APPENDIX 2.4

THE USE OF COMPREHENSIVE GENERAL CIRCULATION MODELLING FOR STUDIES OF THE CLIMATE AND CLIMATE VARIATION

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1. INTRODUCTION

At the beginning, it may be useful to define a comprehensive model of the climate in contrast to statistical-dynamical models. As I understand it, a comprehensive model of the climate is a model in which the effects of large-scale disturbances in the atmosphere are explicitly computed. On the other hand, statistical-dynamical models of the climate parameterize the effect of eddies. Stated in this way, the distinction between the two kinds of models seems to be clear. In practice, however, it is rather obscure. For example, consider the so-called "truncated spectral model" proposed by Lorenz (1). One can retain any number of wave components according to the requirements for the model experiment and the availability of computer time. Such models can fill the gap between comprehensive models and the statistical-dynamical models. I believe that it is desirable to construct many models with varying degrees of parameterization (or wave truncation), so that the optimal approach in the combined use of these models with various degrees of freedom can be found. Although the subject of this position paper is comprehensive models of climate, I do not intend to advocate their use above other models with fewer degrees of freedom. Rather, I believe that it is essential to get preliminary ideas from the relatively simple models before carrying out the time-consuming, numerical experiments which are proposed in this position paper. At the same time, I would like to emphasize that, by adopting the various techniques of economizing the amounts of computer time, one can study the climate change with comprehensive climate models ~~on~~ by presently available computers.

2. PRESENT STATUS OF CLIMATE SIMULATION

Before discussing how one can use the comprehensive general circulation models for the study of climatic variation it may be useful to review briefly the ability of some of the latest models to simulate the climate.

2.1 *The atmospheric model*

Global circulation models of the atmosphere have been developed at many institutions, i.e., Met. Office (2) and (3), GISS (4), NCAR (5), UCLA (6), RAND (7), and GFDL (8). In this subsection, I shall briefly describe, as an example, the structure and the performance of the atmospheric model which has been developed at GFDL (9).

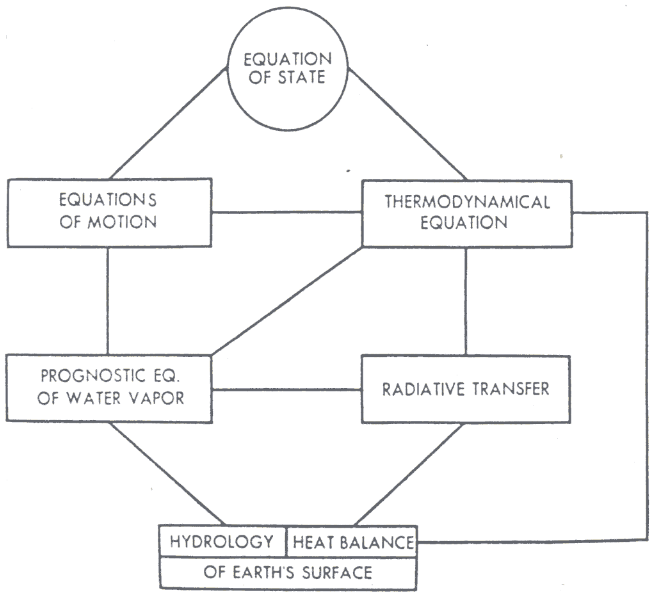

Figure 1 Schematic diagram indicating the model structure (8).

Figure 1 presents a box diagram which shows the basic components of the atmospheric model and the interaction among these components. According to this figure, the model consists of five major components, i.e., the equations of motion, thermodynamical equations, radiative transfer, and the prognostic equation of water vapour. The computational domain covers the entire earth's surface. The finite-difference form of the equations of motion is that developed by Kurihara and Holloway (10) and modified by Holloway and Manabe (11). The horizontal grid size is approximately 250 km, and eleven vertical finite-difference levels are chosen in order that the thermal and the dynamical structure of both the stratosphere and the troposphere can be represented satisfactorily. The dynamical effects of mountains are incorporated by adopting the so-called σ-coordinate system proposed by Phillips (12). For the computation of the flux of solar radiation, the seasonal variation of insolation is given at the top of the model atmosphere. The temperature at the ground is determined such that it satisfies a condition of heat balance at the land surface. Over the sea, the seasonal variation of sea-surface temperatures is given as a lower boundary condition. The prognostic equations for the hydrologic cycle are highly simplified. It is assumed that condensation takes place whenever the relative humidity exceeds 100%. The macroscopic effects of moist convection are represented in an idealized manner by a so-called moist convective adjustment (13). The snow cover and soil moisture are predicted by the equation of the budget of snow and water at a land surface.

To demonstrate the ability of the model to simulate the climate, the global distributions of the rate of precipitation

RATE of PRECIPITATION (DEC.,JAN.,FEB.)

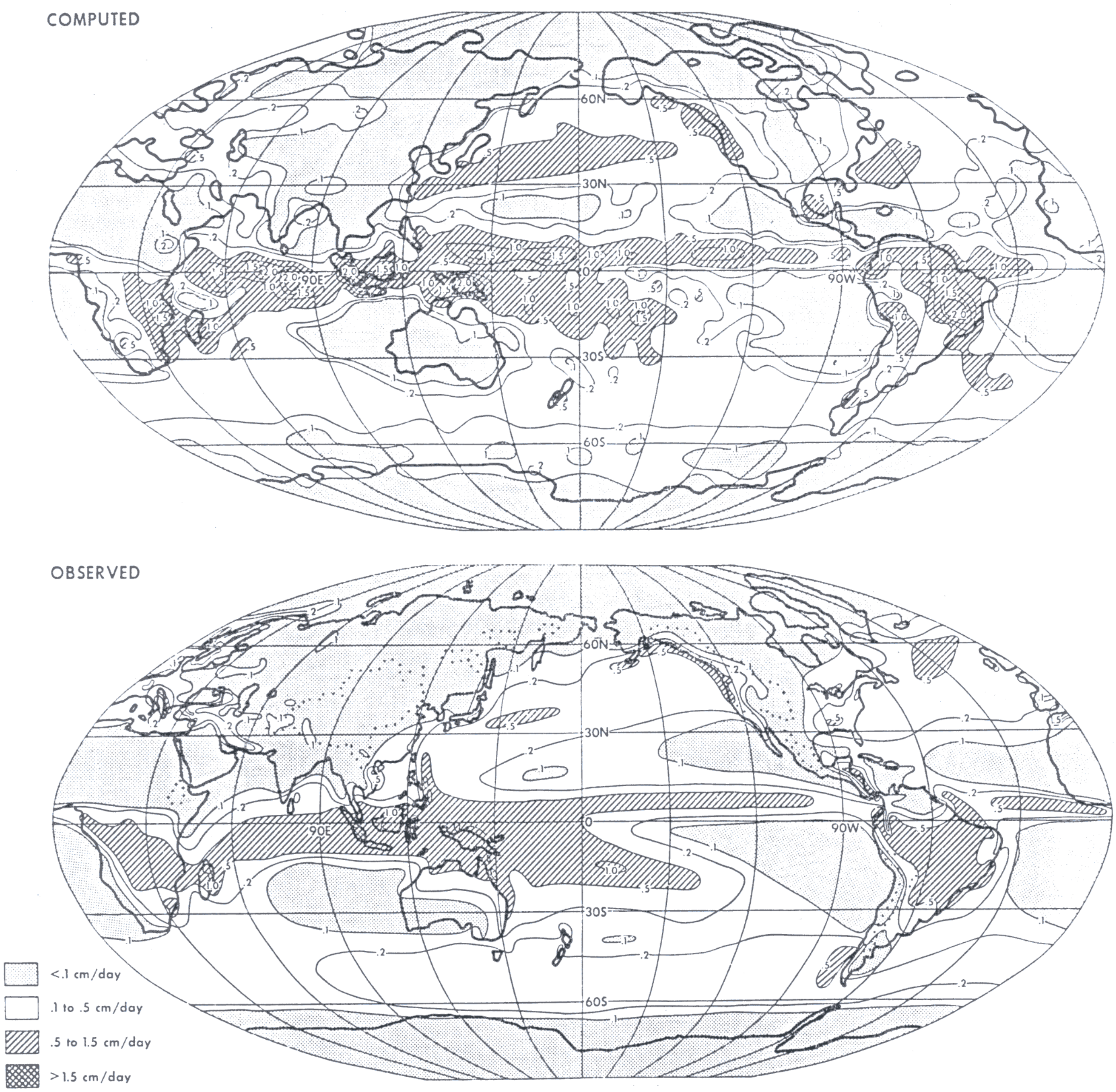

Figure 2 Global distribution of the mean rate of precipitation for December, January and February in cm day^{-1} (9). Upper, simulated by the model; lower, observed (Möller).

produced by the model are compared with those of the observed precipitation. Figures 2 and 3 present the comparison for the periods December through February and June through August, respectively. According to these figures, the model excellently reproduces the seasonal movement of the tropical rainbelt. In Australia, the Sahara, and Central Asia of the model, the rate of precipitation is small throughout the year, in agreement with the features of the observed distribution. The seasonal variation of the rate of precipitation over Eurasia and North America is well simulated except that the rate of precipitation over Texas and southeast China is grossly underestimated during the summer season.

A convenient way of getting a general impression of the skill of a climate simulation is to construct a climatic atlas

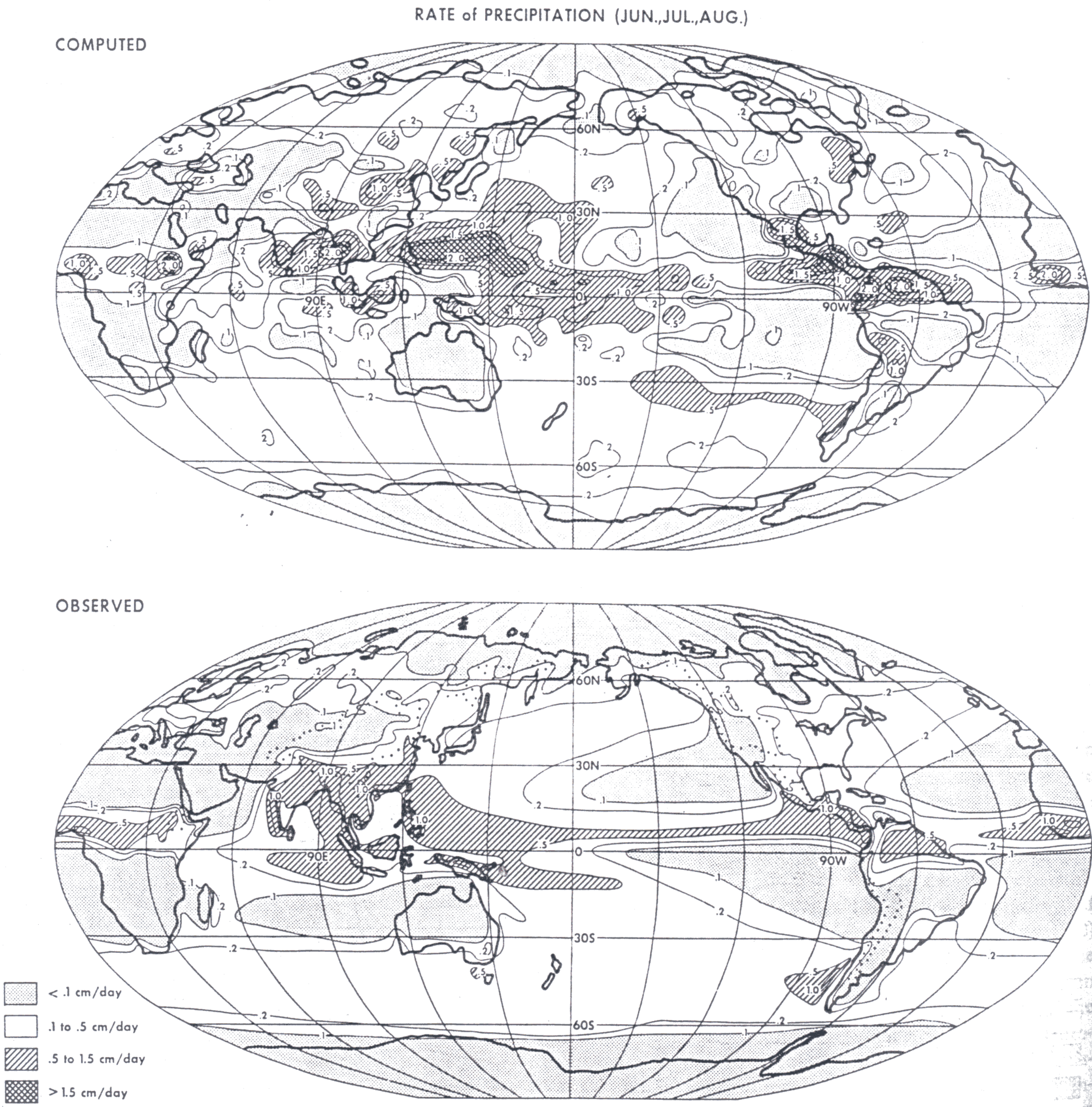

Figure 3 Same as Figure 2 except for June, July and August.

of the model according to Köppen's classification system and compare it with the corresponding atlas of the actual climate (14). Figure 4 presents such a comparison. This figure clearly indicates that the model is capable of simulating most of the large-scale features of climate with the exceptions of climate over southeast China and the southern part of the United States.

2.2 *The joint ocean-atmosphere model*

As is known, the interaction between the ocean and the atmosphere is one of the most important processes controlling climate. For example, the atmosphere exerts wind stress upon the ocean surface and drives the ocean currents. As another example, the ocean has a large heat capacity and strongly controls the long-term variations

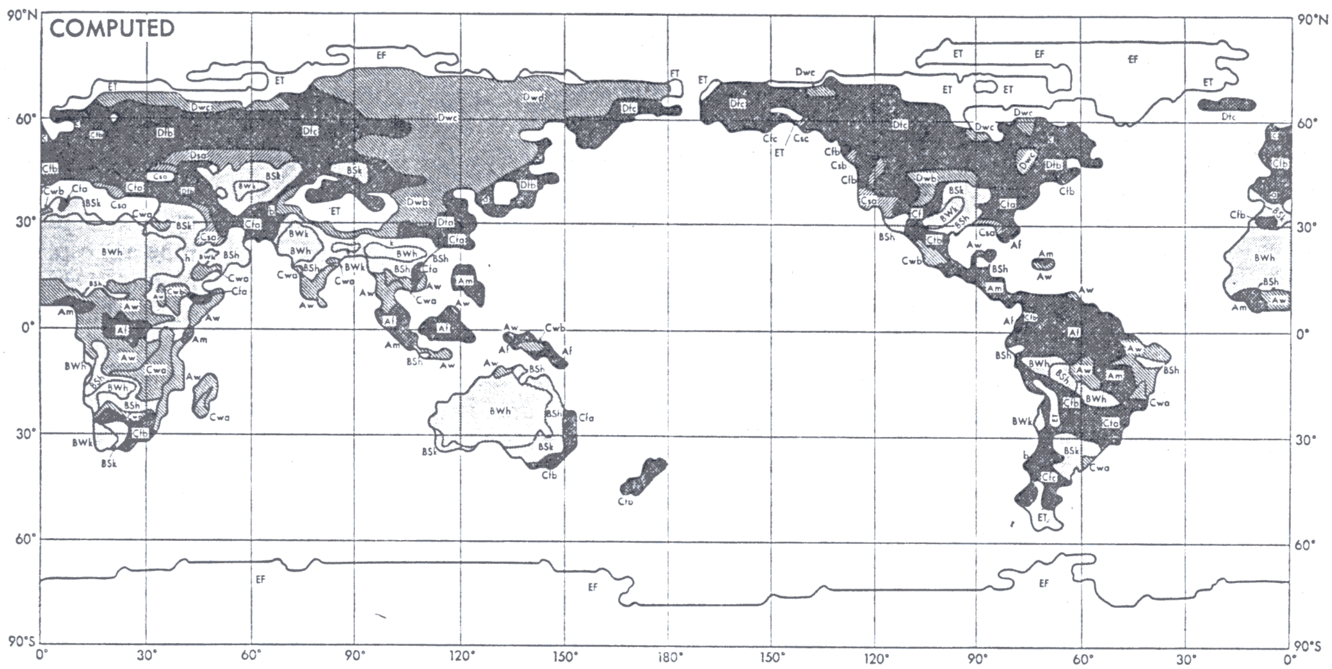

Figure 4 (a) Global distribution of Köppen climate types based on model simulated data (9).

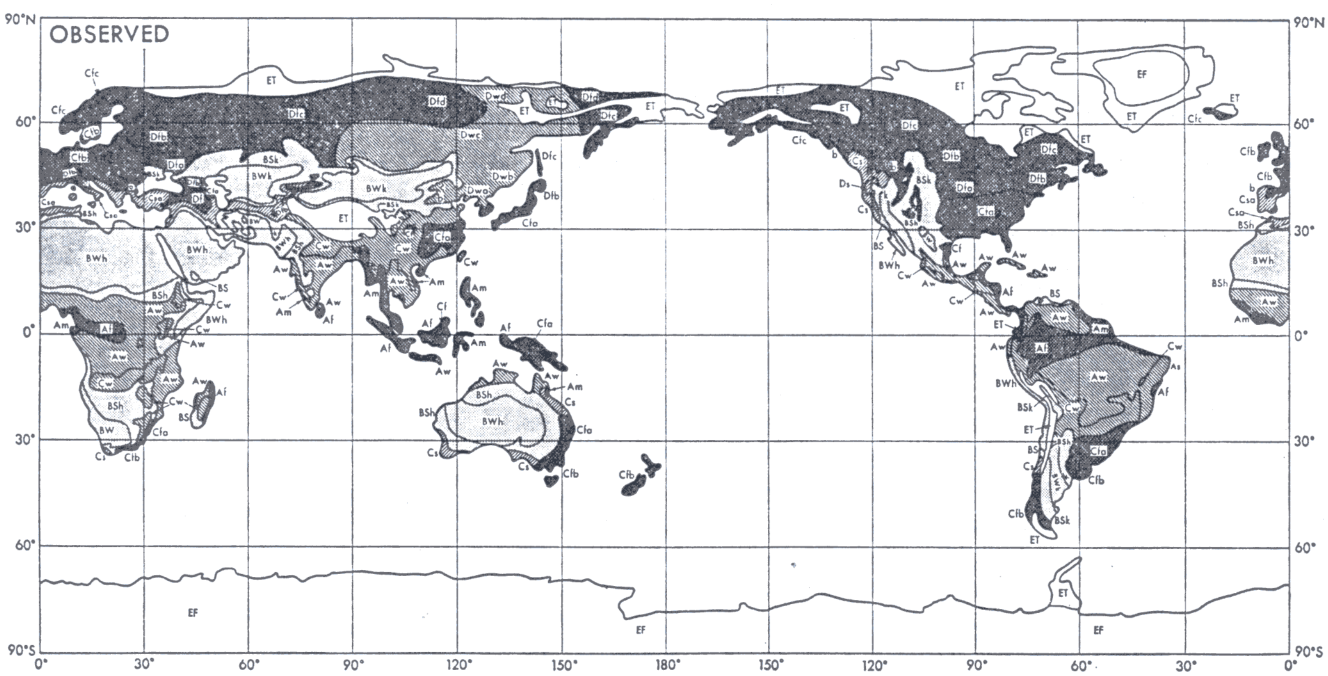

Figure 4 (b) Global distribution of Köppen climate types based on observed data (14).

of atmospheric temperature. Furthermore, the poleward heat transport by ocean currents reduces the meridional temperature gradient and accordingly the baroclinicity of the atmosphere.

The atmospheric model, which is described in the preceding sub-section, assumes the observed distribution of sea-surface temperature as a lower boundary condition and does not take into consideration the interaction between the ocean and atmosphere. For the study of the climatic variation discussed in the following sections, it is, however, essential to have a joint ocean-atmosphere model in view of the strong control of the ocean upon the long-term change of climate.

Attempts have been made to construct a global model of the joint ocean-atmosphere system at various institutions, such as the Naval Postgraduate School (15), UCLA, NCAR, and GFDL (16, 17). As an example of such a model, we shall briefly describe the structure and the performance of the preliminary version of the joint model of climate developed at GFDL.

Figure 5 shows a box diagram which identifies the major components of the joint model and indicates the interactions among these components. The basic structure of the atmospheric part of the model is very similar to the model described in the preceding subsection. The oceanic part of the model is similar to the model of Bryan and Cox (18) except that the field of salinity is calculated explicitly. One of the important features of the ocean model is a simplified method of calculating the growth and the movement of pack ice in polar latitudes. The grid size of approximately 500 km is used for the horizontal finite-differencing for both the atmospheric and oceanic models. For the vertical finite-differencing, nine and eleven levels are chosen for the atmospheric and the oceanic models, respectively.

As is usually done, the equilibrium climate is computed as an asymptotic state which emerges from the long-term integration of the joint model. One of the difficulties involved in this approach is that the thermal relaxation time of the model is so long that it requires an enormous amount of computer time to approach the equilibrium state through the straightforward integration of the joint model. In order to overcome this difficulty, we (19) have developed an economical method of time integration which is described below.

According to the results from a numerical time integration of an atmospheric model, the thermal relaxation time of the atmosphere is less than one year. On the other hand, an estimate of the ratio of heating to heat capacity of the ocean indicates that the thermal relaxation time for the ocean is of the order of centuries. In order to optimize the computation required for reaching the state of quasi-equilibrium, the coupling between the atmospheric and the oceanic part of the model is adjusted such that the evolution of the former during one atmospheric year is coupled with that of the latter during 300 oceanic years. For example, the atmosphere on the 0.5 and first atmospheric years interacts with the ocean on the 150th and 300th oceanic years of the time integration, respectively. The temperature of the surface mixed layer, which is computed by the oceanic part of the model, is used as a lower boundary condition for the atmospheric model. On the other hand, the rates of supply of heat, momentum, and water to the ocean surface, which are computed in the atmospheric model, serve as the upper boundary condition for the ocean model.

Despite the long integration of 300 years, the temperature in the lower half of the model ocean continues to change very slowly toward the end of the integration. However, the temperature in the upper layer of the ocean has hardly any systematic trends and fluctuates around the average value. As Figure 6 indicates, the net flux of

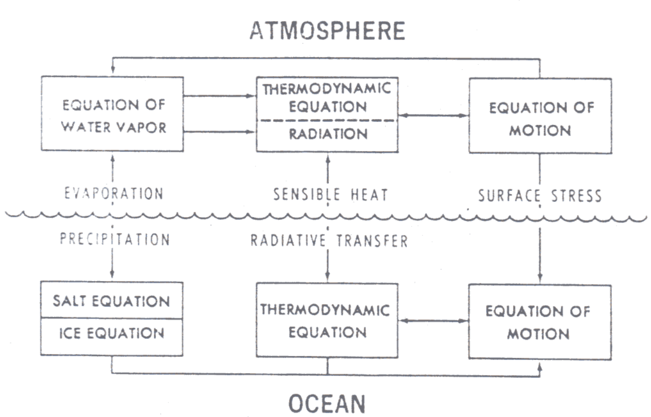

Figure 5 Diagram of the coupling of the major components of the joint ocean-atmosphere model (19, 17).

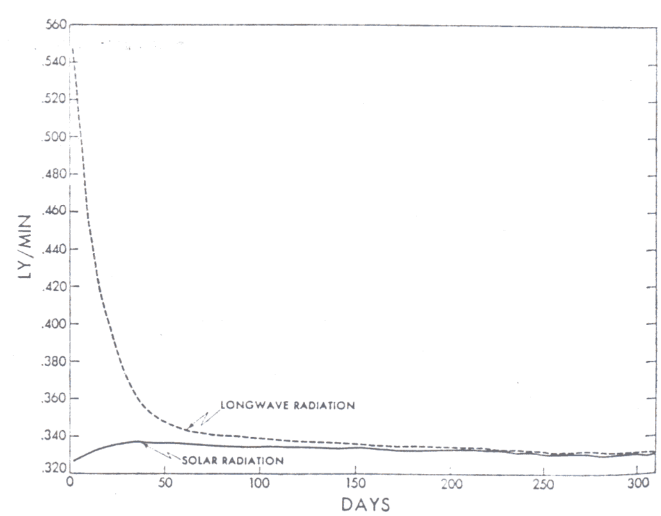

Figure 6 Time variation of the global mean net radiation at the top of the atmosphere in units of ly min^{-1} (17).

radiation approaches a zero value and is practically negligible at the end of the integration. These results suggest that the model climate, which emerged from this economical integration, is very close to the state of quasi-equilibrium.

Table 1 shows the computer time required for the integration of the atmospheric and oceanic parts of the model separately. According to this table, the numerical time integration of the oceanic part of the model is about 300 times faster than that of the atmospheric part of the model, partly because of the difference in the finite-difference time interval for the numerical time integration. Therefore, the computer time required for the integration of the oceanic model over the period of 300 years is the same order of magnitude as for the integration of the atmospheric model over the period of one year. This is one of the reasons why the proposed method is very economical.

TABLE 1

Machine time required for the one-year integration of the atmospheric and the oceanic parts of a global joint ocean-atmosphere model. The TI–ASC computer time is an estimate and not an actual value.

	No. of vertical finite-difference levels	*approx. grid size (km)*	*machine time (hr/yr)*	
			IBM 360–91	*TI-ASC*
Atmospheric model	9	250 500	1280 160	160 20
Oceanic model	12	250 500	4 1/2	1/2 1/16

The economical method of time integration, such as that described above, is indispensable for obtaining a climatic equilibrium from a long-term integration of a comprehensive model of the climate, i.e., one that consumes enormous amounts of computer time. It is recommended that a more economical method than the one described here be developed. It is also desirable to evaluate the validity of such a method by use of a simpler model of climate.

Obviously, it is not possible here to discuss all the details of the results obtained from the integration described above. Instead, one key variable of the model is chosen for this presentation. In Figure 7, the horizontal distribution of sea-surface temperature of the joint model is compared with the observed annual mean distribution. This figure clearly indicates that the model is capable of qualitatively simulating some of the gross features of sea-surface temperature. However, the computed distribution is, in general, more zonal than the observed. Since the computational resolution of the horizontal finite-differencing of this model is poor, it is necessary to use a very large subgrid-scale viscosity in order to obtain results free of modes induced by the comput~~er~~ational scheme. This may be partly * responsible for many of the failures of the model to reproduce the observed features quantitatively. As discussed by Manabe *et al.* (20) and Miyakoda *et al.* (21), the atmospheric part of the model also suffers greatly from the coarseness of the computational resolution. Further reduction in the grid size is required for better simulation.

The joint model described above assumes an annual mean distribution of insolation. A natural extension of this study is to simulate the seasonal variation of climate. In the author's opinion, this is the best way to validate the climate model, because the season is the most drastic change of climate which one can observe. In order to obtain the seasonal equilibrium of the model, it is necessary to adapt the economical method described earlier to the seasonal computation. At GFDL, we are attempting to do this at the present time.

3. POSSIBLE CAUSES OF CLIMATIC CHANGES

Many speculative theories have been proposed to explain why past climatic changes of various time scales have occurred. Reviewing these theories, one can classify the suggested causes of climatic change into two categories — the external and the internal causes. The external ones include the changes in boundary conditions and the basic physical structure of the joint ocean-atmosphere system. On the other hand, the internal causes are related to non-linear interactions among the various physical processes. Although the distinction between these two kinds of causes often becomes obscure, we shall list some examples for each category.

(*a*) External causes — changes in:

- orbital parameters of the earth;
- intensity in solar irradiance;
- rate of rotation of the earth;
- orographic features, such as land-sea distribution;
- atmospheric composition (mixing ratio of carbon dioxide, ozone, etc.);
- aerosol loading in the atmosphere (due to volcanic eruption or man's activity);
- heat output due to man's activity.

* Further improvement of the parameterization of the effects of subgrid-scale eddies may be required for a satisfactory simulation in view of the predominance of meso-scale, almost geostrophic eddies in the ocean (see the main text of this Conference).

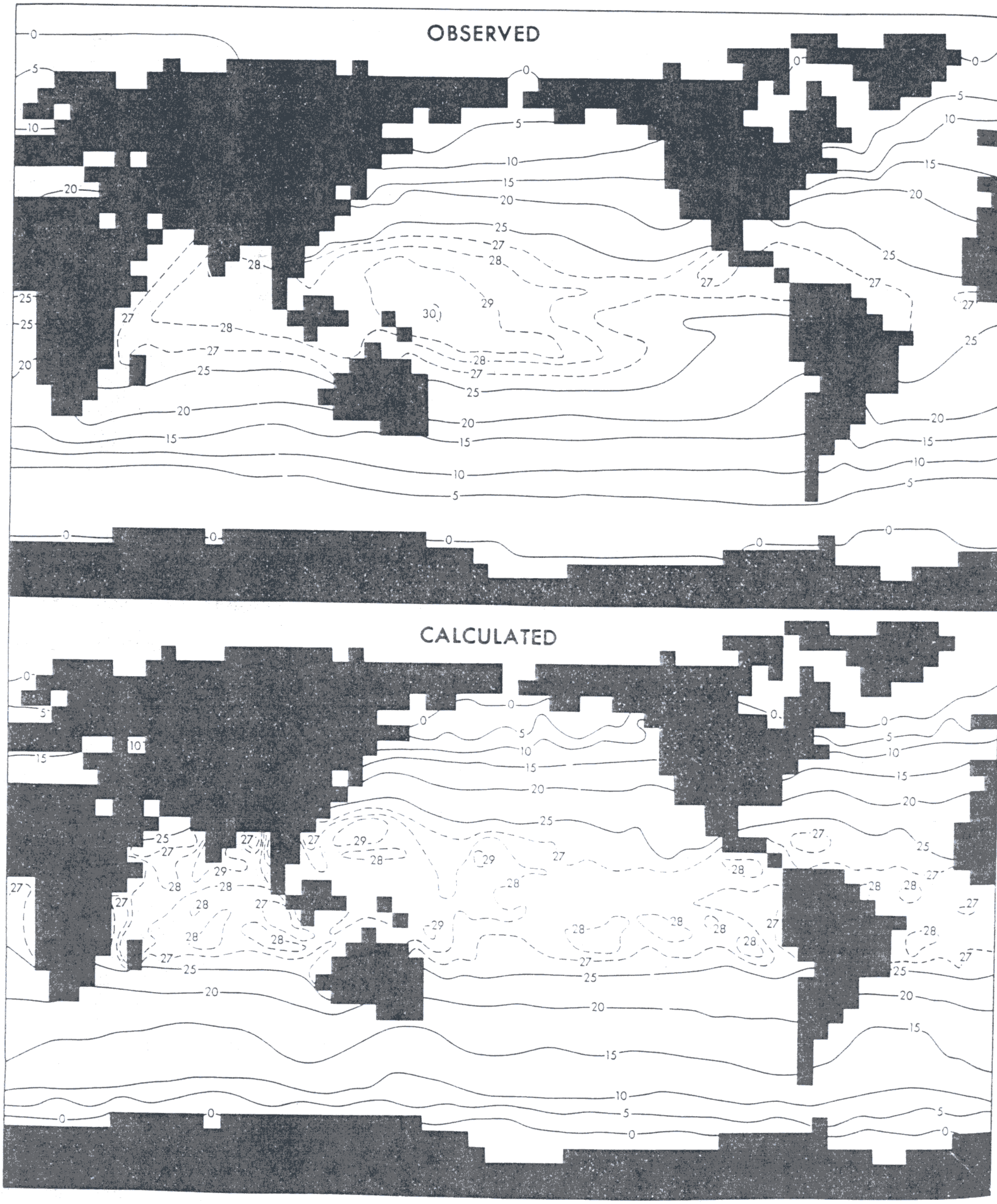

Figure 7 The annual mean ocean surface temperature in degrees C (18). Top; computed distribution. Bottom; observed distribution based upon Navy Hydrographic Office data.

(*b*) Internal causes

- various positive and negative feedback mechanisms which prevail in the atmosphere and in the ocean;
- interaction among the atmosphere, ocean, and cryosphere.

In the following, I would like to discuss how one can use a comprehensive model of climate for evaluating the relative importance of the various possible causes of the climatic changes listed above. To evaluate the climatic effects of various changes listed as due to external causes, one can carry out a so-called "sensitivity study". Performing a set of numerical experiments with a comprehensive model of climate, one can inquire how the equilibrium climate, which emerged from the long-term integration of the model, is affected by these external causes. This subject is discussed in the following section.

To study the climatic changes caused by the internal causes, one can carry out a long-term integration of a climate model with and without a certain feedback mechanism, and try to identify the basic mechanisms responsible for the natural climatic variability having various time scales. This subject is discussed in the latter part of Section 5.

4. EXAMPLE OF A SENSITIVITY STUDY

As an example, results are presented from a recent study which was carried out by using a three-dimensional model of the atmosphere (22). Although the model contains many simplifications and assumptions, this example is chosen for discussion because it brings out many problems which are encountered in a sensitivity study.

According to Machta (23), the concentration of carbon dioxide in the atmosphere may increase by as much as 20% during the last half of this century as a result of fossil fuel combustion. The objective of this study is to get a preliminary idea of the response of the climate to such an increase.

The basic structure of the atmospheric model used for this study is very similar to the model described in Section 2.1, except that the model has a limited computational domain and a swamp-like ocean without any heat capacity. These exceptional features of the model are described below.

Figure 8 shows the idealized distribution of ocean and land adopted for this model. Cyclic continuity from one meridional boundary to another is assumed. At the equatorial boundary, a symmetry condition is imposed. Because of these idealizations, the computer time required for the time integration of this model is approximately one-sixth of that required for a global model with

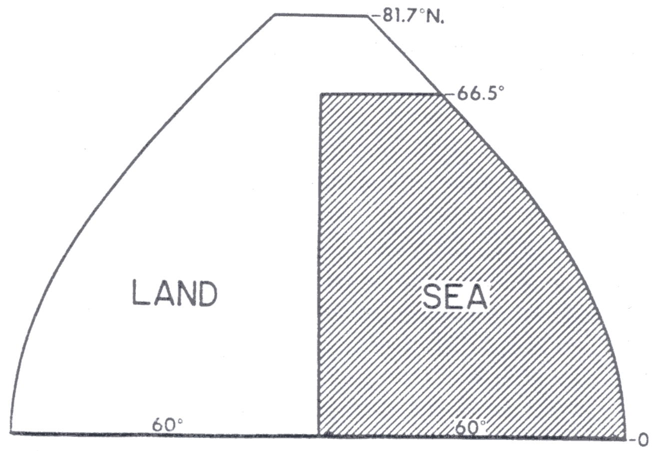

Figure 8 Diagram illustrating the distribution of continent and ocean (22).

comparable finite-difference resolution. The oceanic surface is treated as if it were a swamp. In other words, it resembles the actual ocean in that it is a wet surface with an unlimited supply of water, but differs from the ocean because its temperature is not affected by the heat transport by ocean currents. The temperatures of both oceanic and continental surfaces are computed from the equation of heat balance with the assumption that these surfaces have zero heat capacity. By replacing the ocean with a swamp having instantaneous thermal response, it becomes unnecessary to carry out the long-term integration of the ocean discussed in Section 2.2. In order to incorporate into the model a so-called "ice-temperature feedback" mechanism, the depth of snow cover is predicted by an equation of snow budget, and the extent of sea ice is determined according to the temperature of the swamp surface. The albedos of snow cover and sea ice are assumed to be significantly larger than those of bare soil or open sea. For the economy of computer time, a grid size for the horizontal finite difference is chosen to be 500 km instead of 250 km.

The approach adopted for this study is to compare the climate, which emerges from the long-term integration of the model with standard concentration of carbon dioxide, with the climate of the model having twice the normal concentration of carbon dioxide. The differences between the two model climates are regarded as representing the climatic effects of doubling the concentration of carbon dioxide. In order to obtain a meaningful result from this approach, it is necessary to satisfy the following requirements:

(*a*) The long-term integration of the model yields a stable equilibrium climate.

(*b*) The effects of the doubling of carbon dioxide content are not large enough to force the model climate out of the stable equilibrium into a markedly different state.

(c) The period of the time integration is so long that the difference between the final model climate and the state of perfect equilibrium is much less than the climatic effect of doubling the concentration of carbon dioxide.

(d) To obtain the climate equilibrium for each integration, it is necessary to perform the time averaging of the state of the model atmosphere over sufficiently long periods. The period of averaging must be long enough so that the amplitude of the natural variability of the time-mean state is much less than the climatic effect of the CO_2 doubling.

The actual procedure of time integration is described briefly.

For each concentration of carbon dioxide, two long-term integrations of the model are carried out over a period of 800 days, starting from two quite different initial conditions. Figure 9 shows how the mean temperature (mass-weighted) of the model changes with time from the two initial values. Although the initial values for the two runs are considerably different from one another, the final values are practically indistinguishable near the end of the integrations. The difference between the two mean temperatures averaged over the last 100 days of each integration is about 0.1°C, which is much less than the temperature change caused by the doubling of carbon dioxide discussed below. The final equilibrium climate is obtained by averaging two 100-day mean states computed from the final parts of the two integrations. Figure 9 suggests that the final equilibrium thus computed essentially satisfies requirements *a*, *c*, and *d* listed in the preceding paragraph. Further analysis of the results clearly indicates that requirement *b* is also satisfied.

Having described the model structure and the method of numerical time integration, we can proceed to a brief description of the results. Figure 10 shows the difference in zonal mean temperature between the $2 \times CO_2$ and the standard case. Owing to the increase in the greenhouse effect resulting from the increase in the concentration of carbon dioxide, there is a general warming in the model troposphere. On the other hand, a great deal of cooling occurs * in the model stratosphere. This is caused by the increase in the emission from the stratosphere to space. Qualitatively similar results were obtained by Manabe and Wetherald (24) in their study of the radiative, convective equilibrium of the atmosphere. According to Figure ~~4b~~ 10, the tropospheric warming is most pronounced in the lower troposphere at high latitudes. This large warming is associated with the decrease in the area of snow (or ice) cover, which has a much larger albedo than a soil surface. The increase in the downward terrestrial radiation due to

* This is one of the reasons why one has to take into consideration the vertical distribution of temperature in the discussion of the sensitivity of climate to the change in CO_2 concentration.

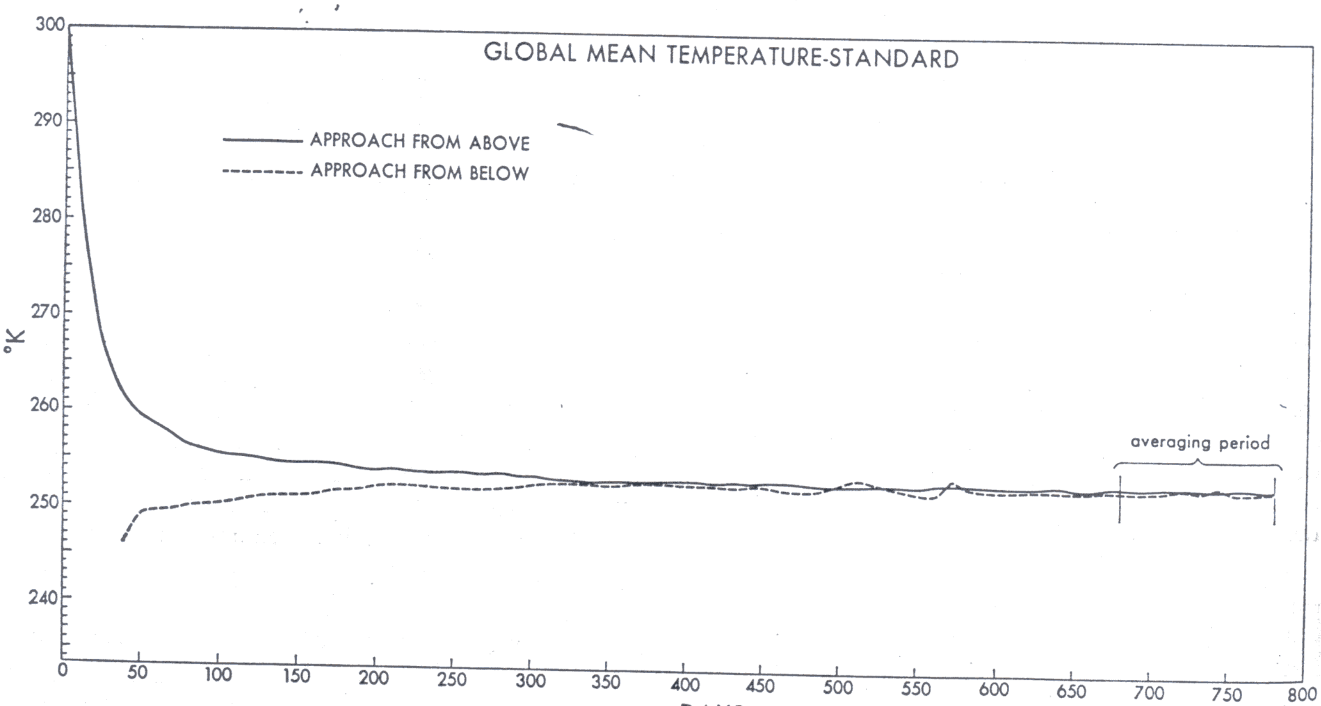

Figure 9 Time variation of (mass weighted)-mean temperature (°K) for the entire period of integration of the two standard runs (22).

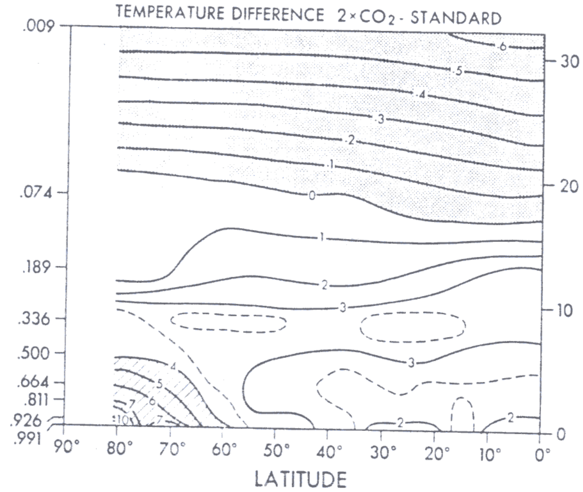

Figure 10 Latitude-height distribution of the zonal mean temperature difference (°K) between the $2 \times CO_2$ and standard cases. Shaded area denotes negative values (22).

TABLE 2

Increase in the equilibrium temperature of the earth's surface resulting from the doubling of the concentration of carbon dioxide. R–W model: radiative-convective equilibrium model which incorporates the modified version of radiation scheme developed by Rodgers and Walshaw (25, 26); M–W model: radiative-convective equilibrium model of Manabe and Wetherald (22); G–C model: the general circulation model described in this study. The figure for the G–C model represents the average value over the entire computational domain. Units are in °K.

Change of CO_2 content (ppm)	*R–W Model*	*M–W Model*	*G–C Model*
300→600	+ 1.95	+ 2.36	+ 2.93

the increase in the amount of carbon dioxide contributes to the decrease in the area of snow cover and accordingly to the increase in the amount of solar radiation absorbed by the earth's surface. As mentioned above, the warming in high latitudes is confined within a relatively shallow layer next to the earth's surface because the vertical mixing by turbulence is suppressed in the stable layer of the troposphere in the polar regions. Therefore, most of the thermal energy goes into raising the temperature of this shallow surface layer rather than being spread throughout the entire troposphere. In short, the effects of suppression of vertical mixing together with those of snowmelt are responsible for the great warming in the polar region.* In the model tropics, the warming spreads throughout the entire troposphere, and thus its magnitude is relatively small when compared with the magnitude of warming in the polar region.

Table 2 is presented to indicate the sensitivity of the mean-surface temperature to the changes in CO_2 concentrations. This table shows the difference in mean-surface temperature as a function of CO_2 concentration for both the general circulation model and the one-dimensional, radiative-convective equilibrium model constructed by Manabe and Wetherald (24). (Note that the scheme for computing radiative transfer which is incorporated into the general circulation model is identical to that adopted by the radiative-convective model of Manabe and Wetherald (24)). Also shown, for the sake of comparison, are the corresponding values obtained using the modified version of the Rodgers-Walshaw radiation model (25) which is constructed by Stone and Manabe (26) and is, in our opinion, a superior model. According to this table, the magnitude of the surface temperature difference is considerably greater for the general circulation model than for the corresponding radiative-convective model by itself. This suggests that the former is more sensitive to changes in CO_2 concentration than the latter. This difference in sensitivity is due, in part, to the snow-cover feedback mechanism present in the general circulation model but not accounted for in the radiative-convective equilibrium model.

Finally, it is of interest to note that doubling of the CO_2 concentration not only affects the temperature of the model atmosphere but also increases the areal mean rate of evaporation, and accordingly that of precipitation, by approximately 7%.

One of the important characteristics of the model is that it used a fixed distribution of cloudiness rather than one determined by the time integration. As discussed by Manabe and Wetherald (24) and Schneider (27), a model climate can be extremely sensitive to the height as well as the amount of clouds, particularly to the amount of low cloudiness. Therefore, it is possible that the sensitivity of the climate produced by the model with fixed distribution of cloudiness is quite different from that produced by the model in which cloudiness is a prognostic variable. Unfortunately, a scheme for predicting cloudiness with sufficient accuracy is not available at the present time. The development of a satisfactory scheme for cloud prediction is one of the most difficult but urgent projects required for climate modelling.

As pointed out already, the sensitivity study described above does not take into consideration the effects of heat transport by ocean currents. In order to do this, it is necessary to carry out similar studies by means of a joint ocean-atmosphere model similar to the model described

* Note also that the surface albedo of snow cover in the cold polar region is assumed to be larger than that in warmer regions. The large polar warming is partly due to the poleward recession of the region of high snow albedo (see (22) for further details).

in Section 2.2. One of the difficulties of such a study results from the very long thermal relaxation time of the ocean. If one performs a straightforward integration of the joint model, it will take an exceedingly long time before one can reach a satisfactory equilibrium state. Therefore, an economical method of time integration, such as that described in Section 2.2, may be useful.

In view of the various idealizations of the model described so far, it is not advisable to take too seriously the quantitative aspect of the results. Nevertheless, this study identifies some of the processes which are important for the evaluation of the climatic effects resulting from the change in concentration of carbon dioxide.

The sensitivity study yields the magnitude of the possible change of the climate due to external causes. However, it does not necessarily indicate the time required for the realization of such a change. In principle, it should be possible to get this information from the long-term integration of a joint ocean-atmosphere model. For example, starting from the equilibrium climate for the standard concentration of carbon dioxide, one can perform a straightforward time integration of the joint model with twice the normal concentration of carbon dioxide. From this integration, it may be possible to determine the time required for the systematic changes of the model climate, which are due to the doubling of the CO_2 concentration, to become significant compared with the amplitude of the natural variability of climate.

It should be emphasized that a sensitivity study should not be confused with a study of a climate prediction, which is discussed in Section 5. Any climatic change due to an external cause is superimposed upon the natural variation of climate. Therefore, the actual climate does not necessarily change in the direction suggested by a sensitivity study. Nevertheless, a sensitivity study should yield an excellent idea about the relative importance of various external causes.

So far, we have investigated the perturbation of the model climate around its stable equilibrium, which occurs in response to the relatively small external forcing. Obviously, it is also very useful to inquire: (*a*) how large an external forcing is required in order to expel the model climate out of its stable equilibrium; or (*b*), how the model climate changes thereafter. Such study may be called a sensitivity study of the second kind.

Examining the procedures of the numerical time integration described earlier, one can see that a sensitivity study consumes a great deal of computer time even if one uses an atmosphere model without an ocean. Therefore, it is desirable to obtain preliminary results from a model with fewer degrees of freedom, such as a truncated spectral model mentioned in the Introduction.

There are other examples of sensitivity studies which are carried out by use of three-dimensional models. For example, Washington (38) attempted to evaluate the climatic effects of thermal pollution resulting from the industrial activities on the eastern coast of North America by using the general circulation model developed at NCAR. It is highly desirable to perform many more sensitivity studies designed for identifying the climatic effect of man's activities.

5. CLIMATE PREDICTION

5.1 *Extended range forecasting*

The studies of Namias (29), Bjerknes (36) and others indicate that the anomalies in the sea-surface temperature have profound effects upon the statistical behaviour of the atmosphere. Therefore, if one can deterministically predict the future change of the oceanic state by use of a joint ocean-atmosphere model, it may then be possible to predict the future statistical state of the atmosphere responding to the variable forcing from the ocean surface. The statistical state of the atmosphere in turn affects the state of the oceans.

One of the basic assumptions, which is implicit in the expectation described above, is that the period for deterministic prediction of the oceanic state is much longer than that for the atmosphere. Studies by Lorenz (31), Leith (32) and Miyakoda *et al.* (21) seem to indicate that the period of atmospheric predictability is approximately a few weeks. On the other hand, it may be reasonable to expect that one can predict a future change of the oceanic state much longer in advance than a few weeks in view of the large heat capacity of the ocean and the long time constant involved in the change of the large-scale anomalies of temperature distribution in the oceans. To obtain a better understanding of this subject, it is very desirable to carry out theoretical studies of the predictability of the oceanic state which are similar to the studies on atmospheric predictability by Lorenz and Leith. Since this subject is covered by the position paper on predictability, it will not be discussed further here.

There are other factors which can significantly affect the long-term statistical behaviour of the atmosphere. For example, Namias (33) suggested that an anomalous rate of precipitation in one season can modify the precipitation in the following season by influencing the amount of water stored in the ground, or an anomalous distribution of snow cover can alter the seasonal variation of climate because of the large albedo of snow cover. Using satellite data, Kukla and Kukla (34) have shown that there is a significant interannual variation of the area of snow cover in the polar region of the northern hemisphere. They have suggested a link between unusually extensive snow cover and anomalous behaviour of the atmosphere. Because of the large negative latent heat stored in the snow cover, it may be possible to predict a future change in snow cover for a much longer time than the period of the predictability for atmospheric disturbances. Therefore, it is very important for the success of the extended-range forecast to develop an accurate scheme for predicting snow cover and to incorporate it into a joint ocean-atmosphere model.

Before attempting to carry out extended range forecasts by use of a joint model with the prognostic system of snow cover and sea ice, it is desirable to study the feasibility of such an attempt by performing the following research.

5.1.1 *Evaluation of the climatic effects of the anomalies of sea-surface temperature and snow cover*

We should carry out numerical experiments designed to identify the responses of the atmosphere to anomalous sea-surface temperature (snow cover or soil moisture). Preliminary studies of this kind have been done by Rowntree (35), Spar (36, 37), Gates (38) and others. Because of the lack of a statistical evaluation of the results, the conclusions from some of these studies are not totally convincing to me. It may be desirable to compute the signal-to-noise ratio proposed by Leith (39) for properly evaluating these results.

5.1.2 *Validation of a joint ocean-atmosphere model*

For the prediction study, it is necessary to make sure that a joint model not only simulates the observed climate equilibrium but also has realistic transient behaviour. Therefore, the validation of a prediction model (particularly the oceanic part of the model) requires much more care than that of a model for a sensitivity study.

Before validating a joint model as a whole, it is desirable to evaluate the atmospheric and oceanic models separately. In Section 2, an attempt to verify the atmospheric model against the seasonal variation of the actual climate is described very briefly. Mintz *et al.* (6) and the NCAR group are making similar comparisons using the results obtained from their general circulation models.

Simulations of the seasonal changes of the oceanic state have been attempted by Cox (40, 41) and Takano *et al.* (42). These studies represent an excellent beginning for validating the oceanic model. Nevertheless, the ocean models present generation fails to simulate quantitatively many of the important features of the ocean, such as the depth of thermocline, the thickness of mixed layers, the concentration of isotherms in the Gulf Stream region, and the extent and thickness of sea ice.

Obviously, further improvements of the atmospheric and oceanic parts of the model are required before one can get a satisfactory verification of a joint model. Since improvements in atmospheric models have been discussed extensively in many GARP documents, they are not repeated here. However, I would like especially to emphasize the improvement of:

- the prognostic system of cloudiness;
- the prognostic system of snow cover.

According to the guideline for this conference, the subject of ocean models will be discussed in a separate position paper. Therefore, I am not going to present an extensive list of the outstanding problems. However, I believe that special emphasis should be placed upon the improvements of:

- parameterization of the effect of vertical mixing in the surface layer of the ocean;
- parameterization of the effects of horizontal mixing due to subgrid scale, almost-geostrophic eddies;
- prognostic system for sea ice.

The observational programmes of NORPAX, MODE and AIDJEX should yield very useful information for these projects.

5.1.3 *Numerical prediction of the oceanic state by an ocean model*

It is desirable to carry out the numerical prediction of the oceanic state by means of an ocean model for which the time variation of the upper boundary conditions is prescribed. Huang (43, 44) has made such an attempt by prescribing the temperature and wind at anemometer level. It is recommended to carry out an observational programme which will yield a data set describing the transient variation of ocean and its upper boundary condition in order to verify the oceanic prediction described above.

5.2 *Natural variability of the climate*

As discussed in Section 3, climatic variation may be caused by internal causes, i.e., by the non-linear interactions among various physical processes which take place in the atmosphere, ocean and cryosphere. To find out how each physical process influences the course of a climatic change, it is desirable to perform a long-term integration of the climate model with and without the processes of our concern.* Using the fastest available computer, we may be able to carry out a straightforward

* As recommended in the preceding section, one can also perform a long-term integration to find out how much time elapses before externally-caused climatic changes become significant.

integration of a joint model with relatively low computational resolution (grid size $\approx$ 500 km) up to fifty years. When it is confirmed that the joint model is sufficiently realistic, it may be worthwhile to carry out such an integration for a study of the natural variability of climate.

For periods longer than fifty years, it is not advisable to perform a straightforward integration because of the enormous computer time involved. Therefore, one should try to use a simpler model. Nevertheless, it is worthwhile to perform such a study with a joint ocean-atmosphere model. One of the possible approaches is to use a procedure similar to the economical method of time integration which is used for reaching the climate equilibrium (see Section 2). For example, 1000 years of oceanic integration may be synchronized with a shorter period, say fifty years of atmospheric integration. One of the basic assumptions which is implicit in the use of this economical method is that the atmosphere adjusts itself to the transitive equilibrium corresponding to a given distribution of sea-surface temperature. As the model ocean evolves with time, the model atmosphere follows the oceans, adjusting quickly to the slow-varying sea-surface temperature. Accordingly, it is expected that in this way we can get essentially the same evolution of the oceanic state and the corresponding climate of the atmosphere as in the case of straightforward integration of the joint model. It is desirable to test the validity of this economical method by applying it to a simpler model.

Finally, it should be emphasized that the long-term integration of a climate model is meaningful only after sufficient validation of such a model. The joint model should be able to reproduce not only the seasonal variation of the atmospheric and the oceanic state, but also the three-dimensional distribution of oxygen, salinity, and other chemical constituents throughout the depth of the ocean. In this regard, the GEOSECS experiment, which is being carried out at the present time, should yield valuable information which will be useful for the verification of the oceanic part of the model.

6. RECOMMENDATIONS

The following recommendations are made with respect to comprehensive models of climate. However, it is desirable first to use models with fewer degrees of freedom.

(*a*) It is recommended that joint ocean-atmosphere models be improved. Special emphasis should be placed on the development or improvement of:

(1) prognostic system of cloud cover;
(2) prognostic system of snow cover;
(3) parameterization of moist convection in the atmosphere;
(4) parameterization of vertical mixing in the upper layer of the ocean;
(5) parameterization of horizontal mixing due to the mesoscale, quasi-geostrophic eddies in the oceans;
(6) prognostic system of sea ice.

(*b*) It is recommended that joint ocean-atmosphere models be verified against:

(1) seasonal variation of the atmospheric and oceanic state;
(2) three-dimensional distributions of temperature, salinity, oxygen, and other trace substances in the deeper as well as the upper layer of the ocean.

To carry out these recommendations, it is desirable to compile a data set describing the seasonal variation of the oceanic and atmospheric state by utilizing all available data.

(*c*) It is recommended that sensitivity studies be performed designed to evaluate the magnitude of possible climatic changes due to various external causes, such as:

(1) change in the concentration of CO_2 due to fossil fuel combustion;
(2) change in the load of aerosol in the atmosphere;
(3) thermal pollution due to industrial activities;
(4) other changes in external parameters, such as orbital parameters of the earth.

To complete these sensitivity studies in limited computer time, it is desirable to develop a method for getting the equilibrium climate of the model with a minimum amount of computation.

(*d*) It is recommended that we

(1) study the mechanism which controls the natural variation of climate over a period less than fifty years by performing the time integration of a joint model with and without certain non-linear coupling;
(2) determine the time required for the realization of significant climatic changes due to an external cause by performing a time integration of a joint model;
(3) devise economical methods for the long-term ($<$ 50 years) integration of a comprehensive climate model.

(*e*) To evaluate the possibility of seasonal and inter-annual forecasting of the climate, it is recommended that we

(1) determine the effects of the anomalies of sea-surface temperature (snow cover or soil moisture) upon the statistical state of the atmosphere based upon the results from numerical experiments with an atmospheric model, as well as results from analyses of actual data;

(2) determine the effects of the anomalies of wind stress and precipitation upon the state of the ocean based upon the results from numerical experiments with an ocean model;

(3) perform a numerical prediction of the oceanic state by an ocean model which is given observed upper boundary conditions;

(4) perform a numerical prediction of snow cover by use of an atmospheric model with given distribution (seasonal varying) of sea-surface temperatures;

(5) perform a seasonal and interannual prediction of the climate by means of a joint ocean-atmosphere model;

(6) initiate an observational programme which will yield a data set describing the transient variation of the upper layer of an ocean and its upper boundary condition (this is necessary to carry out the numerical prediction recommended in (*e*) (3) above).

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