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# Early Development in the Study of Greenhouse Warming: The Emergence of Climate Models

Following the pioneering contributions of Arrhenius, Callendar and others, climate models emerged as a very promising tool for the study of greenhouse warming. In the early 1960s, a one-dimensional, radiative-convective equilibrium model was developed as the first step towards the development of a three-dimensional model of climate. Incorporating not only the radiative but also the convective heat exchange between the earth's surface and the atmosphere, the model overcame the difficulty encountered by the earlier approach of surface radiative heat balance in estimating the magnitude of greenhouse warming. By the 1970s, a three-dimensional, general circulation model (GCM) of the atmosphere, coupled to a very idealized ocean of swamp-like wet surface, had been used for studies of greenhouse warming. Despite many drastic simplifications, the GCM was very effective for elucidating the physical mechanisms that control global warming and served as a stepping stone towards the use of more comprehensive, coupled ocean-atmosphere GCMs for the study of this problem.

## INTRODUCTION

Towards the end of the 19th century, Arrhenius (1) estimated the magnitude of greenhouse warming based upon the assumption of radiative equilibrium. His work was followed by a series of the studies of Callendar (2), Plass (3), Kondratiev and Niilisk (4), Kaplan (5), and Möller (6), which estimated the $CO_2$-induced warming based upon a requirement of radiative heat balance at the earth's surface.

Although atmospheric carbon dioxide ($CO_2$) absorbs solar radiation at near infrared wave lengths, the amount of the absorbed energy is relatively small. On the other hand, it strongly absorbs and emits terrestrial radiation at the wave length of ~12–18 μm. It is therefore expected that in response to the increase in the $CO_2$ concentration of the atmosphere, the downward flux of terrestrial radiation increases at the earth's surface. To satisfy the condition of the surface heat balance, Callendar assumed that this $CO_2$-induced change of downward flux of radiation should be compensated by an increase of equal magnitude in the net upward terrestrial radiation, if other components of surface heat balance were unchanged. By estimating the increase of surface temperature required for the increase of net upward radiation, Callendar estimated the $CO_2$-induced rise of surface temperature.

Möller (6) attempted to improve these estimates considering the effect of the change in the water vapor content of air which results from the $CO_2$-induced warming of the troposphere. Noting that the condition of constant relative humidity is climatologically more reasonable than that of constant absolute humidity, he assumed that an increase in temperature is accompanied by an increase in absolute humidity of air, keeping the relative humidity unchanged. This implies that the $CO_2$-induced increase of surface temperature raises not only the temperature of the troposphere but also its absolute humidity, further enhancing the increase in the downward flux of terrestrial radiation at the earth's surface. Thus, the change of net upward terrestrial radiation associated with a given change of surface temperature becomes very small. To counterbalance the change in the downward flux of terrestrial radiation due to the increase of atmospheric carbon dioxide, it is therefore necessary to increase surface temperature by a very large amount. This explains why Möller obtained a very surprising result: an increase in the water vapor content of the atmosphere with rising temperature causes a self-amplification which results in a large temperature change. When the air temperature is around 15°C, doubling the $CO_2$ content yielded a temperature increase of as much as 10°C. For other temperatures, the results may be completely different. In Möller's study, the net upward radiation at the earth's surface hardly increased with increasing surface temperature because of the assumption of invariable relative humidity. On the other hand, the net upward radiation increases significantly with increasing surface temperature when it is assumed that the absolute humidity of air is unchanged despite the change of tropospheric temperature. This is why the earlier studies of Callendar and others yielded smaller $CO_2$-induced change in surface temperature.

The study of Möller described above exposed the basic difficulty of the surface radiation balance approach, which does not take into consideration the $CO_2$-induced changes in other components of the surface heat balance. Obviously, the change of the atmospheric $CO_2$ concentration alters not only the net radiative flux, but also the boundary-layer exchanges of sensible and latent heat fluxes between the earth's surface and the atmosphere. To estimate the change in the heat fluxes, it is necessary to consider, not only the heat balance of the earth's surface, but also that of the atmosphere. Instead, Möller assumed implicitly that the sum of sensible and latent heat fluxes did not change despite the $CO_2$ -induced increase in the downward flux of terrestrial radiation. This is why his approach yielded a large sensitivity of the surface temperature when he considered the water vapor feedback process in the atmosphere. In his perturbation analysis of radiative equilibrium temperature of the earth's surface, Arrhenius also assumed that the sum of latent and sensible heat fluxes did not change in response to the increase of atmospheric carbon dioxide. Therefore, it is likely that his approach suffers from a similar shortcoming.

## RADIATIVE-CONVECTIVE EQUILIBRIUM

In order to overcome the difficulty encountered by Möller (6), Manabe and Wetherald (7) employed the "radiative-convective model" of the global mean atmosphere which was developed by Manabe and Strickler (8). This one-dimensional model includes not only radiative but also convective heat exchanges between the earth's surface and the atmosphere. The vertical distribution of atmospheric temperature in radiative-convective equilibrium was approached asymptotically through the numerical time integration of the globally averaged, thermodynamical equation with the vertical coordinate of pressure p:

$$C_p \frac{\partial T}{\partial_t} = Q_R + Q_c \qquad \text{Eq. 1}$$

where $C_p$ is the specific heat of air under constant pressure; T is global mean temperature at a given pressure level; $Q_R$ and $Q_c$ are heating rate per unit mass due to radiation and convection, respectively. For the computation of heating (or cooling) due to solar and terrestrial radiation, the effects of water vapor, carbon dioxide, ozone, and cloud cover were taken into consideration.

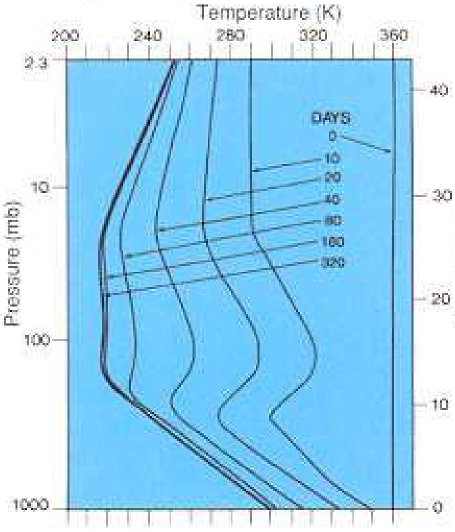
The effect of convection was incorporated into the model by use of the very simple procedure of "convective adjustment". This procedure involves the adjustment of the temperature lapse rate ($-\partial T/\partial p$) to a critical value whenever it becomes supercritical during the course of a time integration. The adjustment was made such that the sum of internal and potential energy was unaltered. For their study, the critical lapse rate was chosen to be 6.5°C km$^{-1}$, roughly the average value for the troposphere. Based upon the assumption that the earth's surface has no heat capacity, the net downward radiative flux received by the earth's surface was immediately returned to the lowest layer of the atmosphere, inducing the convective adjustment in the overlying layer.

Figure 1 illustrates how the temperature of the model atmosphere approaches the equilibrium value starting from an initial condition of a warm isothermal atmosphere. Toward the end of each time integration, the model atmosphere attains a realistic structure consisting of a convective troposphere and a stable stratosphere. The net incoming solar radiation becomes equal to the outgoing terrestrial radiation at the top of the atmosphere, indicating that the atmosphere-surface system of the model is in radiative equilibrium as a whole. In the stable model stratosphere, the rate of radiative temperature change is equal to zero, satisfying the condition of local radiative equilibrium. On the other hand, the model troposphere is not in radiative equilibrium. The net radiative heat loss from the model troposphere is compensated by the heat gain due to the convective transfer of heat from the earth's surface to the atmosphere.

In the numerical time integration described above, it is assumed that the vertical distribution of absolute humidity remains unchanged. On the other hand, noting that the seasonal variation of relative humidity in the troposphere is relatively small, despite a large change in temperature, Manabe and Wetherald (7) assumed that the model atmosphere keeps the relative (rather than absolute) humidity unchanged. As air temperature changed during the course of a time integration, the distribution of absolute humidity was continuously updated such that relative humidity remains unchanged. On the other hand, they assumed that the uniform mixing ratio of $CO_2$ and the vertical distributions of cloud cover and ozone did not change with time.

To evaluate the sensitivity of the model atmosphere to changes in atmospheric $CO_2$ concentration, a set of numerical time integrations was performed with the radiative-convective model of the atmosphere as described above. Figure 2 illustrates the vertical distribution of the equilibrium temperature of the model atmosphere with the normal, half the normal, and twice the normal concentration of $CO_2$. This Figure indicates that, in response to the doubling of the atmospheric $CO_2$, the equilibrium surface temperature of the model increases by about 2.3°C, whereas that of the middle stratosphere decreases by several degrees. In addition, it reveals that the magnitude of the warming resulting from the doubling of $CO_2$ concentration is approximately equal to the magnitude of the cooling from the halving of $CO_2$ concentration. This result suggests that $CO_2$-induced temperature change is approximately proportional to the change in the emissivity of air which is linearly dependent on the logarithm of $CO_2$ concentration (see also 9).

Figure 1. Approaches toward the state of radiative, convective equilibrium (8).

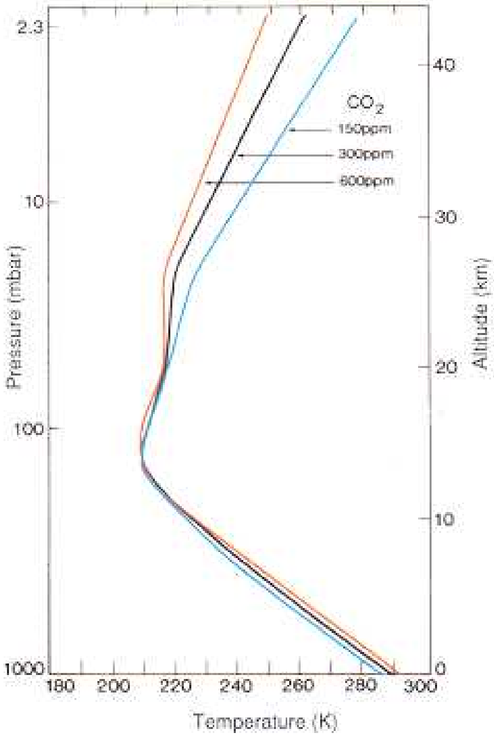


The physical mechanism of the greenhouse effect may be understood by realizing that greenhouse gases such as $CO_2$ and $H_2O$ can absorb and emit terrestrial radiation, but absorb a relatively small fraction of solar radiation. In the mid-troposphere, these gases absorb major fraction of the upward terrestrial radiation emitted from the earth's surface and the lower troposphere and reemit it. Thus, the effective source of emission for the outgoing terrestrial radiation at the top of the atmosphere is located in the mid-troposphere. On the other hand, in an atmosphere without greenhouse gases, the source of emission is confined to the earth's surface which is warmer than the mid-troposphere. In order to maintain the compensation between the net incoming solar radiation and outgoing terrestrial radiation at the top of the atmosphere, it is therefore necessary that the equilibrium temperature of the atmosphere with greenhouse gases be much higher than that of the greenhouse gas-free atmosphere. From the above discussion, it follows that an increase in the atmospheric concentration of carbon dioxide raises the altitude of the effective source of emission and reduces the outgoing terrestrial radiation, contributing to the global warming of the combined surface-troposphere system.

Because of the assumption of fixed relative humidity, the absolute humidity in the model troposphere also increases associated with the $CO_2$-induced warming. This raises further the altitude of the effective source of outgoing terrestrial radiation. Thus, the temperature of the model troposphere increases further, maintaining the radiation balance of the surface-troposphere system as a whole. In addition, the increase of absolute humidity increases the fraction of solar radiation absorbed by the model troposphere, thereby decreasing the planetary albedo and enhancing the $CO_2$-induced warming. This is why the surface temperature in radiative-convective equilibrium with a given distribution of relative humidity is almost twice more sensitive to an increase of atmospheric $CO_2$ than the equilibrium temperature with a given distribution of absolute humidity (7).

As pointed out already, the temperature of the model stratosphere in radiative equilibrium reduces in response to an increase

Figure 2. Vertical distributions of temperature in radiative, convective equilibrium for various values of atmospheric $CO_2$ concentration, i.e., 150, 300, 600 ppm by volume (7).



of the $CO_2$ concentration in the atmosphere. In order to comprehend this result, it is necessary to recognize that the radiative heat balance of the model stratosphere is essentially maintained as a balance between the heating due to the absorption of the solar ultraviolet radiation by ozone and the net radiative cooling due to the excess of the emission over the absorption of radiation by $CO_2$. Because the collision broadening of line absorption is small in the stratosphere where pressure is low, the heating due to the $CO_2$ absorption of upward radiation from the troposphere is much smaller than the cooling due to the emission of radiation, causing the net cooling of the stratosphere due to terrestrial radiation. Thus, an increase of $CO_2$ concentration in air lowers the equilibrium temperature of the model stratosphere.

Table 1 shows the changes of surface temperature due to the doubling of the atmospheric $CO_2$ concentration. The data were obtained from radiative-convective models of the atmosphere developed by various authors. The magnitudes of warming contained in this table range from 1.5 to 2.3°C, and depend partly upon how various $CO_2$ absorption bands are treated for the computation of radiative transfer. For further discussion of the differences among these results, see Augustsson and Ramanathan (9).

## THREE DIMENSIONAL MODEL

The discussion of the greenhouse effect in the preceding section implies that its magnitude depends critically upon the vertical temperature gradient in the atmosphere. In the one dimensional model of radiative-convective equilibrium described in the preceding section, it is assumed that convection prevents the lapse rate of atmospheric temperature from exceeding a given critical value. In the actual atmosphere, the lapse rate is determined, however, through the interaction among not only radiative transfer and cumulus convection, but also large scale circulations. Furthermore, the model does not distinguish latent heat from sensible heat flux from the earth's surface to the atmosphere and thus is not useful for studying changes in the hydrologic cycle. The radiative-convective model also misses various processes such as albedo feedback, which enhances the sensitivity of model climate involving snow cover and sea ice as noted by Budyko (13). This was why Manabe and Wetherald (14) began to investigate greenhouse warming by using three-dimensional GCM of the atmosphere in which many of these feedback processes were incorporated.

Because of the limitations of the available computer at that time, the mathematical model they used contained many simplifications. Figure 3 is a box diagram which illustrates the basic components of the atmospheric model and the interaction among these components. This Figure indicates that the atmospheric model consists of the equations of motion, thermodynamical equation with latent heating and radiative transfer, and the prognostic equation of water vapor which incorporates not only the three-dimensional advection but also condensation of water vapor. The effect of moist convection was represented by the so-called moist convective adjustment (15). For the computation of radiative transfer, the predicted distribution of water vapor was used together with the zonal mean climatologies of observed cloud cover and ozone concentration.

For the finite difference computation of both prognostic and diagnostic equations, a horizontal grid system with ~500 km spacing and nine vertical levels was chosen. The idealized distribution of ocean and continent adopted for this model is illustrated in Figure 4. Cyclic continuity from one meridional boundary to another was assumed. At the equatorial boundary, a symmetry condition was imposed. Because of these idealizations, the numerical computations required for the time integration of this model was approximately one-sixth of that required for a global model with comparable finite-difference resolution.

Over the continental surface, soil moisture was predicted from the requirement of water balance. On the other hand, the oceanic surface was represented by swamp-like wet surface without any heat capacity. It has an unlimited supply of water, but lacks the thermal inertia of the actual ocean. The temperatures of both oceanic and continental surfaces were computed from the equation of heat balance with the assumption that these surfaces have zero heat capacity. To incorporate the albedo feedback process into the model, the depth of snow cover was predicted by an equation of snow budget, whereas the extent of sea ice was determined according to the temperature of the swamp surface. The albedos of snow cover and sea ice were assumed to be much larger than those of bare soil or open sea.

The climatic influence of the change in $CO_2$ concentration was estimated by comparing two quasi-equilibrium model climates with normal (1 x $CO_2$) and twice normal (2 x $CO_2$) concentrations of $CO_2$, which were obtained from the long-term numerical integrations of the model described above. Figure 5 shows the zonal mean temperature difference between the 2 x $CO_2$ and 1 x $CO_2$ cases as a function of latitude and height. In qualitative agreement with the results from the study of radiative-convective

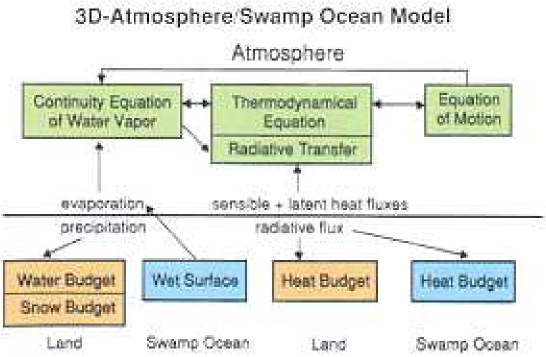


Figure 3. Box diagram illustrating the basic structure of a model constructed by Manabe and Wetherald (14).

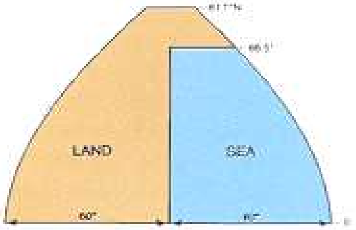


Figure 4. Diagram illustrating the distribution of continent and ocean in a model of Manabe and Wetherald (14).

Table 1. Increase of surface temperature in radiative-convective equilibrium due to the doubling of $CO_2$ concentration of air. The estimates of Wang et al. (12) are inferred from the result of numerical experiments in which $CO_2$ concentration is increased by a factor of 1.25.

| Reference | ΔT(°C) |
|---|---|
| Manabe and Wetherald (7) | 2.3 |
| Manabe (10) | 1.9 |
| Ramanathan (11) | 1.5 |
| Wang et al. (12) | 1.6 |
| Augustsson and Ramanathan (9) | 2.0 |

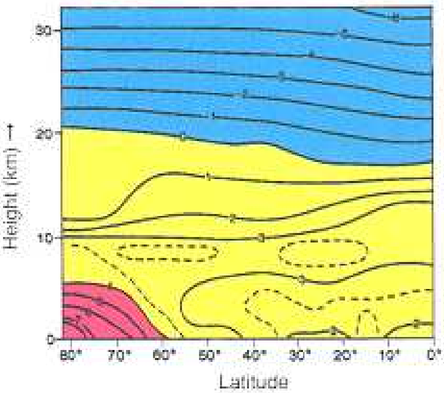


Figure 5. Latitude-height distribution of the zonal mean temperature difference (°K) between the 2 x $CO_2$ and control cases. Shaded area denotes negative values (14).

equilibrium described earlier, the temperature of the model troposphere increases whereas that of the model stratosphere decreases in response to the doubling of $CO_2$ concentration in air. The area-mean increase of surface air temperature is about 3°C and is somewhat larger than that obtained from the one dimensional, radiative-convective model in which the positive feedback mechanism involving snow and sea ice was not taken into consideration. The tropospheric warming is enhanced in high latitudes by the poleward retreat of snow cover and sea ice with high albedo and is confined to the near-surface layer due to stable thermal stratification. At low latitudes, the $CO_2$-induced warming in the upper model troposphere is larger than the warming near the earth's surface due to the moist convective control of the vertical temperature distribution. (Note that the moist adiabatic lapse rate decreases with increasing air temperature.) Accordingly, the increase of surface air temperature at low latitudes is much less than the corresponding increase at high latitudes.

Figure 6. Annual mean surface air temperature (°C) as departures from the reference period 1946–1960 averaged over (a) the Northern Hemisphere (0–85°N) and (b) the Arctic (65–85° N) (17). Note that the scale of the ordinate is larger in (a) than (b) by a factor of two.

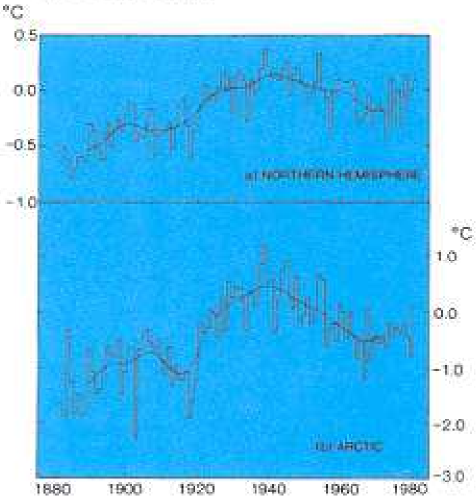
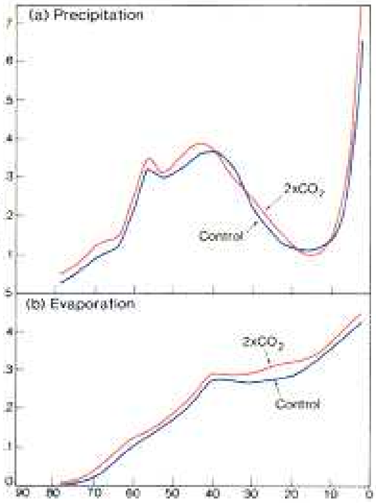


Figure 7. (a) Zonal mean rates of total precipitation, and (b) zonal mean rates of evaporation (14).



The polar amplification of zonal mean surface air temperature change discussed above is also evident in the analysis of the actual atmosphere (see, for example, 16 and 17). Figure 6 illustrates the long-term variations of annual mean surface air temperature averaged over the entire Northern Hemisphere and Arctic Ocean. It indicates that surface air temperature variation over the Arctic is much larger than the rest of the Northern Hemisphere in qualitative agreement with the $CO_2$-induced change of near-surface temperature in the model atmosphere discussed above. However, the polar amplification is missing in the observed surface temperature variation during the last few decades. One can speculate that the recent absence of the polar amplification may be attributable to the accelerated increase in the tropospheric loading of sulfate aerosols which reflect solar radiation (18). As noted by Manabe and Stouffer (19), some of the low frequency variation of climate could be internally generated. Therefore, it is not reasonable to explain the observed temperature variation by the greenhouse effect alone.

The increase of $CO_2$ concentration in air affects not only the thermal structure of the atmosphere but also the hydrologic behavior of the model. For example, the global hydrologic cycle intensifies in response to an increase in atmospheric $CO_2$. As Table 2a indicates, the global mean rates of evaporation increase by almost 8%. In view of the fact that the tropospheric response to the doubling of atmospheric $CO_2$ is practically identical to the response to the 2% increase of solar irradiance (20), this large fractional increase in the global mean rate of evaporation deserves explanation.

The intensification of the hydrologic cycle mentioned above is essentially controlled by the surface heat budget of the model shown in Table 2b. In response to the doubling of atmospheric $CO_2$, the troposphere becomes warmer, resulting in the increase of the absolute humidity of air. Thus, the net downward flux of radiation increases by as much as 3.4% due to the increases of both $CO_2$ concentration and the absolute humidity of air. The increased radiative energy received by the earth's surface is, in turn, removed by the turbulent eddy flux of not only sensible but also latent heat and enhances evaporation from the surface. This partly accounts for the substantial increase of the global mean evaporation shown in Table 2b.

One can identify another important factor which is responsible for the enhancement of global evaporation. According to the Clapeyron-Clausius relationship, the saturation vapor pressure of air increases almost exponentially with increasing temperature (e.g., roughly a factor of two for a ~ 6°C increase). As surface temperature increases, evaporation (rather than sensible heat flux) becomes a more effective means of ventilating the earth's surface. Thus, a larger fraction of radiative energy received by the earth's surface is removed as latent rather than sensible heat. This is why the global mean flux of evaporation increases by almost 8% (whereas that of sensible heat is reduced by 8%), resulting in the 8% increase of the global hydrologic cycle (Tables 2a and b).

In order to satisfy the balance requirement of water vapor in the model atmosphere, the increase in the global mean rate of evaporation discussed above should be matched by the same increase in global mean rate of precipitation. This explains why the global mean rates of both precipitation and evaporation increase in response to an increase of atmospheric $CO_2$ content.

The intensification of the hydrologic cycle due to an increase in atmospheric $CO_2$ is also evident in Figure 7 which illustrates the latitudinal distributions of zonal mean rates of precipitation and evaporation with the normal and twice the normal concentration of atmospheric $CO_2$. This figure indicates that, at high latitudes, the $CO_2$-induced increase in the precipitation rate is larger than that of evaporation rate. Because of the warming of the model troposphere, the poleward transport of moisture increases, causing the marked increase in the excess of precipitation over evaporation in high latitudes. Recent results from a coupled ocean-atmosphere GCM with realistic geography (21) indicates that the large increase of moisture supply into the Arc-

Table 2. (a) Global mean rates of evaporation (or precipitation) from the control and $CO_2$-doubling (2 x $CO_2$) experiments in units of m $yr^{-1}$. (b) Global mean flux of various heat balance components at the earth's surface in units of W $m^{-2}$. Note that net downward radiation includes both solar and terrestrial radiation (14).

a.

| | Control | 2 x $CO_2$ | Increase |
|---|---|---|---|
| Evaporation Rate (Precipitation) | 0.93 | 1.00 | +0.07 (+8%) |

b.

| | Control | 2 x $CO_2$ | Increase |
|---|---|---|---|
| Net Downward Radiation | 102.6 | 106.1 | +3.5 (+3.4%) |
| Latent Heat | 75.4 | 81.0 | +5.6 (+8%) |
| Sensible Heat | 27.2 | 25.1 | −2.1 (-8%) |

tic and surrounding ocean slows down the intensity of thermohaline circulation in the North Atlantic Ocean, moderating the $CO_2$-induced warming in Western Europe.

The study of Manabe and Wetherald (14) described above was followed by a series of studies which consider, in addition, the seasonal variation of insolation and realistic geography (e.g., Manabe and Stouffer (22, 23); Washington and Meehl (24); Wilson and Mitchell (25); Hansen et al. (26)). In these studies, the swamp-like ocean was replaced by simple mixed-layer models of the surface layer of oceans, which moderate the amplitude of the seasonal variations of surface temperature. In addition to confirming the basic features of the results described above, the atmosphere-mixed layer ocean models thus constructed have enabled us to explore the seasonal and geographical distributions of the $CO_2$-induced change of climate and hydrologic cycle.

The studies described so far deal with the so-called equilibrium response of climate which represents a response of climate to an increase of atmospheric $CO_2$, given sufficient time. Actually, the equilibrium response of climate is seldom realized due to the thermal inertia of ocean which delays the response of climate. This is why the equilibrium response studies have been complemented by the so-called transient response studies which investigate the transient response of climate to increasing atmospheric $CO_2$. By coupling the atmospheric GCM to an oceanic GCM which incorporates the oceanic uptake of heat, the delay of climatic response due to the thermal inertia of ocean is taken into consideration. Since some of the latest results from a coupled ocean-atmosphere GCM are presented by Bengtsson (27) in this volume, I will not discuss the transient response studies in this article. Readers can also refer to our recent article published in Ambio (21) for the results which were obtained earlier from coupled ocean-atmosphere models.

## CONCLUDING REMARKS

In this article, I have reviewed how and why the pioneering studies of Arrhenius, Callendar and others evolved into more comprehensive studies which employed GCMs of climate. It was shown that a one dimensional model of radiative-convective equilibrium and a highly simplified GCM were very useful for understanding various physical mechanisms involved in global warming, serving as a stepping stone towards transient response studies which use coupled ocean-atmosphere GCMs.

Although we have made great progress in the modeling study of the greenhouse effect during the last century, large uncertainties still remain in estimating the magnitude and distribution of the global climate change. According to the 1995 report of the Intergovernmental Panel on Climate Change, the equilibrium response of global mean temperature to the doubling of atmospheric carbon dioxide ranges between 1.5°C and 4.5°C. The uncertainty in estimating the sensitivity of climate stems in no small part from our inability to reliably incorporate into a climate model various feedback processes involving cloud, sea ice and snow cover which substantially affect incoming solar and/or outgoing terrestrial radiation at the top of the atmosphere. Other processes of critical importance include cumulus convection and heat and water budgets of land surface. Increased usage of data from remote sensing and *in situ* monitoring of the earth-atmosphere system should be essential for evaluating and improving the parameterizations of the important processes identified above.

Obviously, the reduction of uncertainty in projecting the future climate change may not be achieved by the improvement of parameterizations alone. In order to assess how realistic the sensitivity of a climate model is, it is necessary to simulate observed, long-term change of climate by driving the model with the time series of the actual thermal forcing such as changes in solar radiation and increased concentrations of greenhouse gases and aerosols in the atmosphere. When the simulations are done, one could then assess the performance of the models by comparing simulated and observed long term climate changes. In order to reduce the uncertainty in the model projection, it is therefore necessary to reliably monitor the basic structure and thermal forcing of climate as it emerges from the natural, internally generated fluctuations.

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