00	15.00
2.00	15.68	15.74	15.81	15.87	15.93	15.99
4.00	16.07	16.17	16.28	16.38	16.47	16.56
6.00	16.29	16.42	16.55	16.67	16.78	16.89
8.00	16.42	16.56	16.70	16.83	16.96	17.08
10.00	16.49	16.65	16.79	16.93	17.06	17.18
12.00	16.54	16.69	16.84	16.98	17.12	17.25
14.00	16.56	16.72	16.87	17.01	17.15	17.28
16.00	16.57	16.73	16.89	17.03	17.17	17.30
18.00	16.58	16.74	16.90	17.04	17.18	17.31
20.00	16.59	16.75	16.90	17.05	17.19	17.32
22.00	16.59	16.75	16.90	17.05	17.19	17.32
24.00	16.59	16.75	16.91	17.05	17.19	17.32
26.00	16.59	16.75	16.91	17.05	17.19	17.32
28.00	16.59	16.75	16.91	17.05	17.19	17.32
30.00	16.59	16.75	16.91	17.05	17.19	17.32
32.00	16.59	16.75	16.91	17.05	17.19	17.32
34.00	16.59	16.75	16.91	17.05	17.19	17.32
36.00	16.59	16.75	16.91	17.05	17.19	17.32
38.00	16.59	16.75	16.91	17.05	17.19	17.32
40.00	16.59	16.75	16.91	17.05	17.19	17.32
42.00	16.59	16.75	16.91	17.05	17.19	17.32
44.00	16.59	16.75	16.91	17.05	17.19	17.32
46.00	16.59	16.75	16.91	17.05	17.19	17.32
48.00	16.59	16.75	16.91	17.05	17.19	17.32
50.00	16.59	16.75	16.91	17.05	17.19	17.32

TABLE 2b. Temperatures resulting from increases in carbon dioxide concentrations for a 50 year equilibrium period. Concentrations range from 440 ppm (C7) to 540 ppm(C12) with an interval of 20 ppm carbon dioxide.

YEAR	C13	C14	C15	C16	C17
0.00	15.00	15.00	15.00	15.00	15.00
2.00	16.04	16.09	16.14	16.19	16.23
4.00	16.64	16.72	16.80	16.88	16.95
6.00	16.99	17.09	17.18	17.27	17.36
8.00	17.19	17.30	17.40	17.50	17.60
10.00	17.30	17.42	17.53	17.63	17.73
12.00	17.37	17.49	17.60	17.71	17.81
14.00	17.41	17.52	17.64	17.75	17.85
16.00	17.43	17.55	17.66	17.77	17.88
18.00	17.44	17.56	17.68	17.79	17.89
20.00	17.45	17.57	17.68	17.80	17.90
22.00	17.45	17.57	17.69	17.80	17.91
24.00	17.45	17.57	17.69	17.80	17.91
26.00	17.45	17.58	17.69	17.80	17.91
28.00	17.45	17.58	17.69	17.80	17.91
30.00	17.45	17.58	17.69	17.80	17.91
32.00	17.45	17.58	17.69	17.81	17.91
34.00	17.45	17.58	17.69	17.81	17.91
36.00	17.45	17.58	17.69	17.81	17.91
38.00	17.45	17.58	17.69	17.81	17.91
40.00	17.45	17.58	17.69	17.81	17.91
42.00	17.45	17.58	17.69	17.81	17.91
44.00	17.45	17.58	17.69	17.81	17.91
46.00	17.45	17.58	17.69	17.81	17.91
48.00	17.45	17.58	17.69	17.81	17.91
50.00	17.45	17.58	17.69	17.81	17.91

TABLE 2c. Temperatures resulting from increases in carbon dioxide concentrations for a 50 year equilibrium period. Concentrations range from 560 ppm (C13) to 640 ppm(C17) with an interval of 20 ppm carbon dioxide.

YEAR	CF1	CF2	CF3	CF4	CF5	CF6
0.00	15.00	15.00	15.00	15.00	15.00	15.00
2.00	16.17	16.45	16.68	16.88	17.05	17.24
4.00	16.83	17.28	17.65	17.96	18.23	18.53
6.00	17.21	17.75	18.19	18.57	18.23	19.27
8.00	17.42	18.01	18.50	18.91	18.89	19.68
10.00	17.54	18.16	18.67	19.10	19.27	19.91
12.00	17.61	18.24	18.77	19.21	19.48	20.04
14.00	17.64	18.29	18.82	19.27	19.60	20.11
16.00	17.67	18.31	18.85	19.31	19.66	20.15
18.00	17.68	18.33	18.87	19.33	19.70	20.17
20.00	17.68	18.34	18.88	19.34	19.72	20.18
22.00	17.69	18.34	18.89	19.34	19.73	20.19
24.00	17.69	18.34	18.89	19.35	19.74	20.20
26.00	17.69	18.35	18.89	19.35	19.74	20.20
28.00	17.69	18.35	18.89	19.35	19.74	20.20
30.00	17.69	18.35	18.89	19.35	19.74	20.20
32.00	17.69	18.35	18.89	19.35	19.75	20.20
34.00	17.69	18.35	18.89	19.35	19.75	20.20
36.00	17.69	18.35	18.89	19.35	19.75	20.20
38.00	17.69	18.35	18.89	19.35	19.75	20.20
40.00	17.69	18.35	18.89	19.35	19.75	20.20
42.00	17.69	18.35	18.89	19.35	19.75	20.20
44.00	17.69	18.35	18.89	19.35	19.75	20.20
46.00	17.69	18.35	18.89	19.35	19.75	20.20
48.00	17.69	18.35	18.89	19.35	19.75	20.20
50.00	17.69	18.35	18.89	19.35	19.75	20.20

TABLE 3. Temperatures resulting from increases in carbon dioxide for a fixed cloud fraction of 0.49. Concentrations increase from a value of 320 ppm(CF1) to 640 ppm(CF6) with an interval of 60 ppm, except between 560 and 640 ppm CO^2.

YEAR	CF7	CF8	CF9	CF10	CF11	CF12
0.00	15.00	15.00	15.00	15.00	15.00	15.00
2.00	15.16	15.44	15.68	15.87	16.04	16.23
4.00	15.26	15.70	16.07	16.38	16.64	16.95
6.00	15.31	15.85	16.29	16.67	16.99	17.36
8.00	15.34	15.93	16.42	16.83	17.19	17.60
10.00	15.36	15.98	16.49	16.93	17.30	17.73
12.00	15.37	16.01	16.54	16.98	17.37	17.81
14.00	15.37	16.02	16.56	17.01	17.41	17.85
16.00	15.38	16.03	16.57	17.03	17.43	17.88
18.00	15.38	16.04	16.58	17.04	17.44	17.89
20.00	15.38	16.04	16.59	17.05	17.45	17.90
22.00	15.38	16.04	16.59	17.05	17.45	17.91
24.00	15.38	16.04	16.59	17.05	17.45	17.91
26.00	15.38	16.04	16.59	17.05	17.45	17.91
28.00	15.38	16.04	16.59	17.05	17.45	17.91
30.00	15.38	16.04	16.59	17.05	17.45	17.91
32.00	15.38	16.04	16.59	17.05	17.45	17.91
34.00	15.38	16.04	16.59	17.05	17.45	17.91
36.00	15.38	16.04	16.59	17.05	17.45	17.91
38.00	15.38	16.04	16.59	17.05	17.45	17.91
40.00	15.38	16.04	16.59	17.05	17.45	17.91
42.00	15.38	16.04	16.59	17.05	17.45	17.91
44.00	15.38	16.04	16.59	17.05	17.45	17.91
46.00	15.38	16.04	16.59	17.05	17.45	17.91
48.00	15.38	16.04	16.59	17.05	17.45	17.91
50.00	15.38	16.04	16.59	17.05	17.45	17.91

TABLE 4. Temperatures resulting from increases in carbon dioxide for a fixed cloud fraction of 0.54. Concentrations increase from a value of 320 ppm(CF7) to 640 ppm(CF12) with an interval of 60 ppm, except between 560 and 640 ppm CO^2.

YEAR	CF13	CF14	CF15	CF16	CF17	CF18
0.00	15.00	15.00	15.00	15.00	15.00	15.00
2.00	14.15	14.43	14.66	14.86	15.03	15.22
4.00	13.66	14.10	14.47	14.77	15.04	15.34
6.00	13.37	13.91	14.35	14.73	15.05	15.42
8.00	13.21	13.80	14.28	14.70	15.05	15.46
10.00	13.11	13.73	14.25	14.68	15.06	15.49
12.00	13.05	13.69	14.22	14.67	15.06	15.50
14.00	13.02	13.67	14.21	14.67	15.06	15.51
16.00	13.00	13.66	14.20	14.66	15.06	15.52
18.00	12.98	13.65	14.20	14.66	15.06	15.52
20.00	12.98	13.64	14.19	14.66	15.06	15.52
22.00	12.97	13.64	14.19	14.66	15.06	15.52
24.00	12.97	13.64	14.19	14.66	15.06	15.52
26.00	12.97	13.64	14.19	14.66	15.06	15.52
28.00	12.97	13.64	14.19	14.66	15.06	15.52
30.00	12.97	13.64	14.19	14.66	15.06	15.52
32.00	12.97	13.64	14.19	14.66	15.06	15.52
34.00	12.97	13.64	14.19	14.66	15.06	15.52
36.00	12.97	13.64	14.19	14.66	15.06	15.52
38.00	12.97	13.64	14.19	14.66	15.06	15.52
40.00	12.97	13.64	14.19	14.66	15.06	15.52
42.00	12.97	13.64	14.19	14.66	15.06	15.52
44.00	12.97	13.64	14.19	14.66	15.06	15.52
46.00	12.97	13.64	14.19	14.66	15.06	15.52
48.00	12.97	13.64	14.19	14.66	15.06	15.52
50.00	12.97	13.64	14.19	14.66	15.06	15.52

TABLE 5. Temperatures resulting from increases in carbon dioxide for a fixed cloud fraction of 0.59. Concentrations increase from a value of 320 ppm(CF13) to 640 ppm(CF18) with an interval of 60 ppm, except between 560 and 640 ppm CO^2.

YEAR	ML1	ML2	ML3	ML4	ML5	ML6
0.00	15.00	15.00	15.00	15.00	15.00	15.00
2.00	15.16	16.23	15.11	15.82	15.06	15.49
4.00	15.26	16.95	15.19	16.41	15.12	15.89
6.00	15.31	17.36	15.24	16.84	15.16	16.23
8.00	15.34	17.60	15.28	17.14	15.20	16.52
10.00	15.36	17.73	15.31	17.36	15.23	16.75
12.00	15.37	17.81	15.33	17.52	15.26	16.95
14.00	15.37	17.85	15.35	17.63	15.28	17.11
16.00	15.38	17.88	15.36	17.71	15.30	17.25
18.00	15.38	17.89	15.36	17.77	15.31	17.36
20.00	15.38	17.90	15.37	17.81	15.32	17.45
22.00	15.38	17.91	15.37	17.84	15.33	17.53
24.00	15.38	17.91	15.38	17.86	15.34	17.60
26.00	15.38	17.91	15.38	17.88	15.35	17.65
28.00	15.38	17.91	15.38	17.89	15.35	17.70
30.00	15.38	17.91	15.38	17.89	15.36	17.73
32.00	15.38	17.91	15.38	17.89	15.36	17.76
34.00	15.38	17.91	15.38	17.89	15.37	17.79
36.00	15.38	17.91	15.38	17.89	15.37	17.81
38.00	15.38	17.91	15.38	17.89	15.37	17.83
40.00	15.38	17.91	15.38	17.89	15.37	17.84
42.00	15.38	17.91	15.38	17.89	15.37	17.85
44.00	15.38	17.91	15.38	17.89	15.38	17.86
46.00	15.38	17.91	15.38	17.89	15.38	17.87
48.00	15.38	17.91	15.38	17.89	15.38	17.88
50.00	15.38	17.91	15.38	17.89	15.38	17.89

TABLE 6 a. Temperatures resulting from increases in carbon dioxide for the equivalent mixed ocean depths of 75m(ML1 and ML2) to 175m(ML5 nad ML6). The depth of the mixed layer increases with an interval of 50m, while the CO^2 concentrations are set at 320 ppm and 640 ppm for each depth.

YEAR	ML7	ML8	ML9	ML10
0.00	15.00	15.00	15.00	15.00
2.00	15.08	15.61	15.05	15.40
4.00	15.14	16.09	15.10	15.75
6.00	15.20	16.48	15.14	16.06
8.00	15.23	16.78	15.17	16.32
10.00	15.27	17.02	15.20	16.54
12.00	15.29	17.21	15.23	16.73
14.00	15.31	17.36	15.25	16.90
16.00	15.33	17.48	15.27	17.04
18.00	15.34	17.57	15.28	17.16
20.00	15.35	17.64	15.30	17.27
22.00	15.35	17.70	15.31	17.36
24.00	15.36	17.75	15.32	17.44
26.00	15.37	17.78	15.33	17.51
28.00	15.37	17.81	15.34	17.56
30.00	15.37	17.83	15.34	17.61
32.00	15.37	17.85	15.35	17.66
34.00	15.38	17.86	15.35	17.69
36.00	15.38	17.87	15.36	17.72
38.00	15.38	17.88	15.36	17.75
40.00	15.38	17.89	15.36	17.77
42.00	15.38	17.89	15.37	17.79
44.00	15.38	17.90	15.37	17.81
46.00	15.38	17.90	15.37	17.82
48.00	15.38	17.90	15.37	17.84
50.00	15.38	17.91	15.37	17.85

TABLE 6b. Temperatures resulting from increases in carbon dioxide for the equivalent mixed ocean cepths of 225m(ML7 and ML8) to 275m(ML9 nad ML10). The depth of the mixed layer increases with an interval of 50m, while the CO^2 concentrations are set at 320 ppm and 640 ppm for each depth.

APPENDIX C

SIMULATION TEMPERATURE PROFILES

LIST OF FIGURES

```
The setup is now as follows:
parameter              parameter                           current     standard    percent
  number                 name                                value       value        diff
      1    solar parameter (w/sq m)                      1360.0000   1360.0000        0.0
      2    co2 concentration (ppm)                        320.0000    320.0000        0.0
      3    cloud fraction                                   0.5400      0.5400        0.0
      4    cloud albedo                                     0.4300      0.4300        0.0
      5    clear albedo                                     0.1500      0.1500        0.0
      6    t-albedo feedback (per deg)                     -0.0040     -0.0040        0.0
      7    cloud emission factor                            0.8000      0.8000        0.0
      8    above-cloud ir absorbtivity                      0.2500      0.2500        0.0
      9    clear emission factor                            0.3100      0.3100        0.0
     10    clear sky ir absorption                          0.7000      0.7000        0.0
     11    equiv. mixed ocean depth (m)                    75.0000     75.0000        0.0
     12    co2 ir effect                                    1.0000      1.0000        0.0
     13    t-cloud feedback (per deg)                       0.0000      0.0000        0.0

Enter the parameter number you want to change followed by its new value
(0,0 for no change)    >
Your response:          0     0.0000

Enter:    0-run    1-new temp    2-new parms    3-time step    4-exit   >
Your response:     4
```

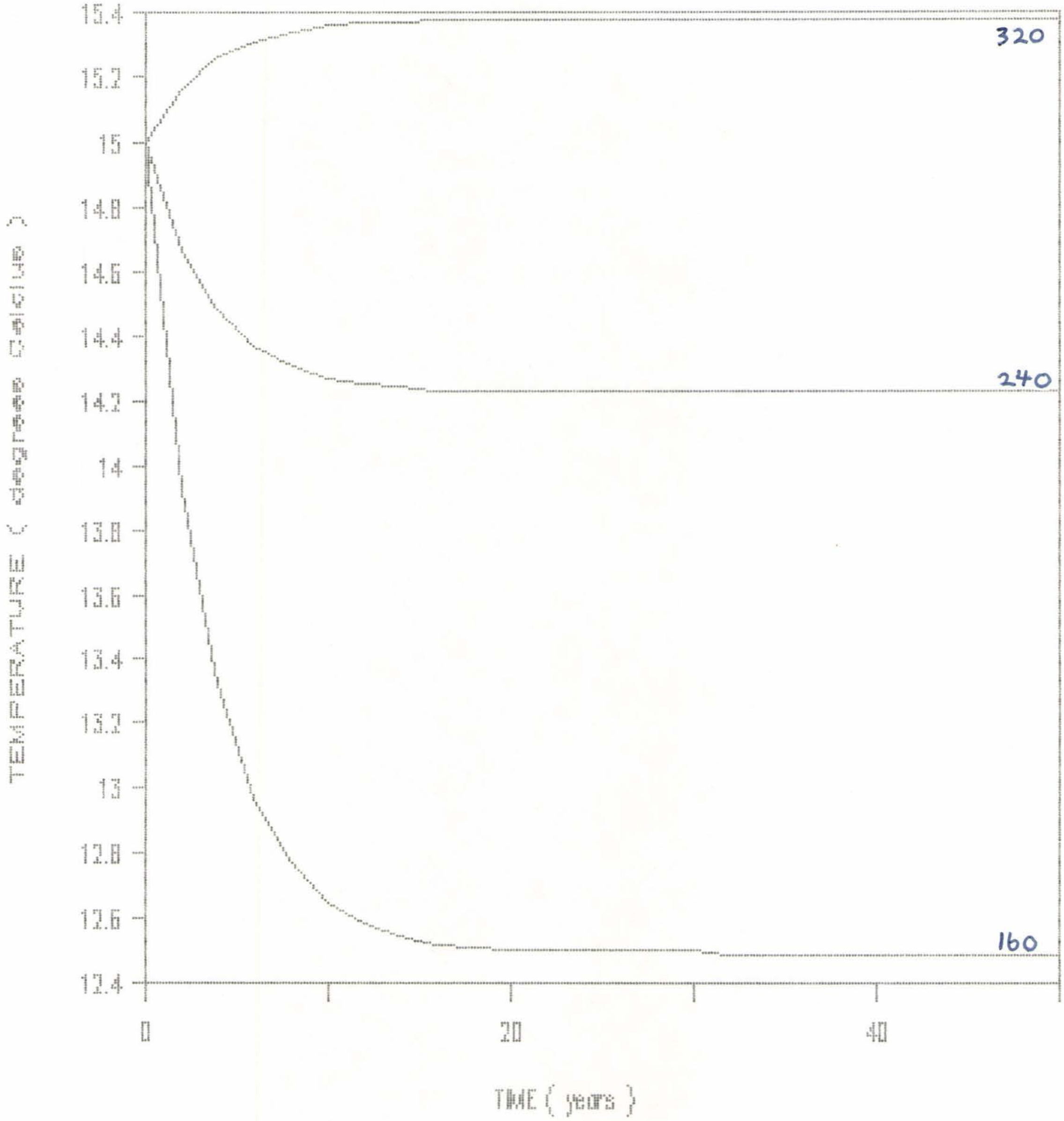
FIGURE 1. Table of model parameters listed on the screen.

```
Global Energy Balance Climate Model
Copyright (C) James E. Burt, 1984

The temperature is 0.0 degrees Celsius,
and all parameters are at their standard values.

Enter:    0-run    1-new temp    2-new parms    3-time step    4-exit   >
Your response:     0

                        dT/dt    s clr    s cld    ir clr   ir cld    total    total
  year        temp     deg/yr   w/sq m   w/sq m    w/sq m   w/sq m    cloud   albedo
   0.0        0.00      3.714    123.3     93.4      88.6    102.3    0.540    0.363
  10.0       14.29      0.300    132.3    103.9     108.6    125.4    0.540    0.306
  20.0       15.31      0.019    132.9    104.6     110.2    127.2    0.540    0.301
  30.0       15.38      0.001    132.9    104.6     110.3    127.3    0.540    0.301
  40.0       15.38      0.000    132.9    104.7     110.3    127.3    0.540    0.301
  50.0       15.38      0.000    132.9    104.7     110.3    127.3    0.540    0.301

Enter:    0-run    1-new temp    2-new parms    3-time step    4-exit   >
Your response:     2
```

FIGURE 2. Example of screen output for temperature results.

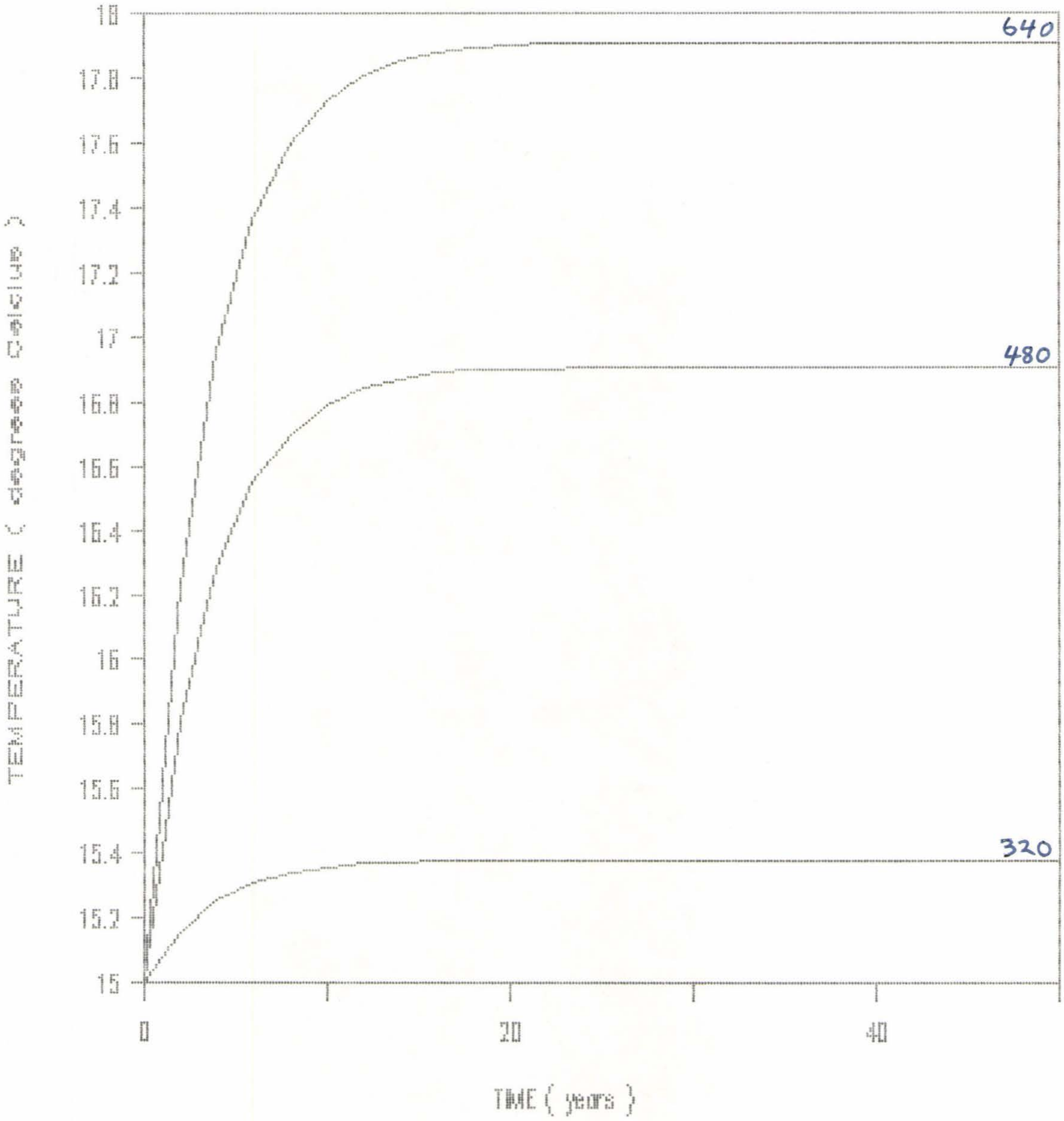
CARBON DIOXIDE CONCENTRATIONS

figure 3.



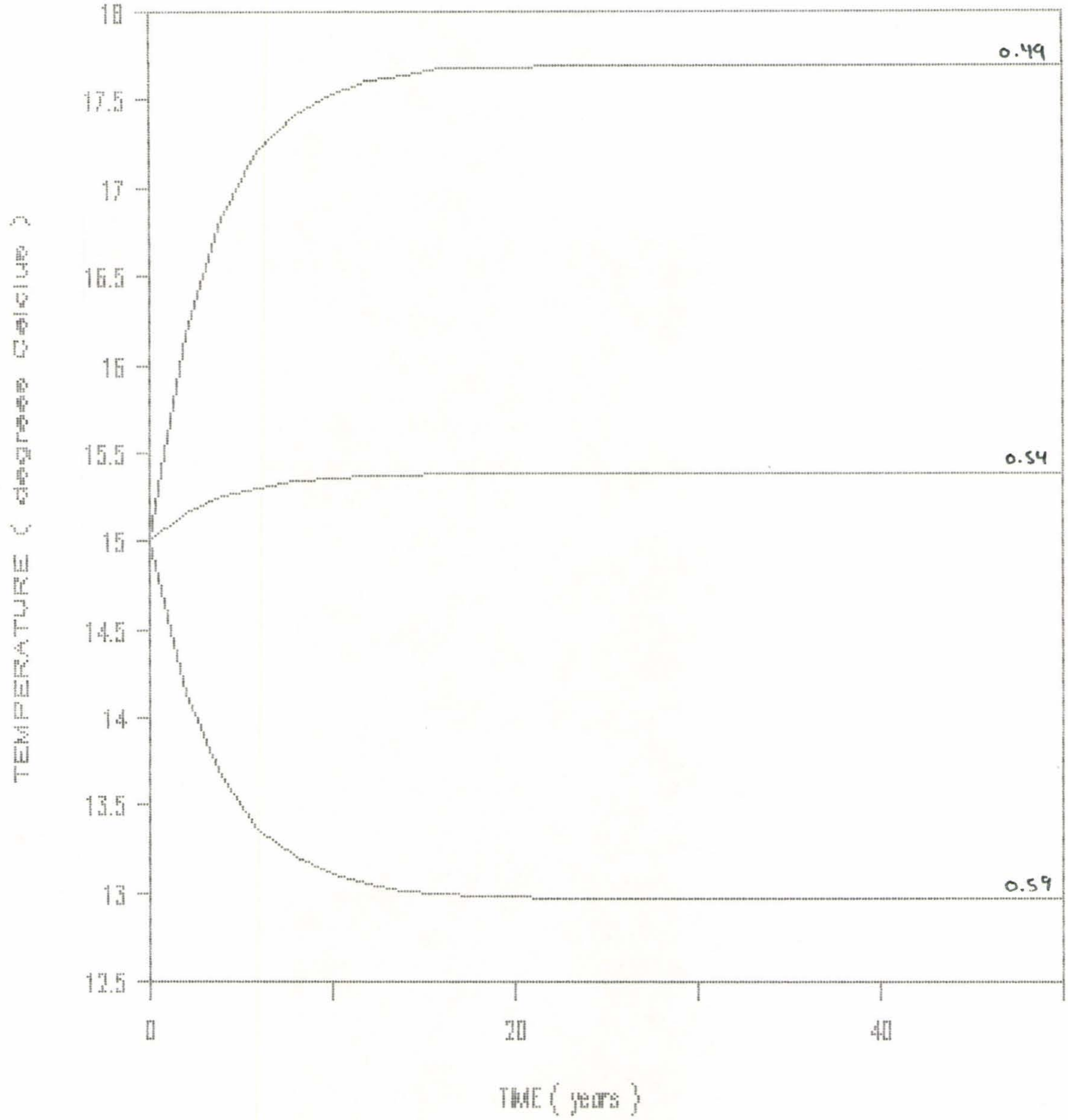
CARBON DIOXIDE CONCENTRATIONS

figure 4.



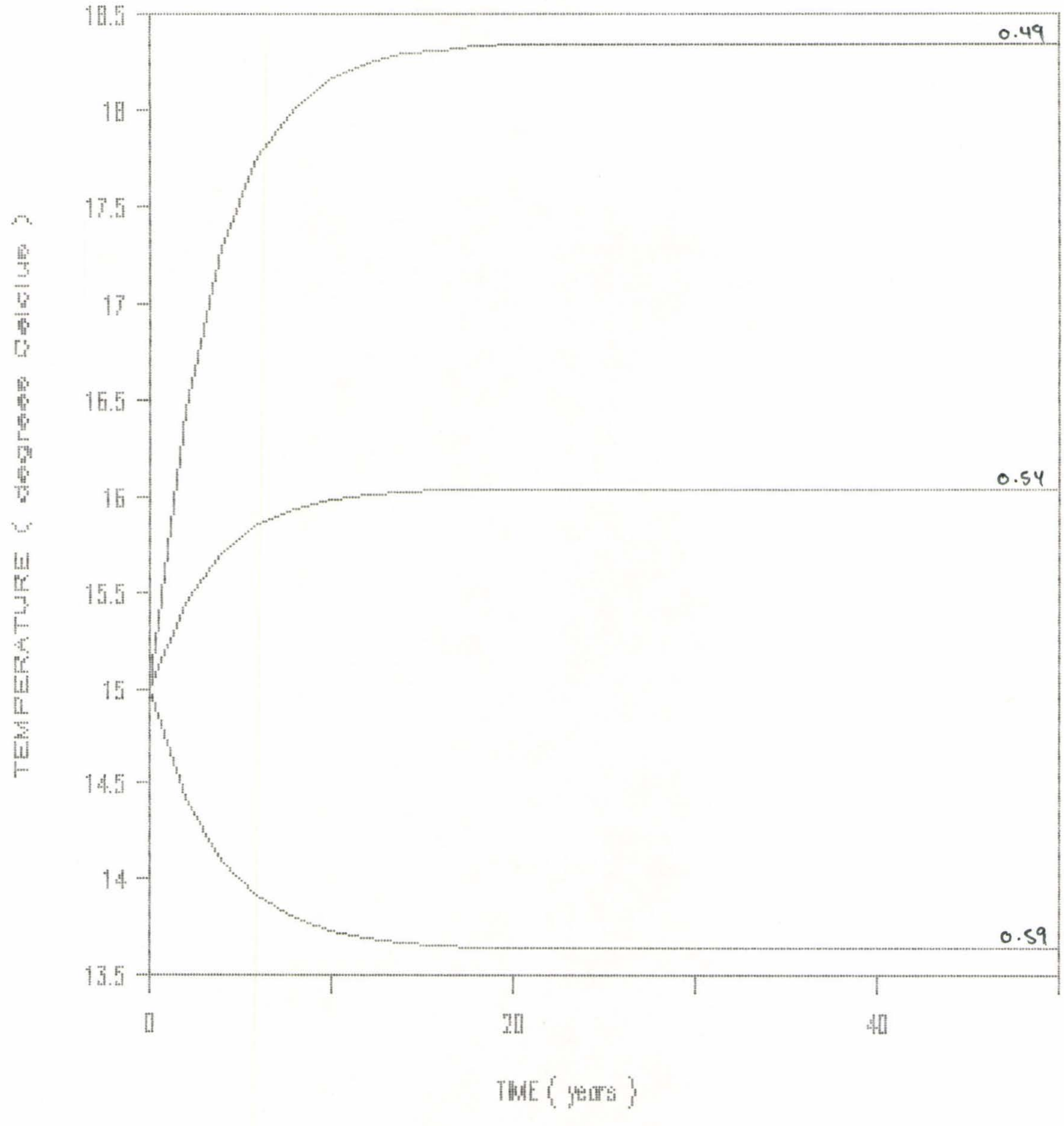
INCREASING CLOUD FRACTIONS

figure 5.



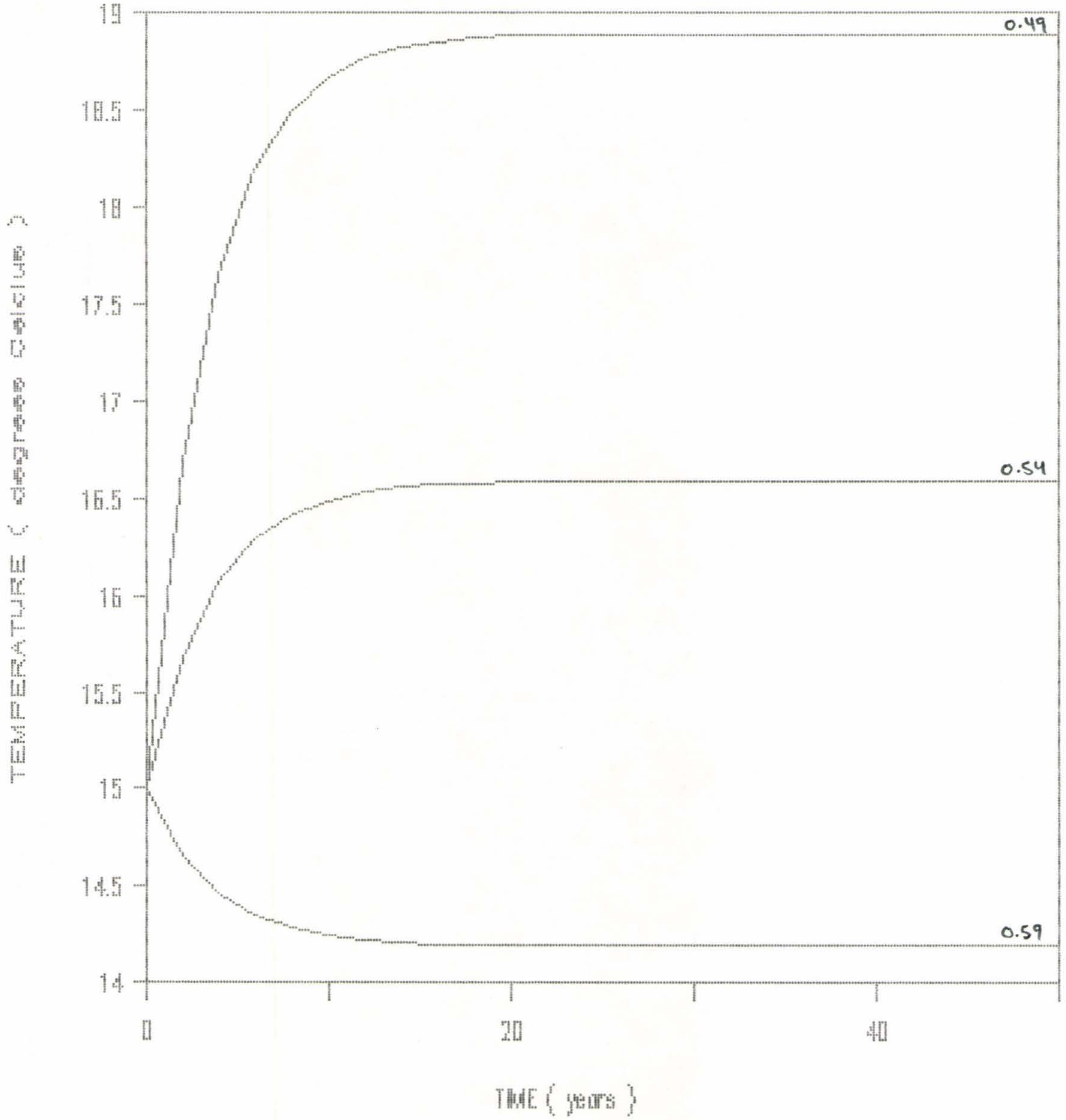
INCREASING CLOUD FRACTIONS

figure 6.



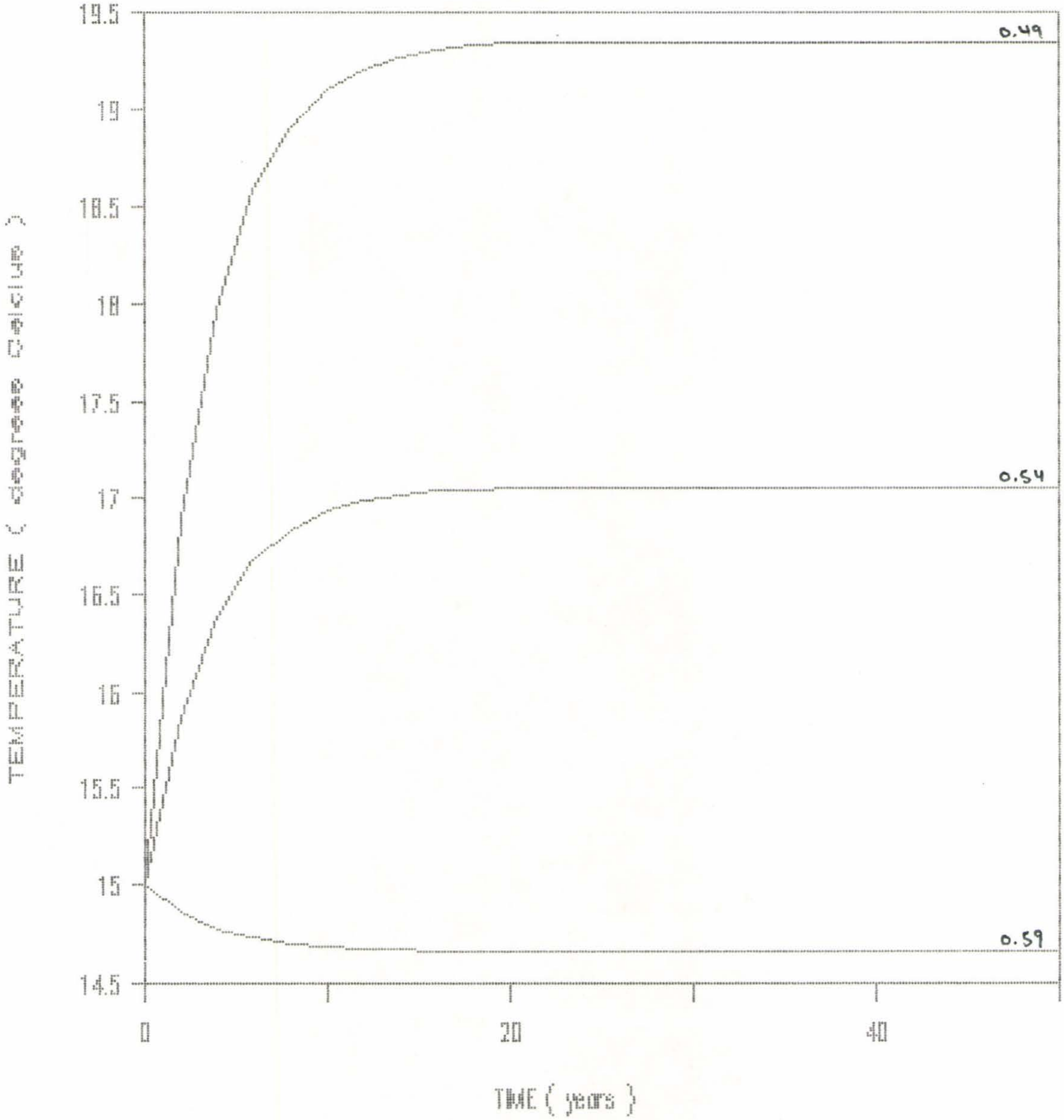
INCREASING CLOUD FRACTIONS

figure 7.



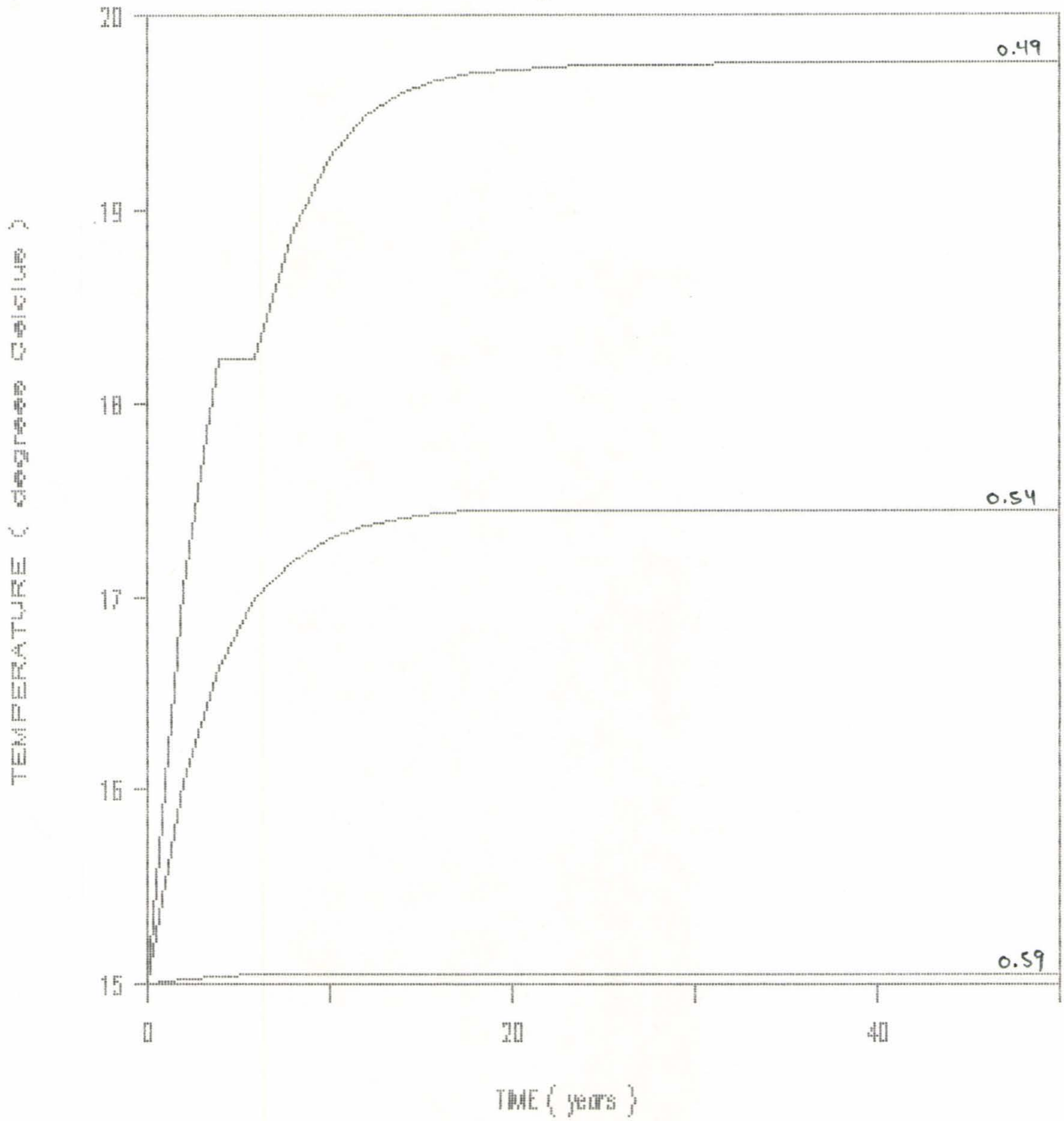
INCREASING CLOUD FRACTIONS

figure 8.



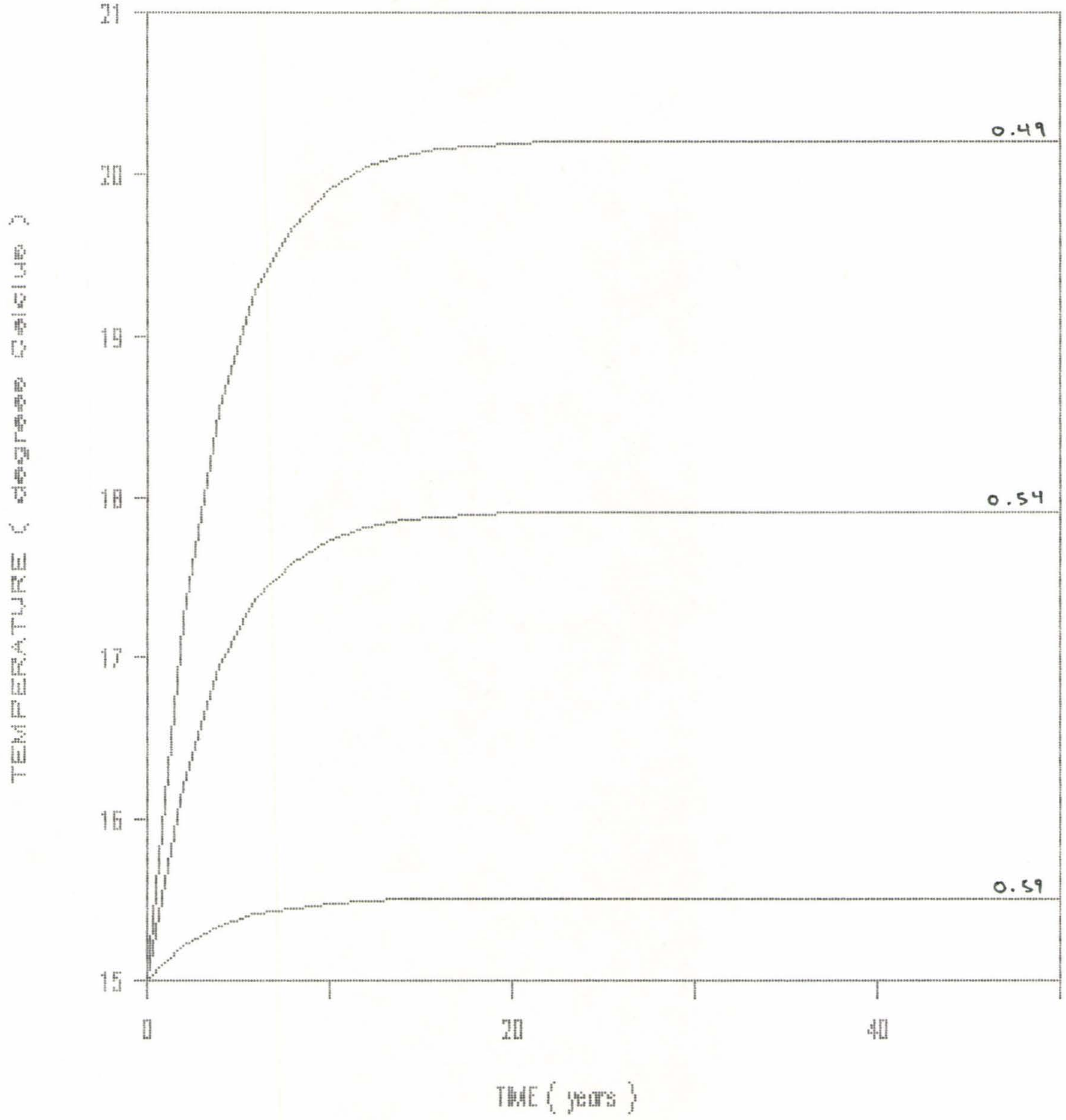
INCREASING CLOUD FRACTIONS

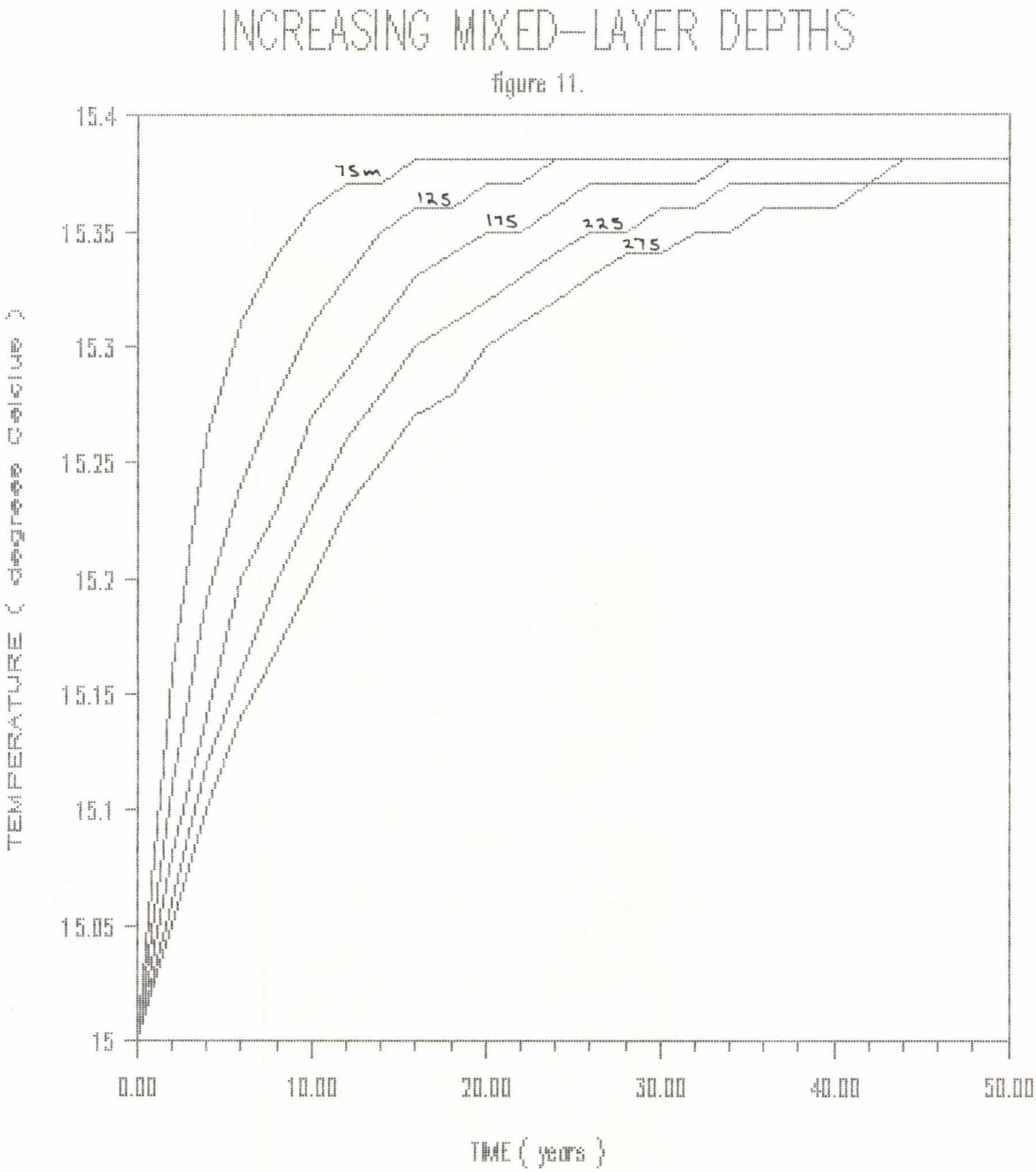
figure 9.

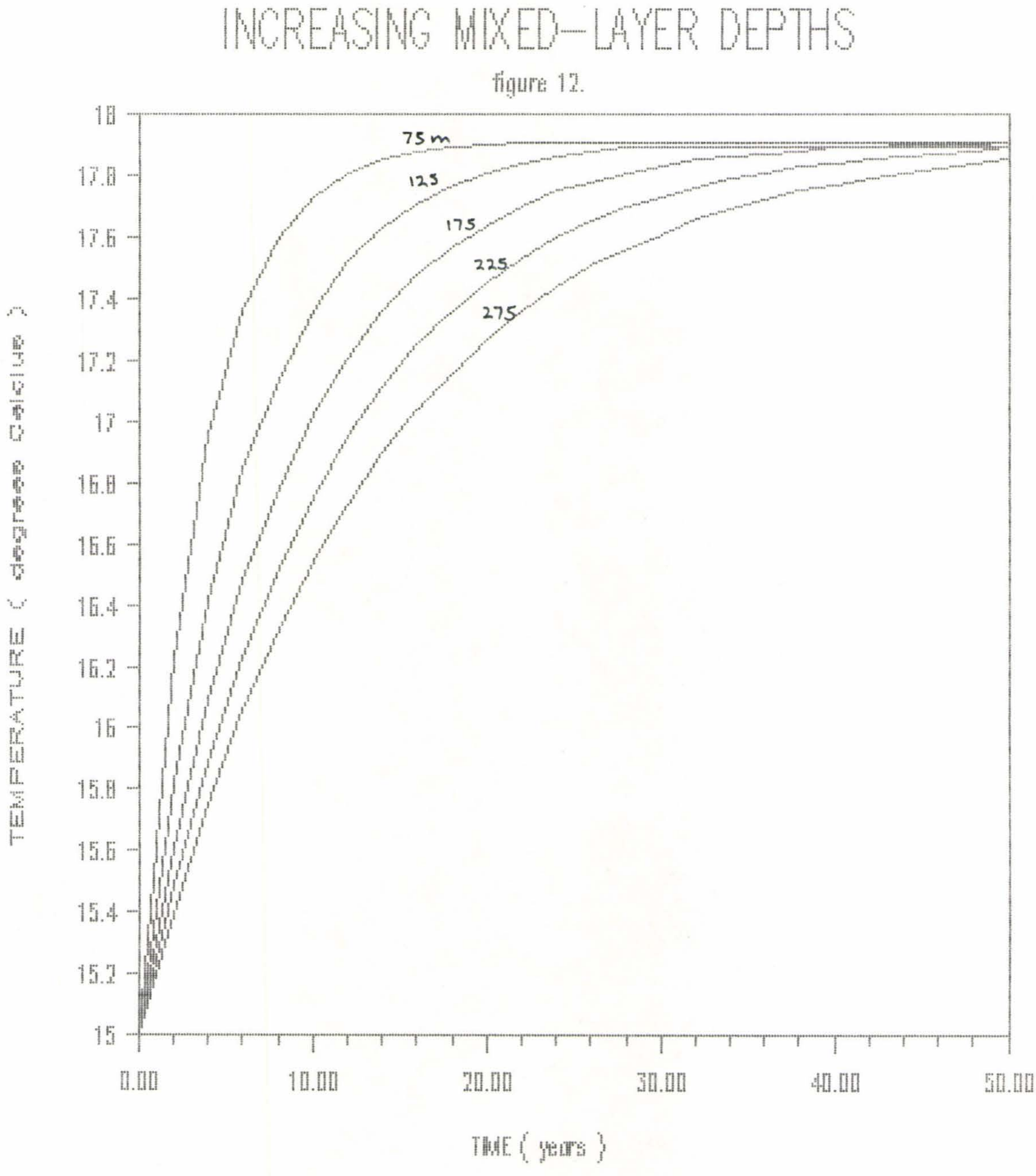


INCREASING CLOUD FRACTIONS

figure 10.




INCREASING MIXED-LAYER DEPTHS
figure 11.
15.4
15.35
15.3
15.25
15.2
15.15
15.1
15.05
15
TEMPERATURE (degrees Celcius)
75m
125
175
225
275
0.00
10.00
20.00
30.00
40.00
50.00
TIME (years)


INCREASING MIXED-LAYER DEPTHS
figure 12.
TEMPERATURE (degrees Celsius)
TIME (years)
18
17.8
17.6
17.4
17.2
17
16.8
16.6
16.4
16.2
16
15.8
15.6
15.4
15.2
15
0.00
10.00
20.00
30.00
40.00
50.00
75 m
125
175
225
275

APPENDIX D

RADIATIVE CONVECTIVE MODEL DATA

LIST OF TABLES

TABLE 7. Temperature results for the 1/2xCO_2 atmospheric scenario from selected Radiative Convective Models. (negative values indicate decreases)

STUDY	ΔT_s (°C)
Manabe and Wetherald (1967) Fixed absolute humidity	−1.25
Manabe and Wetherald (1967) Fixed relative humidity	−2.28
Sellers (1974) Fixed relative humidity	−1.64

TABLE 8. Temperature results for the 2xCO_2 atmospheric scenario from selected Radiative Convective Models.

STUDY	ΔT_s (°C)
Manabe and Wetherald (1967)	1.33−2.92
Manabe (1971)	1.9
Augustsson and Ramanathan (1977)	1.98−3.20
Hansen et al. (1981)	1.22−3.50
Hunt (1981)	0.69−1.82

REFERENCES

AUGUSTSSON, T. and V. RAMANATHAN 1977. ' A radiative convective model study of the CO^2 climate problem ', Journal of Atmospheric Science 34, 448-51

BURT, J.E. 1984. ' Notes on a simple climate model ' (unpublished).

CLARK, W.C. ed. 1982. Carbon Dioxide Review (New York: Oxford University Press) pp?

DICKINSON, R.E. 1982. ' Modelling climate changes due to carbon dioxide increases ' in W.C. Clark ed. Carbon Dioxide Review (New York: Oxford University Press) pp?

GAL-CHEN, T. and S.H. SCHNEIDER 1976. ' Energy balance climate modelling: Comparison of radiative and dynamic feedback mechanisms ', Tellus 28, 108-121

HANSEN, J.E., JOHNSON, D., LACIS, A., LEBEDEFF, S., LEE, P., RIND, D. and RUSSEL, G. 1981 'Climatic impact of increasing atmospheric carbon dioxide ', Science 213, 957-66

HUNT, B.G. 1981. ' An examination of some feedback mechanisms in the carbon dioxide climate problem ', Tellus 33, 78-88

LIAN, M.S. and R.D. CESS 1977. ' Energy balance climate models ', Journal of Atmospheric Science 34, 1058-62

MANABE, D. 1971. 'Estimates of future changes of climate due to increase of carbon dioxide concentration in the air ' in W.H. Mathews, W.W. Kellogg and Robinson, G.D. eds. Man's Impact on Climate. (Boston: MIT Press)256

MANABE, S. and R.T. WETHERALD 1967. ' Thermal equilibrium of the atmosphere with a given distribution of of relative humidity ', Journal of Atmospheric Science 24, 251-59

MANABE, S. and R.T. WETHERALD 1980. ' On the distribution of climate change resulting from an increase in CO^2 content of the atmosphere ', Journal of Atmospheric Science 37, 99-118

RAMANATHAN, V. and J.A. COAKLEY 1978. ' Climate modelling through radiative convective models ', Review of Geophysics and Space Physics 16, 465-489

SELLERS, W.D. ed. 1965. Physical Climatology (Chicago: University of Chicago Press)

SELLERS, W.D. 1969. ' A global climatic model based on the energy balance of the Earth-Atmosphere system ', Journal of Applied Meteorology 8, 392-400

SELLERS, W.D. 1974. ' A reassessment of the effect of CO^2 variations on a simple global climate model ', Journal of Applied Meteorology 13, 831-833

THOMPSON, S.L. and S.H. SCHNEIDER 1979. ' A seasonal zonal energy balance climate model with an interactive lower layer ', Journal of Geophysical Research 85, 2401-14

WATTS, R.G. 1980. ' Climate models and CO^" induced climate changes ', Climatic Change 2, 387-408