Climate Models and CO_2 Warming
A Selective Review and Summary

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CLIMATE MODELS AND CO_2 WARMING

A Selective Review and Summary

Prepared for the American Petroleum Institute

by

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CONTENTS

SUMMARY

This report is a selective summary and discussion of the types of models that have been applied to the prediction of the anthropogenic warming of the atmosphere. All of the quantitative predictions involve only the CO_2 effect although it is recognized that other trace gases may contribute from 50 to 100 percent additional warming. The types of models discussed are, from simple to complex: radiation balance, energy balance, radiative-convective, thermodynamic and general circulation models. The results given in the summary table below have been generated by the most physically complete versions of the models in each category. Additional results, discussed in the report, are omitted from this selection. It seems clear from the discussion herein that all models are still sufficiently unrealistic that a definitive evaluation of the problem requires continued effort.

Table 1.

Model Predictions of 2 × CO_2 Warming of Atmosphere

Model Type and Source	Mean Surface Effect	High-Latitude Effect
Radiation Balance		
Jason Group [2]	Globe: 3.0°C	
Energy Balance		
Jason Group [2]	Globe: 2.4°	7.5°C
Budyko [12]	Globe: 3.1°	9.0
Radiative-Convective		
Augustsson & Ramanathan [18]	Globe: 2°	
Hansen et al. [17]	Globe: 2.8°	
Hummel and Reck [39]	Globe: 2.1°	
Thermodynamic		
Adem (Preliminary)	Hem: 0.6°	2°
General Circulation Model		
Manabe & Stouffer [26]	Globe: 2°	7°
Hansen et al. [1]	Globe: 3.5°	7°

I. INTRODUCTION

In this report we summarize and discuss with some qualitative evaluation the types of models that have been applied to the prediction of the atmospheric warming consequent upon the increasing CO_2 content of the atmosphere. The examples selected in each of the climate model categories are those that have been developed to the highest state of the art in each category at this time. The report is organized so as to first explain the problem, including an explanation of what is meant by climate, followed by a qualitative summary of the types of models in order of increasing complexity. This is followed by a discussion of the key scientific problems involved, namely the quantitative evaluation of the increased "greenhouse effect". After this discussion a more detailed presentation of the appropriate climate models is given followed by an appraisal of each of the models and categories discussed.

Carbon dioxide is the most studied of the combustion gases since it plays an important role in the interaction between the sun's radiation and the atmosphere. The carbon dioxide concentration has increased steadily since the beginning of the industrial revolution from about 290 parts per million (ppm) to about 340 ppm today (1981). It is expected to double some time in the next century. Just when depends on the particular estimate of the level of increasing energy use per year and the mixture of carbon based fuels [1, 2]. None of these estimates includes the role of the oceans and the biosphere as sources or sinks of CO_2 since the mechanisms of their exchange with the atmosphere are too uncertain at this time. Climate modelers begin with the assumption that atmospheric CO_2 will double (with corresponding increases in other combustion gases) and try to predict what climate changes will occur.

They all predict some kind of increase in temperature within a global mean range of 4°C. The consensus is that high latitudes will be heated more than the equator and the land areas more than the oceans. Such a warming can have serious consequences for man's comfort and survival since patterns of aridity and rainfall can change, the height of the sea level can increase considerably and the world food supply can be affected. The detailed consequences of a CO_2 warming are not yet known. The conclusion is that optimum forecasting of climate changes is a necessity for any realistic long term planning by government and industry.

II. THE NATURE OF CLIMATE AND CLIMATE MODELS

An operational definition of 'climate' is that it is a time-mean state of the atmosphere [3]. Time means are averaged over a given period of time such as 30 days, a season, a year, etc. 'Climate changes' refer to changes of state of the atmosphere over intervals greater than the averaging time.

'Climate models' are mathematical descriptions of the earth-atmosphere system as it is driven by the radiation from the sun. The models range in complexity from a crude picture of the earth as a uniform rotating ball in radiation balance with the solar radiation to the complex general circulation models (GCM) that treat atmospheric dynamics by numerical solutions of fluid dynamical equations. Regardless of complexity, all climate model studies indicate that a doubling of CO_2 will produce a significant increase in the global and annual mean temperature of the earth. Climate model predictions range from 0.6°C to over 4°C, depending more on the physical assumptions than upon the complexity of the model. Several empirical studies [4, 5] give a lower estimate of about 0.26°C. There is sufficient uncertainty in the range of predictions to leave the consequences of the CO_2 doubling in considerable doubt. The difference between the low end of 0.26°C and the high end of ~4.°C has obvious consequences regarding the amount and speed of polar ice melting and the degree of sea level rise. Other uncertainties are the effect of the warming on: snow and sea-ice cover, the distributions of temperature, rainfall and aridity over the globe, the ocean circulation and oxygen budget, and the related world food supply [1, 6].

A summary of the models to be given further elaboration in Section III is given here for a quick overview of approaches to the CO_2 problem. These do not exhaust the different kinds of models used for climate studies but they are the principal tools, either singly or in combination, applied for predicting the outcome of a CO_2 doubling. (Schneider and Dickinson [3] give a thorough and readable survey of the many approaches to climate modeling that is still current.)

A. The Lowest Order: Radiation Balance Model

In this model the earth is treated as a uniformly rotating sphere with a homogeneous atmosphere in radiative equilibrium with the sun's energy flux. What this means is that the sun bathes the earth with radiation (that is primarily in the visible), that the earth absorbs some of that radiation and in the equilibrium state reradiates it back to space with a spectrum that is primarily in the infrared. All that is needed to compute the "effective radiation temperature" of the earth T_e is to give the known solar energy flux at the top of the atmosphere and that fraction of the solar flux absorbed by the earth-atmosphere system and radiated back as infrared radiation.

It turns out that the mean surface temperature of the earth T_s is about 30°K larger than T_e. This is accounted for by the "greenhouse gases" that absorb and trap thermal (infrared) energy in the atmosphere. Some atmospheric structure must be added to the originally simple picture to compute the absorption of the constituent gases and to maintain the mechanical stability of the lower troposphere. The model as amended is used to estimate a global warming due to the doubling of CO_2 when the remaining physics is unchanged.

B. Energy Balance Models (EBM)

These models add a latitude dependence by dealing with quantities such as surface temperature, heat capacity and albedo that are averaged over a complete latitude strip. One more term is needed to balance the energy equation in each strip. The new term represents horizontal heat transported out of the strip by fluid motions. In equilibrium, the energy balance for each strip would now read: (net transport out) + (infrared out) = (solar in). The transport term is usually parameterized as a diffusion operator (familiar from ordinary heat transfer theory).

Energy balance models have the added attraction that they can be used to estimate the latitude distribution of a CO_2 warming with its effects on the polar ice caps. As with the original radiation balance model, separate calculations with vertical structure in the atmosphere are required to give the infrared terms. The EBM diffusion equation itself, however, admits only a latitude dependence in the equilibrium case with the addition of a time dependence when seasonal and other time varying conditions are treated.

C. Radiative - Convective Models

Radiative-convective models are more complex versions of the radiation balance model described above. Physical parameters are treated as global averages with spatial variation only in the vertical direction. Mathematical computations are performed for convenience in a plane parallel configuration. The atmosphere is divided up into many uniform layers for numerical computation. For such models the principal equations to be solved are those of radiative transport with the convective part appearing as adjustments to the temperature structure to prevent the lower troposphere from becoming mechanically unstable. These models are applied principally to numerical experimentation in which atmospheric parameters can be varied one at a time to estimate the sensitivity of the atmosphere to change. These include experiments with radiative models of clouds, changes in distribution of particulate matter with height, the effects of CO_2 and other combustion gases, solar constant, volcanic dust, aerosols and atmospheric chemistry. Occasionally experiments are performed in which the physical parameters of a particular latitude strip are taken as the global mean values in order to get a sense of the changes in vertical structure to be expected at different latitudes and in particular to estimate how the structure varies under perturbation.

Much of the mathematical details of the radiative transport calculations of these models can, with some modification, be used in tandem with those models that treat horizontal transport since the radiative part is calculated separately to give heating rates.

D. The Thermodynamic (Adem) Model

The thermodynamic model of Adem is an operating climate model developed on the basis of the assumption that for periods of a month or longer climate can best be described by determining the mean thermal state of the atmosphere. The model uses two basic equations, one for the conservation of thermal energy for the atmospheric layer and one for the conservation of thermal energy for the ocean layer. The two layers are coupled in the full model. In each equation there is a two dimensional horizontal eddy diffusion term (the two dimensional version of the one dimensional transport term in the energy balance equation of section II.B). In addition to the eddy diffusion terms there is a term that parameterizes the transport by the mean winds in the atmospheric equation and a term that parameterizes transport by horizontal currents in the ocean equation. Continents and oceans have appropriate values of the albedo - the fraction of solar energy reflected to space - as functions of position on the globe. The chief effect of the continents is a varying albedo due to changing snow and ice cover. Although an initial input variable, albedo-feedback permits computation of changes in snow cover extent.

At present the model computes thermal and solar radiative absorption for each grid point as a function of time with a computed cloud cover. As with all global models the amount of atmospheric structure required for transport by diffusion and advection need not be the same as for the radiative terms, since the time scale for radiative equilibrium is so much smaller.

E. General Circulation Models (GCM)

General circulation models differ from the previously described models in that they treat horizontal momentum directly. That is, they use the analogue of Newton's second law relating the change in momentum to the applied forces. The atmosphere is broken up into several layers and in each layer there are equations for the energy and the horizontal components of the wind velocity. As with the previous models the radiative transport equations must be solved in order to get the radiative heating or cooling at each layer and at each grid point. In order to follow the horizontal velocity components the GCM requires much shorter time steps than is necessary for the other models. The GCM also differs from the prior models in starting with an initial condition and then integrating forward in time from basic principles. It uses more explicit dynamics and less parameterizations then other types of models.

Compared with GCMs, the thermodynamic model differs significantly in method, purpose and simplicity. The GCM attempts to predict climate from first principles while Adem's model generates climate anomalies based on the use of the stored data fields. These data fields represent analog solutions that contain implicitly whatever scales of motion contribute to climate. The model is limited by the quality and extent of the data fields and related parameterizations. In predicting perturbations from normal climate by the subtraction of computed normal from actual fields, the model avoids common biases or errors that may be introduced by computational schemes and common parameterizations.

III. THE 'GREENHOUSE-EFFECT'

A. Explanation of the Effect

The sun supplies the energy that drives the motions of the atmosphere and oceans. Solar radiation enters the top of the atmosphere with a characteristic spectrum that is mostly in the visible. A fraction of this radiation, called the planetary albedo, is reflected to space. The remainder is absorbed and transformed as it interacts with the earth and reaches equilibrium. The transformed radiation has a characteristic spectrum that is mostly in the infrared. It is referred to variously as long-wave or thermal radiation. The spectra of both incoming solar and outgoing thermal radiation are defined by the equilibrium black body emission function (the Planck formula). This is a strictly thermodynamic relation because radiation and matter come to equilibrium on time scales much shorter than those of the macroscopic motions.

The Planck formula depends on the absolute temperature of the emitting surface and wavelength. The solar radiation, shown in Fig. 1, has the spectrum of an emitting surface with a mean temperature of 6000°K. For contrast the spectrum corresponding to the present mean temperature of the earth of about 288°K appears on the right. Both curves have been normalized relative to their respective maxima so they appear to have the same height. The actual intensity of the solar curve is about four million times that of the thermal curve. Thermal radiation, for temperatures characteristic of the earth and its atmosphere, is predominantly in the range 4 to 40 μm.

As will be seen in Section IV.A where we elaborate on the lowest order radiation balance model, if we assume that the planetary albedo of the earth is 0.30, then the remaining fraction, 0.70, of the solar radiation will be

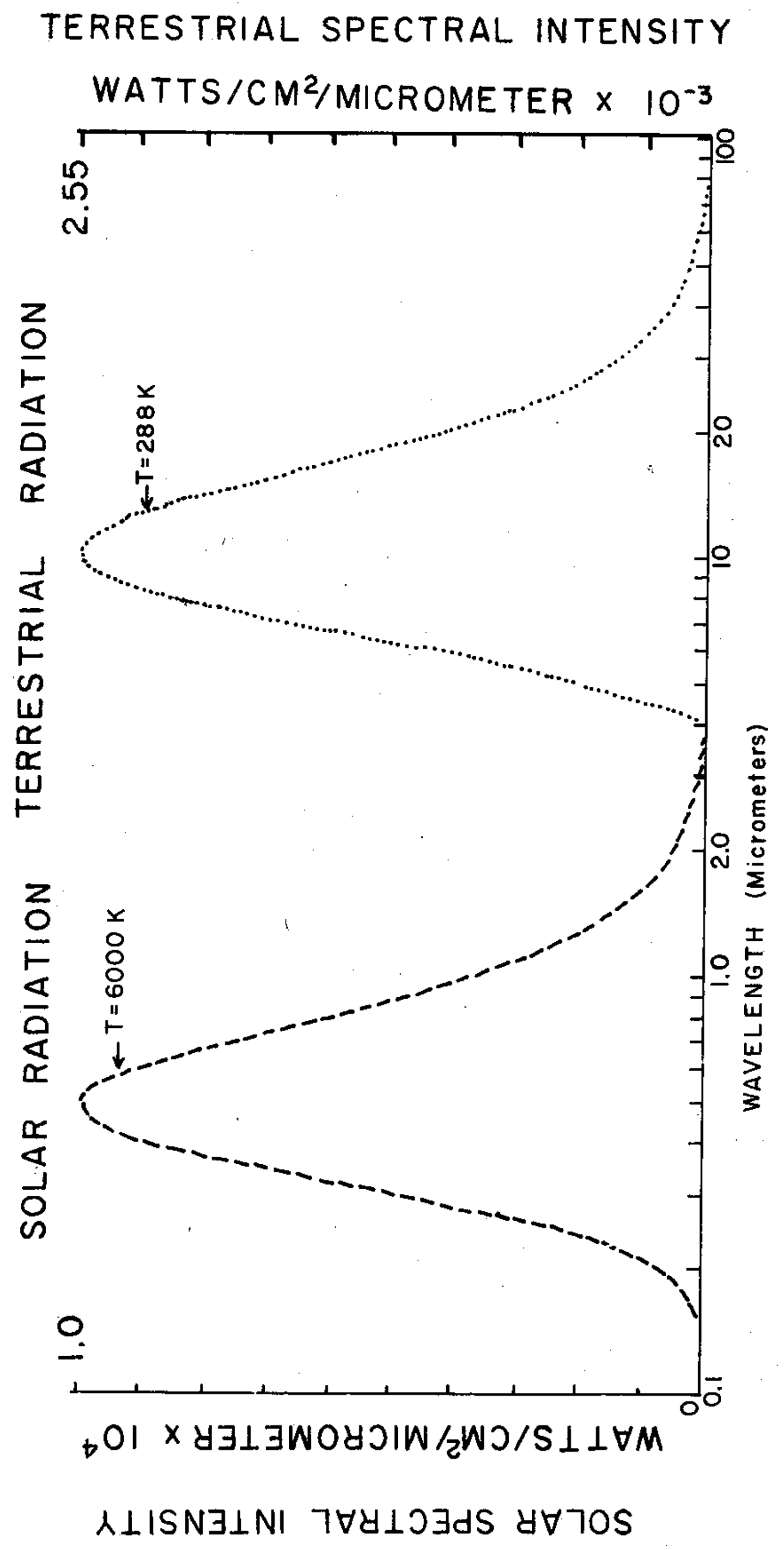

Figure 1. Comparison of solar spectral intensity (left-side scale) with terrestrial spectral intensity (right-side scale).

absorbed and transformed into thermal radiation with a mean temperature of T_e=255°K (or -18°C). T_e is called the effective radiation temperature of the earth. Just as the sun appears to be radiating at the relatively cool effective temperature of its outer layers (6000°K) there appears to be an effective radiating temperature for the earth from its relatively cooler upper troposphere (255°K). The surface temperature of the earth is 288°K. The reason that the surface temperature is warmer is due in part to the presence of the so called greenhouse gases that absorb strongly within the 4 to 40 μm thermal spectrum. Absorbing gases very quickly reradiate the energy they get from the surface of the earth, but in the atmosphere a gas radiates both upward and downward, while the surface merely radiates upward. The spectrum of the equilibrium radiation in the atmosphere will be determined by the actual temperature of the air. It is the mediating effect of the atmospheric absorbers and the fact that they radiate downward as well as upward that provides an additional bath of heat for the surface. This heating is called the "greenhouse effect" simply because the role of the absorbing gases resembles what was once thought to be the role of the glass of the greenhouse in trapping infrared radiation.

A key scientific problem to be solved is the evaluation of the increased greenhouse effect resulting from an increase in combustion gases in the atmosphere.

B. The Greenhouse Gases

The expected role of the greenhouse gases can be illustrated with use of Fig. 2. The figure shows part of the envelope of the thermal emission curve for T = 288°K from 4 to 20 μm. Estimates of the absorption curves of H_2O, CO_2

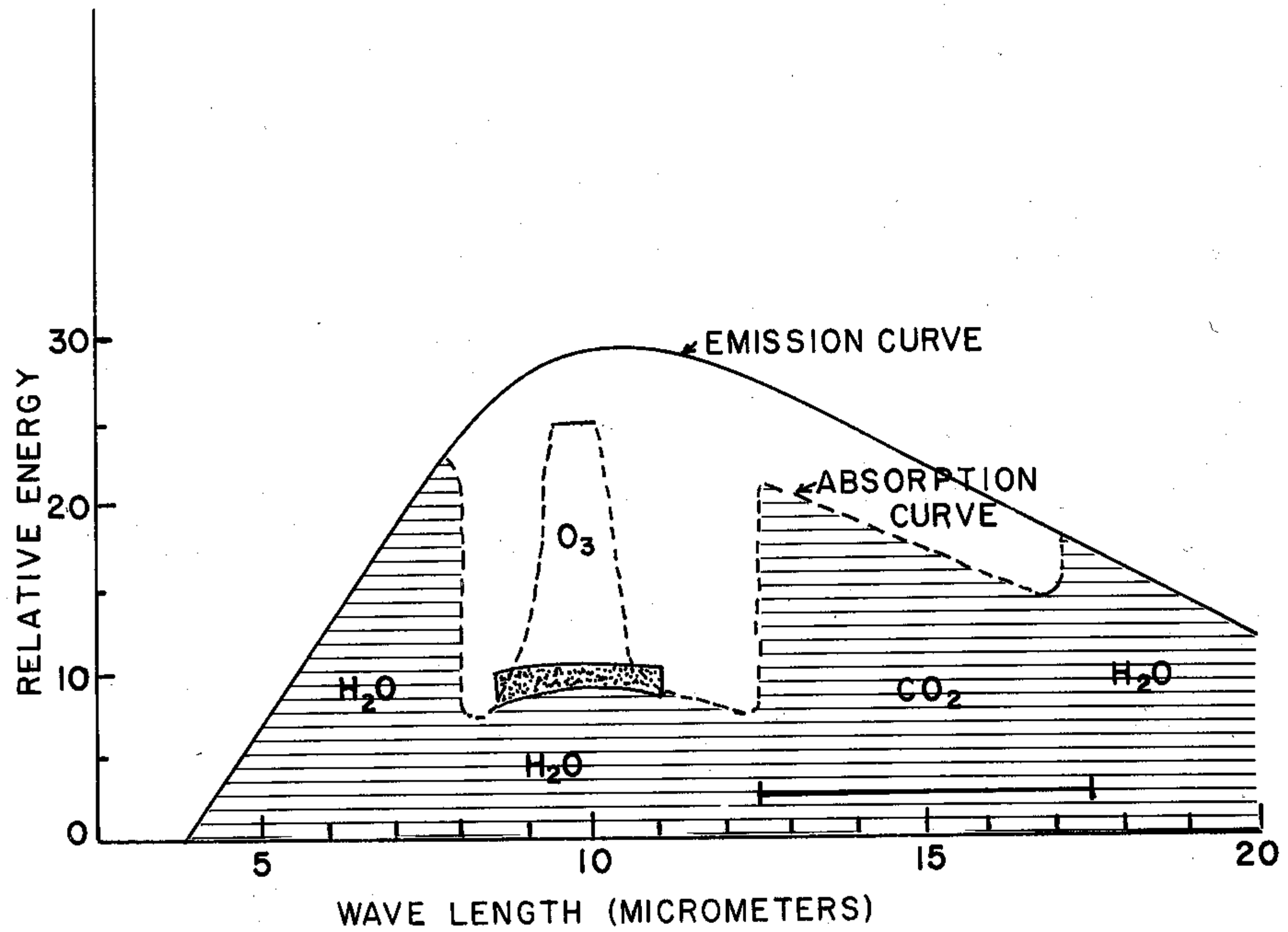

Figure 2. The spectral distribution of emitted and absorbed radiation in the atmosphere. The region of strong absorption by water vapor and CO_2 is horizontally lined. The main CO_2 absorption band is shown by the bracket centered on 15 micrometers. Weak CO_2 absorption is shown by the stippled region.

and O_3, which are sketched from computations based on data in Kondratyev [7] correspond well with a similar figure in Ref. [2]. The horizontally striped region indicates roughly: the main absorption regions of water vapor between 4 μm and 8 μm and above 17 μm; and of CO_2 between 12.5 μm and 17 μm. The principal infrared window to space is between 8 μm and 12 μm. Within the window are an ozone (O_3) absorption band and a relatively unimportant (for present climate) set of CO_2 bands (stippled). If CO_2 were to increase in the atmosphere the principal effect would be a filling in of the presently weak absorption band in the window to space as well as a filling in to the left of the strong absorption band that begins at 12.5 μm. If the CO_2 is more absorbing, it will reradiate more both upward and downward. If all of the other physics remains the same, the effect of this increased downward radiation would be to further increase the temperature of the surface. If the water vapor content were to increase there would be a similar filling in of the window region with more absorbing gases. The other greenhouse gases with absorption bands within the window include NO_x, methane (CH_4), ammonia (NH_3), the halomethanes (freons), carbon monoxide (CO) and hydrocarbons. Moreover, increased emission of NO_x and CO can increase CH_4 and O_3 in the troposphere [8, 9] via chemical reactions that compete with reactions that would otherwise remove them.

Most attention has been directed to the roles of H_2O and CO_2 principally because the data base on them is far more extensive and because the steady increase of CO_2 has been well established while the future increase seems a rational projection.

According to the Jason group [2] the freons have absorbing bands in the middle of the atmospheric window so that if they were to increase by a factor of about one hundred they could contribute strongly to the greenhouse effect.

N_2O, CH_4 and NH_3 appear to be marginally important at present. These gases would fill in the window from the left as CO_2 does from the right if they were to increase. Most recently Lacis et al. [9] calculated that the warming from the increase in trace gases, CH_4, N_2O and chlorofluorocarbons during 1970-1980 amounts to 50% to 100% of that due to CO_2 in the same period. Apparently then, all increases in greenhouse gases plus aerosols should be considered in the total anthropogenic effect.

IV. DESCRIPTION OF THE MODELS

A. Radiation Balance Model

The description and results given here for this most primitive of models follows the standard derivations and results of others, eg Chamberlain [10].

Picture the earth as a uniformly rotating ball with a homogeneous atmosphere in radiative balance with the mean solar heat flux at the top of the atmosphere of $S_0 = 1367$ watts/meter^2. Moreover, suppose that in equilibrium the earth radiates as a black body at the effective temperature T_e. The sun's radiative flux is plane parallel with a certain fraction, the albedo α, being reflected into space. The amount $\pi R^2 (1 - \alpha) S_0$ is absorbed; πR^2 is the effective area for plane parallel rays striking a spherical earth with radius R. The absorbed energy is reradiated according to the radiation balance equation:

$$\frac{dQ}{dt} = -\epsilon A\sigma (T^4 - T_a^4)$$

$$(4\pi R^2)\, \sigma T_e^{\,4} = (\pi R^2)\, (1 - \alpha) S_0, \qquad (1)$$

where the Stefan-Boltzmann constant $\sigma = 0.56687 \times 10^{-7}$ watts/m^2/°K^4. For the value $\alpha = 0.3$, the effective radiation temperature of the earth $T_e = 254.4$°K.

A simple relation between surface temperature, T_s and T_e can be derived from the following conditions: the thermal radiation is in local thermodynamic equilibrium with the atmospheric gases; the absorption coefficient is independent of frequency (the grey gas approximation); the atmosphere can be treated in a plane parallel geometry; and the thermal radiation flux goes either vertically up or vertically down. From this it is simple to derive [10] the relation

$$T_s^{\,4} = T_e^{\,4}\, (1 + 0.75\, \tau_g), \qquad (2)$$

where τ_g is the effective optical depth of the atmosphere - a non dimensional measure of the opacity or absorbing capacity of the atmosphere. So far the theory does not give a value for τ_g.

From Eqs. (1) and (2) we get

$$\frac{\sigma T_s^{\,4}}{A_s} = \sigma T_e^{\,4} = \frac{(1 - \alpha) S_0}{4} \qquad (3)$$

where $A_s = 1 + 0.75\, \tau_g$.

If, as is the present practice, one assumes that α remains constant if CO_2 is doubled, then T_e remains unchanged. However, τ_g is a measure of absorbing material in the infrared so that τ_g must increase with the CO_2 increase and with it, A_s. The ratio $T_s^{\,4}/A_s$ must remain constant by assumption so that $T_s^{\,4}$ will increase just enough to compensate for the increase in A_s.

A more sophisticated calculation is required to get τ_g. The Jason group [2], in a calculation that summed up the contributions of the absorption coefficients of the major atmospheric constituents found a mean τ_g of 0.748 for the present CO_2 and 0.828 for double CO_2. Substitution of these values gives

$$T_s \text{ (present } CO_2) = 284.9°K$$

and

$$T_s \text{ (double } CO_2) = 287.6°K.$$

The actual values of T_s are not important but any change in T_s is important. The warming is $\Delta T_s = +2.7°C$. In a more complete calculation involving nine absorption bands, the Jason group [2] obtained a 3°C change. The result for a model like this can be only suggestive.

The model producing these results gives the wrong temperature lapse rate for the lower troposphere. The lapse rate is the rate at which temperature falls with altitude. For the case of purely radiative equilibrium, the lapse rate in the lower troposphere will be steep enough for the upper air to be colder and denser than the lower air. Because ~~this~~ is mechanically unstable (a convective instability) the upper air will tend to sink and mix with lower air until the lapse rate reaches a stable value, that is; equal to or less than the adiabatic curves shown in Fig. 3. Because a solution with a stable lapse rate is required for a meaningful result it is necessary to modify the procedure. The simple procedure followed is the replacement of the lower portion of the initially-derived lapse rate curve with one of the adiabatic curves, i.e. the dashed curve of Number 3. The use of such an atmospheric structure would supply enough thermal radiation from the lower troposphere to maintain the radiative profile above the point of intersection C [10]. This

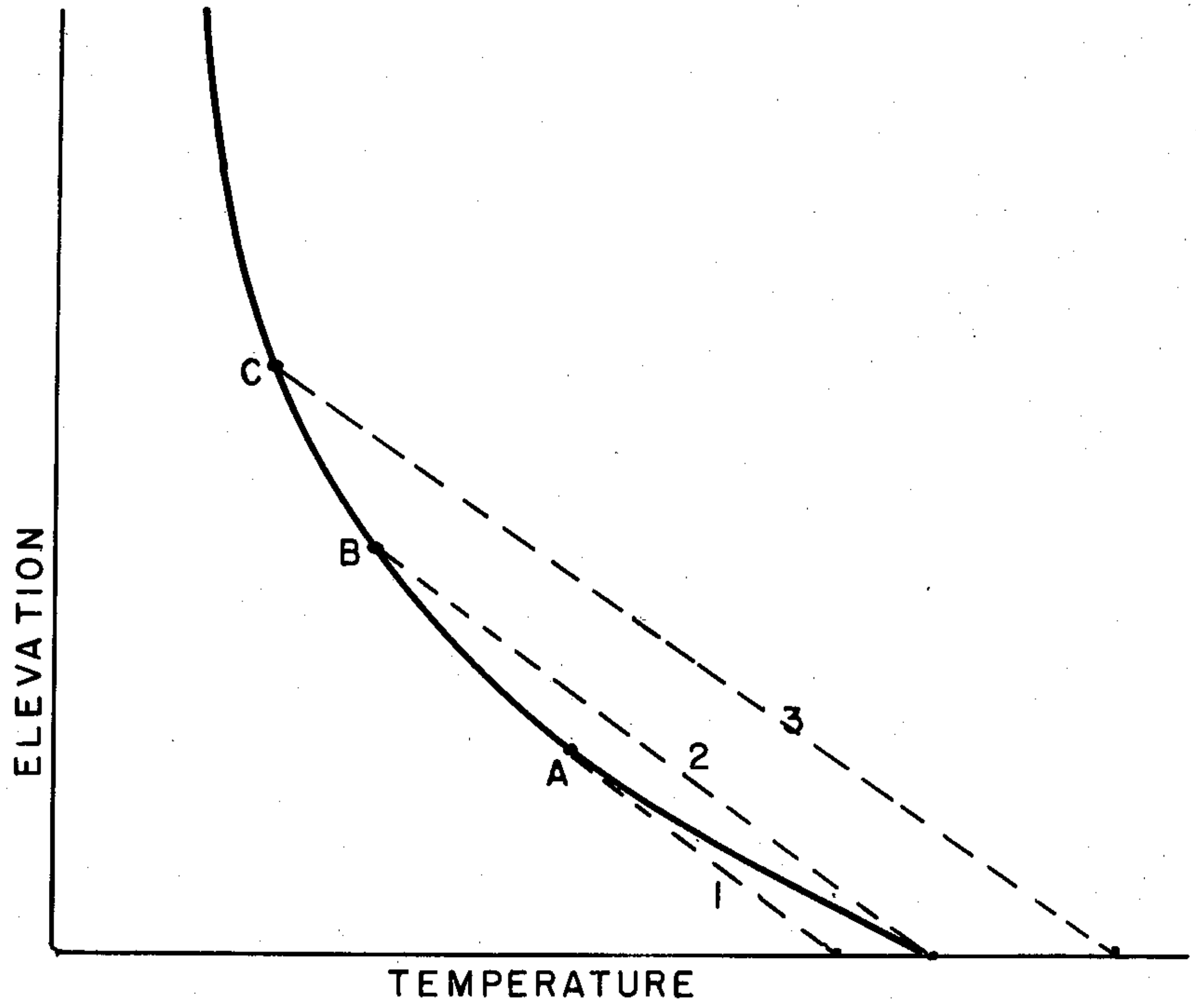

Figure 3. The vertical temperature lapse rate curve resulting from radiation balance solutions (solid curve). Dry adiabatic (constant) lapse rate curves are shown by broken lines 1,2 and 3. Below A the lapse rate curve is unstable. Adiabatic curve 3 is substituted for the lower portion of the lapse rate curve below the point of intersection at C to achieve convective stability and the maintenance of the radiation profile above C.

converts the radiation balance model into the crudest of the radiative-convective models (to be given more attention in Section C).

B. Energy Balance Models

Energy balance models are the next in complexity. They add a latitude dependence and therefore the capacity to treat snow-ice feedback. Moreover, they are capable of analytical solutions limited to highly idealized situations. For these models [11] the globe is divided into latitude strips or zones over which a balance equation states that the solar heat energy flux entering each latitude belt is exactly balanced by the loss rate. In the steady state, the equation for latitude belt i is

$$(\text{net transport out})_i + (\text{infrared out})_i = (\text{solar energy in})_i . \quad (4)$$

Each term would be in units of energy/second/area after the common area of the latitude belt has been divided out. Recall that Eq. (3), the corresponding equation for the radiation balance model has the form

$$(\text{infrared out}) = (\text{solar energy in}).$$

The extra term in (4) represents horizontal transport of heat carried by fluid motions. The properties for each latitude belt are average quantities. The only spatial variable is the quantity $x = \sin\theta$ where θ is the latitude.

In (3) the quantity $\sigma T_s^4/(1 + 0.75\tau_g)$ represents the total infrared radiation back to space. One could use such a formula for each strip. However, it is more convenient to convert $T_s = T_s(x)$ to Celsius degrees by $T_s(x) = 273 + T(x)$ where $T(x)$ is in °C and replace the infrared radiation term on the left side of Eq. (3) with the linear version on the left hand side of (5):

$$A(x) + B(x)T(x) = S_0(x)[1 - \alpha(x)]/4 \qquad (5)$$

where A and B, in the linearization, absorb the constants of $\sigma T^4/A_s$ but are given experimentally derived values below. $S_0(x)$ is the average value of the solar flux and $\alpha(x)$ the average albedo at altitude x. The variable x is convenient for this work because the differential dx is proportional to the area of the latitude circle. If (5) is multiplied by dx and integrated over latitude the result would be equivalent to (3). Present cloud cover, variation of water vapor content over the globe and the presence of greenhouse gases are accounted for in (5) by writing

$$\begin{aligned} A(x) &= a(x)/(1 + 0.75\tau_g) \\ B(x) &= b(x)/(1 + 0.75\tau_g) \end{aligned} \qquad (6)$$

where A(x) and B(x) are deduced from measurements. The Jason group [2] computes τ_g by using the U.S. Standard Atmosphere for 1976 and allowing the assumed structure to radiate to space. They break the thermal region into nine frequency bands, compute the flux for each band separately and then sum them for the total. Thus τ_g accounts for the presence of the greenhouse gases. Then a(x) and b(x) account for variations in cloud cover and water vapor via the measured quantities A(x) and B(x) in (6).

If one assumes that a(x) and b(x) do not change up to a doubling of CO_2 then a computation of τ_g for the case of CO_2 doubled (all other quantities remaining the same) will give a new set of A(x) and B(x) through Eqs. (6).

This approach is not based on solving the equations of radiative transfer hence, again, an estimate for the greenhouse effect rather than a precise number results.

The energy balance equations deal only with the energy content in the total column of atmosphere above the complete latitude strip. These are represented by an average heat capacity multiplied by the surface temperature T(x). Since there are no horizontal velocities in this picture we have to parameterize "net transport out" in terms of T(x) and its derivatives. The parameterization uses the form of molecular diffusion but here the diffusion term has to account for turbulent and eddy transport of heat. For energy balance models the parameterization takes the form of Eq. (7) (or alternate but similar forms)

$$[\text{net transport out}] = -\frac{d}{dx}\left[D(1-x^2)\frac{d}{dx}T(x)\right], \qquad (7)$$

where D, the diffusion coefficient, is at our disposal. It can be a global constant or vary with x or be prescribed in any way that tunes solutions to present climate. At present, whatever method is taken for fixing D, it is kept the same for estimates of doubled CO_2.

In steady state, the full equation has the form

$$-\frac{d}{dx}\left(D(1-x^2)\frac{dT(x)}{dx}\right] + A(x) + B(x)\cdot T(x) = S_0(x)\left[\frac{1-\alpha(x)}{4}\right] \qquad (8)$$

In (8) the surface albedo can be prescribed or it can be written $\alpha(x) = \alpha[x,T(x)]$ in order to account for variations in the ice line if one perturbs the climate. The Jason group [2] uses this parameterization in slightly different notation

$$[1-\alpha(x)] = Z(x)\cdot\begin{cases}0.7 \text{ if } T(x) > -10°C\\ 0.4 \text{ if } T(x) < -10°C\end{cases} \qquad (9)$$

where Z(x) is a correction for variation of zenith angle with x.

Eq. (8) and its time varying counterpart are useful for numerical experimentation. In their most realistic experiment the Jason group finds that by doubling CO_2 an increase of 2.4°C resulted when water vapor increased (constant relative humidity) from the effect of temperature feedback and sea ice was allowed to shrink to zero. High latitudes increased by 7.5°C. The corresponding results from the original Budyko version of this type of model [12] was 3.1°C for the global change and 9°C at high latitudes.

C. Radiative-Convective Models

Manabe and his collaborators [13, 14, 15] developed these models as a prelude to the incorporation of radiative transfer into general circulation models. All of the physical parameters in these models are taken as global averages and all of the computations are in one spatial dimension with variation only in the vertical (z-axis) measured upward from the surface. The equations of radiative transfer can be considered as bookkeeping relations that keep track of the change in radiation intensity I(f) (in watts/meter^2/unit solid angle/unit frequency interval about the frequency f) in some distance dz. They have the form: the change in intensity in distance dz = - the amount absorbed - the amount scattered out of the beam + the amount scattered into the beam + the amount emitted by matter into the beam. In principle the equations are first solved for each narrow frequency interval df with boundary conditions specified at the top and bottom of the atmosphere: at the top the net upward flux of thermal radiation must equal the net downward flux of solar radiation; at the surface the net upward thermal flux equals the net downward solar flux. To reduce the computational burden [14, 16] the solar and long wave fluxes are given different emphasis. That is, the solar radiation may be absorbed, scattered or reflected but emission is neglected, while the long wavelength thermal radiation may be absorbed or may be emitted but scattering is neglected. Molecular absorption is a process in which the molecules absorb radiation and go into excited energy states; they then reradiate energy in all directions. Quantum mechanics locates the energy levels and thermodynamics shows how the absorption coefficient is broadened by pressure and temperature variations. Further simplifications involve breaking the frequency spectrum into representative bands and computing mean absorption coefficients over each band. This reduces considerably the number of intervals for which the radiative transfer equations need solution.

In radiative-convective models the atmosphere is divided into uniform layers for numerical solution of the radiative transfer equations. Carbon dioxide is treated as uniformly mixed but water vapor and ozone are given vertical distributions appropriate to present mean climate. Clouds strongly influence both solar and thermal fluxes. The distribution of clouds as high, medium and low is generally prescribed according to present climate statistics. Hansen et al. [17], for example, take climatological cloud cover to be 50% with distributions in the fraction: 0.1 for high, 0.1 for medium and 0.3 for low clouds. (Low clouds cool the surface while high clouds warm it.)

Wavelength dependences of cloud and aerosol properties are included in some of the later R-C models [17].

The essential point is that the radiative transport equations are treated with considerable detail in R-C models. At any level they give the net heating or cooling after summing over all frequencies.

In Section IV A we saw that the atmosphere is unstable under purely radiative balance for the very simple model described. To avoid this problem in R-C models another set of conditions is required for stability. There must be some mechanism to transport heat upward from the surface (a convective adjustment) so that a stable temperature lapse rate will exist. One of the several alternative methods for performing these adjustments is via the time-stepping procedure of Refs. [14, 17]. (In this and the more complex models that follow, artificial time steps can be used to go from an initial state to the desired equilibrium state without changing the external conditions or solar forcing.) One begins with a standard atmosphere having a given composition and temperature structure subject to the given incoming solar flux and suitable boundary conditions at the surface. Then the equations of radiative transfer are solved to compute the radiative heating terms at each atmospheric level. Given these, the density of the air, the width of the level, and a suitable time step Δt one can compute ΔT_i the temperature adjustment within the i^{th} level. If the lapse rate exceeds 6.5°C/km -- a standard normal for mid-latitudes used in most R-C models -- the atmosphere is unstable and enough heat (or equivalently a convective adjustment to ΔT) must be added to ensure that the lapse rate will be 6.5°C/km or less. With the new temperature structure the radiative transport equations are solved again subject to the same boundary conditions to get new heating rates. The procedure is iterated until the atmosphere is in radiative and convective balance.

Hansen et al. [17] performed different experiments for doubled CO_2 -- the differences are with cloud parameterization, relative humidity, snow and ice and vegetation albedo feedback. With relative humidity and cloud temperatures fixed at present values and with the 6.5°C/km limiting lapse rate they find that the mean surface warming is $\Delta T_s = 2.8°C$ with an uncertainty of a factor of 2. In contrast, Augustsson and Ramanathan [18] give $\Delta T_s = 2°C$ for a different cloud parameterization. The quoted numbers are those preferred by the authors of [17] and [18] out of sets of runs with a variety of parameterizations. However, similar assumptions lead to similar results (see table 1 of Ref. [17] and table 2 of Ref. [18] -- a clear indication of the sensitivity of the results to assumptions about the cloud physics.

Hummel and Reck [39] improved on previous radiative-convective models by adding water vapor transport to their version of the early Manabe-Wetherald model thus permitting calculation of cloud location and thickness. Prior models used a constant relative humidity profile and cloud distribution. For a doubled CO_2 content and a standard cloud cover input their modification gives an increase of surface temperature of 2.05° compared with 1.71° for the Manabe-Wetherald model. This difference is due to a larger, more realistic water content.

References [14, 16, 17] give a balanced and clear picture of the techniques of radiative-convective modeling.

D. The Thermodynamic (Adem) Model

The basic assumption of this model is that for periods of a month or longer the mean state of the atmosphere depends primarily on the thermodynamics of the atmosphere and seems to be but weakly dependent on the dynamical

$\frac{dQ}{dt} = -hA(T-T_a)$

motions -- those governed by the fluid dynamics version of Newton's laws. The model follows the time evolution of the thermodynamic state of an atmospheric layer about 10 km high that includes a cloud layer, an ocean layer of 50 to 100 meters in depth and a continental layer of negligible depth and heat storage. It also includes a layer of snow and ice over the continents and oceans. The basic prognostic equations used in this system are those of conservation of thermal energy applied to variables that are time averaged over a prescribed interval. It is assumed that the equations of hydrostatic equilibrium, the perfect gas law, and the continuity equation are valid for the time averaged variables.

The thermal energy equations for atmosphere and oceans are integrated over their respective vertical heights -- about 10 km in the atmosphere and 50 to 100 m in the oceans. The resulting equations follow the mean energy of the atmosphere chosen proportional to the absolute temperature T_m at an altitude equal to one half of the mean height of the atmosphere, and the mean energy of the oceans chosen proportional to their surface temperature T_s.

Three basic equations are used to describe the atmosphere, oceans and continents respectively. For the atmosphere and oceans, the equations (which have the same form and are coupled in a full solution) have terms on the left side for local rate of change of thermal energy, heat transport by eddy diffusion, heat transport by mean winds (currents) and vertical heat transport (below the ocean mixed layer). These are balanced on the right side by the heat sources and sinks: radiation, latent heat and sensible heat. For the continents, which have insignificant storage depth and mobility, the left side terms are zero and only the balance among the heat sources and sinks is considered.

Albedo feedback for snow and ice is obtained by adjusting the snow-ice margin to a selected isotherm (currently 0°C) by iterative solutions until convergence is obtained. All of the terms of the atmosphere-earth radiation balance are also computed internally in the model solutions. Changes in cloud amount are computed as a function of latent heat changes.

Solutions of the linearized differential equations are carried out at 512 grid points over the hemisphere. Output is in the form of hemispheric maps for surface (land and water) and mid-tropospheric temperatures. In addition, all of the diagnostic terms involved are also printed out in separate charts. These include evaporation at the surface, latent heat of condensation in the atmosphere, computed meridional and zonal winds and associated heat transports, absorbed surface radiation, long wave and net radiation and cloud cover.

The model has been applied with success to the calculation of absolute and anomalous values of all of the above terms. It has also been applied with good results to the computation of known long-range climate changes during geologic time.

Although this model was developed primarily for prediction of current climate, it can be modified to be applied to predict the anthropogenic changes in climate for increased combustion gases.

The current model has been used to get a provisional prediction of a doubled CO_2 effect by using published values of the changes that would occur in black-body emission. A mean increase of 0.6°C is predicted in the experiment with a high-latitude change of 2° and a low to mid-latitude change of about 0.5°. These values may be revised when the model is optimized for the experiment.

The mathematical version of the model is given below.

In the present form of the model the equations for T_m (the mid-tropospheric temperature) and T_s (the surface temperature) both have the general form

$$\frac{\partial T}{\partial t} + \vec{V}\cdot\nabla T - K\nabla^2 T = \text{heat sources and sinks} \qquad (11)$$

The first term is proportional to the local time rate of change of the energy. The second term represents the transport of heat by mean motions: for the atmosphere $\vec{V}$ is determined by thermodynamic relations -- the geostrophic wind relations -- and for the oceans is determined from the surface wind speeds [19]. The third term represents horizontal diffusion of heat by eddy and turbulent motions. The right hand sides, the heat sources and sinks (HSS) are:

$$\text{HSS for the atmosphere} = E_t + G_5 + G_2, \qquad (12)$$

and

$$\text{HSS for the oceans} = E_s - G_3 - G_2. \qquad (13)$$

In addition, with neglect of heat storage in the continents the third equation reads:

$$0 = E_s - G_3 - G_2 \qquad (14)$$

for the continental surfaces.

In (12) E_t is the heat energy added to the atmosphere by radiation, G_5 is the heat added by condensation of water vapor in the clouds and G_2 is the heat added by vertical turbulent transport from the surface - a parameterization of the convective transport that is dealt with by the convective adjustments in radiative-convective models. In (13) and (14) E_s is the rate at which energy is added to the surface by radiation, and G_3 is the rate at which heat is lost by evaporation.

The parameterization of E_t and E_s is based on assumptions that the cloud layers and the earth radiate as black bodies and that the clear sky atmosphere has a window for wavelengths between 8 μm and 13 μm. They are given in terms of T_s, T_m, the insolation I at the given latitude, the cloud cover, the total radiation received at the surface (for E_s) under clear sky conditions and the surface albedo α. Over the oceans the quantities G_2 and G_3 are parameterized in terms of measured normals, departures of $(T_s - T_m)$ from their normal values and normal surface wind speeds. Over the land G_2 has the same parameterization while G_3 simply depends on empirical normals, and a known function of map coordinates. Similarly, the heat gained by condensation of water vapor in the clouds G_5 is given in terms of its normal seasonal values G_{5N} and $(T_m - T_{mN})$ and its first order derivatives with respect to map coordinates. (The subscript N indicates normal values.)

The cloud cover E is a variable given by:

$$\varepsilon = \varepsilon_N + D_2\,(G_5 - G_{5N}) \qquad (15)$$

where ε_N is the normal cloud cover and D_2 is a constant. Details of the parameterizations are given in Refs. [20, 21, 22, 23].

E. General Circulation Models (GCM)

The design of general circulation models begins with the basic equations governing large scale atmospheric motions and follows by transforming them into some kind of finite differences scheme suitable for solution on digital computers. In this process, the original equations and boundary conditions (or the finite differences scheme itself) would be altered to remove the physical mechanisms responsible for wave motions that would otherwise be generated by errors in initial data. These waves would be spuriously amplified by computational rather than actual physical instabilities and ultimately swamp the motions under study [24].

The first of the basic equations is the equation of conservation of mass. It states that if you follow an individual parcel of gas in time the total mass of the parcel remains constant. This becomes:

The fractional change in density of the parcel with time = the negative of the fractional rate of change of its volume with time... (16)

(Thus a fractional increase in volume of 1% would be accompanied by a fractional decrease in density of 1%.)

The next equation describes the evolution of the internal energy per unit mass e of the parcel in time. In terms of the absolute temperature T and C_v the specific heat at constant volume:

$$e = C_v T \qquad (17)$$

The energy equation (the First Law of Thermodynamics) reads:

The time rate of change of internal energy + the rate of working by the fluid system = the rate at which heat is added to the system. (18)

Equation (8) of the energy balance models is derived as an approximation to Eq. (18). For Adem's model, Eqs. (16) and (18) together with a parameterization of the mean motion reduce to equations (11) and (12) for the atmosphere and (11) and (13) for the oceans.

The new equations for GCM are the fluid dynamical versions of Newton's Second Law F = ma. In cartesian coordinates, for the horizontal west to east coordinate x and velocity u and the south to north coordinate y and velocity v the equations read:

$$\rho \left(\frac{du}{dt} - f\ v\right) = - \frac{\partial p}{\partial x}\ , \qquad (19)$$

and

$$\rho \left(\frac{dv}{dt} + f\ u\right) = - \frac{\partial p}{\partial y}\ , \qquad (20)$$

where the symbol $\frac{d}{dt}$ stands for the time rate of change as we follow the given parcel of fluid, p is the pressure, $\frac{\partial p}{\partial x}$ and $\frac{\partial p}{\partial y}$ are components of the pressure gradient (the force terms), ρ is the density of the parcel, f the Coriolis parameter is equal to $2\Omega \sin\phi$ where Ω is the angular rotation of the earth (2π radians/day) and ϕ is the latitude. Eqs. (19) and (20) when multiplied by the volume of the parcel are in the form of Newton's Law

$$ma = F \qquad (21)$$

in a rotating frame.

Vertical accelerations (which would be perturbations on the fundamental hydrostatic pressure balance equation of the atmopshere) are important on smaller space scales than the motions followed in meteorology and must be parameterized in order to include an adequate treatment of convective heat transport from the surface to the atmosphere.

Adem's model uses a thermodynamic parameterization of (19) and (20) by setting the d/dt terms equal to zero and computing u and v from

$$u = - (\rho f)^{-1}\ \partial p/\partial y,\ v = (\rho f)^{-1}\ \partial p/\partial x. \qquad (22)$$

These are the geostrophic winds and are used wherever advection terms are used. For large scale motions of the kind used in climate studies this is a reasonable approximation since the geostrophic wind approximates the true horizontal velocity to within about 15% in midlatitudes.

For GCM the full set of equations must be transformed into some version of a finite differences scheme suitable for solution by a digital computer. Typical horizontal grid spacings might range from a 4° × 5° net to an 8° × 10° net. For the vertical structure, 2, 7, 9 or more levels are used. With each choice of net there are wavelengths of motions smaller than the grid spacings that cannot be resolved. Because these subgrid motions are important transport mechanisms for energy and momentum their effects must be parameterized in terms of the grid scale variables and their derivatives.

At present the GCM use oceans without surface currents as sources and sinks of heat. In addition to the convection of moisture and sensible heat (described above for the thermodynamic model) the GCM must also provide for convection of momentum.

In a survey of this size it is difficult to describe in detail the computational complexities of the major models or the various schemes for parameterization of physical processes that can not be treated directly or simply. It is relevant to note that all of these are active areas of present research and that year by year models undergo modification to accomodate changes in knowledge. Reference [1] contains a summary of predictions of the outcome of CO_2 warmings from two of the principal GCM modeling groups: the group led by Hansen at the Goddard Institute for Space Studies in New York and the group led by Manabe at the Geophysical Fluid Dynamics Laboratory at Princeton, N.J. The global mean warming for the most complete of the two sets of models is 2°C for Manabe et al. and 3.5°C for Hansen et al., quoted in [1]. As might be expected different parameterizations and different feedback mechanisms produce different results within the above range.

In the latest published GCM experiment, Gates et al. [27] used a two layer atmospheric model which included an ocean constrained with prescribed climatological temperature and obtained a global surface air temperature warming of only 0.2°C and a surface warming of only 0.1°C. This low result is primarily a function of the use of a prescribed sea surface temperature.

The magnitudes of the warmings by GCM, as with all models are higher at high latitudes. The maximum value, according to Ref. [1], is between 4°C and 8°C in polar and adjacent regions for the annual mean surface ΔT. All models also indicate increased warming in summer and over land, but the magnitudes differ.

V. ASSESSMENT OF THE MODELS

A. Common Assumptions

In climate modeling certain physical processes must be parameterized in order to make computations tractable on current generation computers. This includes eddy diffusion of heat and momentum, convective transport of heat, moisture and momentum, and the radiative properties of the atmosphere. In many of these parameterizations a particular constant (the parameter) is given a value that tunes the final result to present climate. This is a perfectly respectable procedure and enables one to perform experiments involving small changes in solar constant or some physical input with a reasonable expectation that the constants will remain valid for the altered climate state.

Common practice involves the assumption that present parameterizations will be valid for a doubling of CO_2. Some of these parameterizations have a very strong influence on the outcome of the doubling. One such assumption is that the mean planetary albedo α and consequently T_e, the effective radiation temperature of the earth, remain unchanged. An example of this in the simplest case is seen with equation (3):

$$\sigma T_s^4 / A_s = \sigma T_e^4 = (1 - \alpha) S_0 / 4, \qquad (3)$$

where $A_s = 1 + 0.75\,\tau_g$. It is clear that depending on whether α goes up or down T_e can be colder or warmer.

Another assumption is that the present mean distribution of relative humidity remains fixed for a CO_2 doubling. Since a CO_2 warming will increase the water vapor content of the atmosphere, if relative humidity remains constant, the greenhouse effect of water vapor in the atmospheric window will result in a strong positive feedback. Thus, the Jason group model [2] predicts an additional warming of about 50% of the bare 2 × CO_2 warming. However, in the complex feedback mechanism, increased CO_2 leads to increased temperature with a consequent increase in evaporation and increased moisture content of the atmosphere. Although this effect leads to a further warming, the probable increase in cloud cover would increase albedo and offset the warming effect [38]. The true effects of all of these sensitive relationships are not yet known.

Wherever the models agree on these two assumptions it is likely that the predicted global warmings will be close simply because the final results are very sensitive to the planetary albedo and the relative humidity. The assumptions serve as constraints and as modeling efforts evolve these constraints will be relaxed.

B. Energy Balance Models

Energy balance models are extremely tractable for both analytical and numerical treatment [11, 2]. With them one can follow the lowest order effects of climate change on the ice line and the latitudinal distribution of a warming. The ice line separates the region of snow and ice where the albedo is high from the region of bare earth where it is low. In these models, the ice line can be made a function of surface temperature and will shift latitudinally with the surface temperature.

The principal difficulties with this class of models are:

i. they define all physical variables over a complete latitude strip so that there is no proper separation of oceans and continents;

ii. they have absolutely no advection parameterization -- an important transport mechanism for mid-latitudes;

iii. they have no hydrological cycle and

iv. any interaction between oceans and air would be too crude to offer any reliable time estimates for a warming.

In summary, the models are extremely useful for preliminary experiments since they are fast and simple but they can give no definitive answer about a climate warming.

C. Radiative-Convective Models

Radiative-convective models are one dimensional representations of the earth's atmosphere with variation possible only in the vertical and in time. They were designed originally as precursors for the incorporation of radiative transfer into GCM but have served for a considerable amount of interesting experimentation.

The principal weakness of these models are:

1. they treat a mean earth;
2. they have no horizontal heat transport and
3. the convective adjustments are very crude mechanisms introduced to maintain mechanical stability of the lower troposphere.

Treatments with horizontal transport and realistic oceans and continents could modify any conclusions drawn from radiative-convective models. Nonetheless, these models can be powerful tools for exploring radiative properties of the atmosphere especially parameterizations of cloud cover and dynamics and the effect of industrial pollutants. The fact of a predicted change will be important rather than the magnitude. For accurate magnitudes the radiative computation package must be appended to models with two dimensional horizontal variation and a realistic geography.

Reck and collaborators have studied the effects of a wide range of industrial pollutants on climate with a version of the Manabe-Wetherald radiative-convective model. These include the effect of aerosols on climate [28, 29, 30] and the effects of the freons on atmospheric surface temperature [31]. These and related numerical experiments and others on CO_2 warmings [16, 32] are suggestive rather than definitive at this time.

D. The Thermodynamic (Adem) Model

The thermodynamic model of Adem is the only operating climate model that gives reasonable forecasts of current temperature anomalies. It has also been used on a quasi-operational basis to predict monthly climate with very good performance and has been successful in simulating past climates related to ice ages and different continental locations [33, 34]. Since early in 1980 it has been generating monthly forecasts with good skill for the northern Hemisphere [35, 36]. Other strong points of the model are:

i. it is fast -- a one month forecast takes about 1 minute on an IBM 360/95;

ii. it is the only existing model with a realistic mean ocean having wind driven currents parameterized in a useful way and

iii. it generates cloud cover, the radiation balance, snow-ice feedback and sea surface temperatures internally.

The weak point of the model is that many of its parameterizations, while adequate for present climate predictions, require adjustment for optimum application of the model to the CO_2 warming problem. As with all models, parameterization of physical processes require better and more fundamental understanding of the role of cloud physics, the distribution of moisture in the atmosphere, and the way subgrid scale motions contribute to time mean motions followed by the equations of motion. Further work is necessary on this model to optimize it for application to the CO_2 problem.

E. General Circulation Models

Despite the fact that General Circulation Models include simultaneously details of those processes that control climate, they may not be, at least at this time, the appropriate vehicles for predicting long term climate change for the following reasons (paraphrased from Refs. [2] and [3]:

i. the computing time for current GCM could take from a half of a year to a full year to calculate a century of climate for a single combination of initial conditions or prescribed external parameters;

ii. in order to be useful for climate studies it may require calculation of statistics from an ensemble of numerical integrations and

iii. it is difficult to track down cause and effect relationships with the many degrees of freedom involved in GCM.

No GCM (as of this writing) can predict present climate or give even a two-week forecast. There is a phenomenon of "intrinsic stochasticity" referred to in Ref. [2] which refers to a kind of internal chaotic motion (not driven by external noise) that occurs even in simple dynamical systems that are deterministic. For certain values of the constants in the equation these systems become extremely sensitive to initial conditions so that closely neighboring initial physical states can evolve into quite different final states. Since GCM have so many constants and adjustable parameters the authors of Ref. [2] expect a good amount of such chaotic behavior.

In addition to these difficulties, it is much more difficult to assess the effects of any input assumptions, including errors, on results of the complex GCM than it is for simpler models. Example of effects already detected in which large changes occur are evident in the change from a swamp ocean (no heat storage) to a mixed-layer (heat storage) ocean in the GCM models of Manabe and Wetherald [37] and Manabe and Stouffer [26]. The warming of 3° in the former case falls to 2° in the latter. And in the case of Gates _et al._ [27] who used effectively an ocean of infinite heat storage a warming of only 0.1° resulted. These are gross effects. Changes due to the many more subtle aspects are much more difficult to trace.

Both Ref. [2] and [3] suggest that simpler models would be more tractable and useful for probing long term variations in climate.

F. Future Directions

Most models prescribe the data for the radiation balance at the top of the atmosphere. Involved with this is the tuning to present conditions of cloud cover, relative humidity and planetary albedo. These terms have a profound influence on the warming due to a change in combustion gas input. It is essential that these terms evolve in some parameterized way, with changing climate. In this connection we note that Ohring and Clapp [38] deduced from observations that the net albedo cooling effect of clouds is slightly greater than the greenhouse warming effect.

In addition to the problems connected with the meteorological parameters, a basic problem appears to exist in the computation of heating rates. This computation requires the solution of the equations of radiative transfer, a process which currently uses in part, analytical expressions devised prior to the advent of present high-speed computers. The magnitude of potential errors in the above procedure should be evaluated and computational strategies devised to determine transmission in sufficiently small frequency bands over the spectrum of interest.

In addition to the above fundamental areas, necessary improvement must still be carried out for many of the parameterizations of both atmospheric and ocean terms.

Despite all of the uncertainties in the classes of models described, their very errors serve to give outside limits of global warming of 0.1°C to 3.5°C from a doubling of CO_2. Effects of trace gases, referred to earlier, might lead to a near doubling of these numbers.

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