Aust. J. Phys., 1980, **33**, 897–910

Numerical Modelling of Climate

B. G. Hunt

Australian Numerical Meteorology Research Centre, CSIRO,
P.O. Box 5089AA, Melbourne, Vic. 3001.

Abstract

Numerous ways of modelling climate exist, ranging from a single, simple mathematical equation up to complex global atmospheric–oceanic coupled models which explicitly forecast the basic weather elements such as temperature, pressure, wind velocity etc. These models, known as general circulation models, currently provide the most comprehensive and credible representations of climatic systems. The structure of these models is briefly outlined, and results from a number of models are presented to illustrate their versatility. A number of other simpler modelling approaches to climate are discussed to emphasize the opportunities which this problem presents for creative and rewarding research.

1. Introduction

Currently, interest in climate and the prediction of climate is at an all time high. This is partly due to the fact that with modern computers and numerical integration methods hitherto impractical techniques have now become viable. More importantly the realization that we are on a planet with limited resources and growing population pressures has emphasized our increasing vulnerability to climatic fluctuations. Finally, there is a widening appreciation that mankind now has the capacity to alter inadvertently the future climate via a number of pollutants, and that this could result in undesirable climatic changes.

Numerical simulation of climate has proceeded in a large number of diverse ways, as befitting an intellectually challenging and exciting area of science which involves complex interactions between nonlinear systems. A large deal of the complexity arises because climate involves variations in the atmosphere, the oceans, snow and ice cover and land surfaces, and the mutual interactions between these components on all major temporal and spatial scales. There are two basic types of climatic predictions which can be made. The first concerns changes to the boundary conditions, such as solar constant variations, where predictions of some value are possible. As of now we are unable to predict climatic perturbations of the second type which presumably arise from naturally occurring fluctuations of the climatic system, and are therefore dependent on the initial state. In addition to satisfying the obvious demand for climatic predictions, there is an urgent need to understand the principles which control climate and its variations. Thus climatic simulation is concerned with both of these tasks, resulting in a very fruitful area of research.

Rather than attempt to review comprehensively all possible methods of climatic simulation, a few selected approaches will be considered to illustrate the present state of the art. Schneider and Dickinson (1974), the National Research Council

(1974), GARP (1975) and Saltzman (1978) provide useful surveys of both the present state of climatic research and the possible simulation techniques.

2. General Circulation Models

These models attempt to simulate the large scale meteorological distributions (pressure, temperature, wind etc.) of the atmosphere, normally on a global or hemispheric basis. Elaborations of the basic models to include simulations of oceanic properties, cloud cover, ice variations, atmospheric composition and other relevant climatic terms are in various stages of advanced development or assessment. Such complex interactive models are necessary for many problems of climatic interest. Comprehensive descriptions of a general circulation model have been given by Manabe *et al.* (1965) and Smagorinsky *et al.* (1965) and the interested reader is referred to these, as only a bare outline of the model will be given here.

The models are based on first order partial, nonlinear, differential equations which permit the basic meteorological fields to be integrated forward in time. The equations are slight variants of well known equations in general physics: the Navier–Stokes equations for momentum, the thermodynamic equation embodying the first law of thermodynamics, the equation of state, the equation of mass continuity etc. Thus to a certain extent this branch of meteorology is really part of applied mathematics. The equations are usually solved by representing the spatial fields of the variables by a network of gridpoints over the region of interest which, for given initial conditions, permits the variables to be numerically integrated with time by typically a few minutes. This generates a new set of initial conditions, and the process can then be repeated to simulate the atmospheric evolution into the future. Since the process has to be carried out at numerous gridpoints for a lengthy sequence of time integration steps it is ideal for application to a computer. In fact large scale atmospheric simulation is one of the major scientific fields encouraging the development of 'super computers'. Many complex problems have to be resolved in order to simulate the atmosphere apart from the actual time integration of the equations; problems such as the inclusion of radiative and dissipative processes, convective activity and coupling the atmosphere with the Earth's surface are involved. Moreover, interpretation of the model's output to obtain new insights into atmospheric behaviour is an inherently difficult task, to which rather few scientists seem able to contribute. As a consequence, general circulation models have been restricted to a limited number of international groups, which have the facilities and the dedicated teams of scientists necessary for success in this field.

Although much scope for model improvement remains in a number of areas, the rapid progress made in the last 10 years is encouraging and augurs well for the future. The models have tremendous potential for numerous problems of social importance, and some examples are given below to illustrate this point.

First, a comparison of simulated fields with observation is shown in Figs 1 and 2 to emphasize the current capability of the models. The agreement with observation is gratifying and, although not all aspects of the simulation are as satisfactory as this, nevertheless it supports the use of the models in geophysical problems. For example, the model which produced the surface temperature distribution in Fig. 2 is now being used in a long term program of drought simulation, with a view to identifying the underlying causes of this chronic problem in Australia.

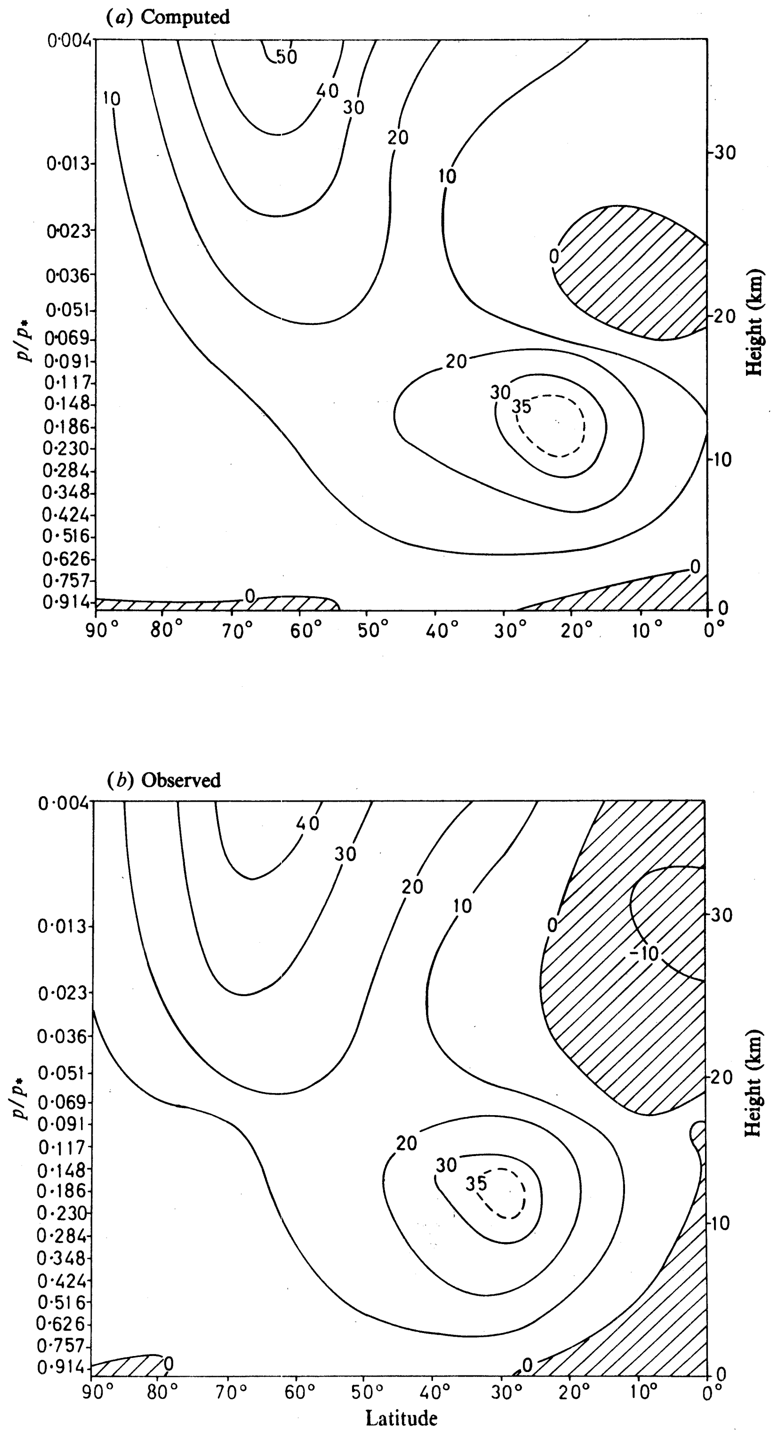

Fig. 1. Computed (*a*) and observed (*b*) mean zonal (east–west) winds (in units of $m\,s^{-1}$). The shaded areas are regions with east winds. The left-hand ordinate is the local pressure p normalized by the surface pressure p_*.

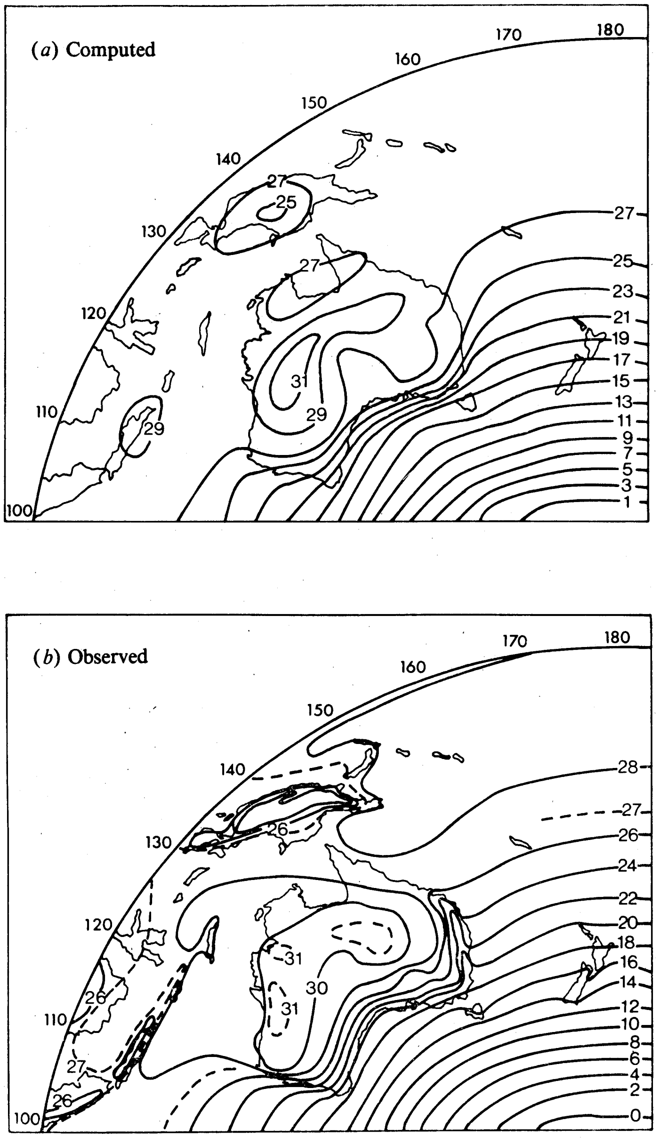

Fig. 2. Computed (*a*) and observed (*b*) January surface temperatures (°C) for the Australian region. The sea surface temperatures are specified in the model. The computed results were generated in a global model. [Figure supplied by courtesy of M. E. Voice, ANMRC.]

An indication of the present ability to forecast clouds is shown in Fig. 3. Overall the basic agreement between model and observation is quite good, although detailed improvements are necessary. Clouds play a very important role in determining the radiation balance of the Earth–atmosphere system; hence the need to improve cloud forecasting techniques, particularly in experiments where climatic perturbations are being explored.

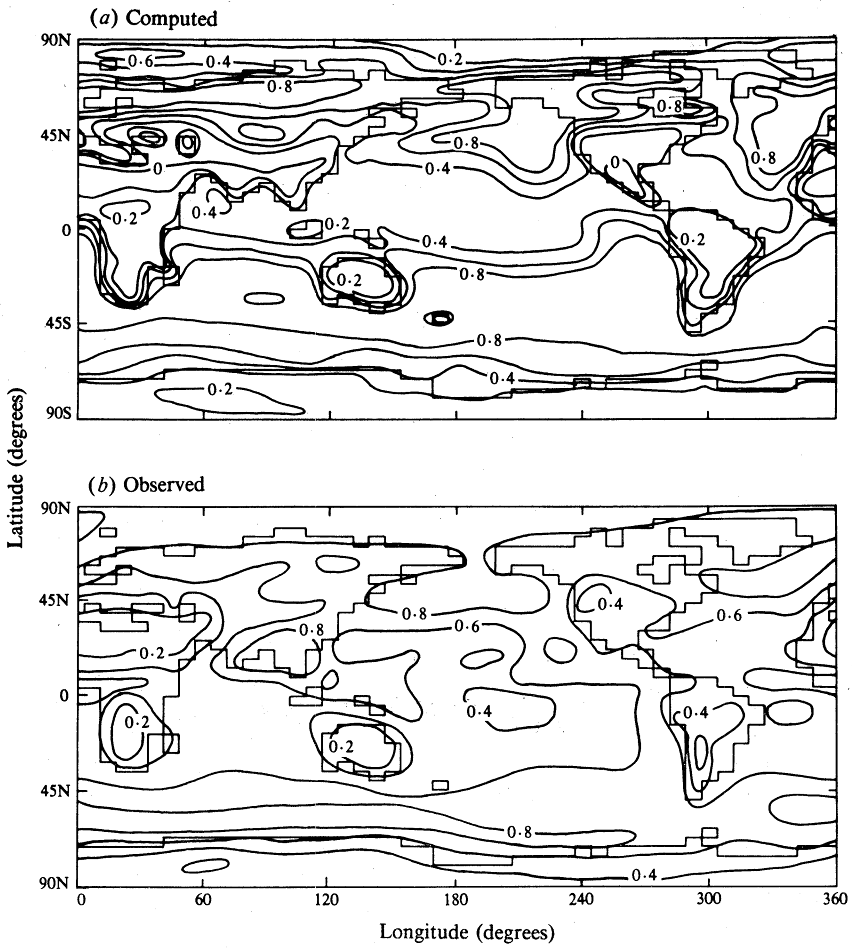

Fig. 3. Time averaged global cloud covers (in tenths) as computed in a model (*a*) and observed (*b*), for July conditions. [Figure supplied by courtesy of H. B. Gordon, ANMRC.]

The results in Figs 1–3 were obtained with three distinct models. A hierarchy of general circulation models exists which have varying horizontal and vertical resolutions, physical processes and numerical techniques.

A considerable number of experiments designed to assess potential climatic changes have now been performed with general circulation models. For example, the influence of waste heat release has been examined by Williams *et al.* (1979), the role of soil moisture in controlling desertification by Walker and Rowntree (1977), the atmospheric consequences of a large sea surface temperature anomaly by Wells (1979), solar constant variations by Wetherald and Manabe (1975), atmospheric carbon dioxide increases by Manabe and Wetherald (1975) and volcanic eruptions by Hunt (1977). General circulation models have also been used for a variety of other purposes, such as the simulation of ice ages by Gates (1976), the climatic impact of removing the Arctic Ocean ice sheet by Newson (1973), the transport of nuclear bomb debris in the atmosphere by Hunt and Manabe (1968), the simulation of the atmosphere of Venus by Young and Pollack (1977) and the consequences of variations in the Earth's rotation rate by Hunt (1979).

Two examples will be given to illustrate these studies. In Fig. 4 the latitudinal temperature change predicted for a doubling of the atmospheric CO_2 content is shown. Notice that in addition to a general warming of the surface and lower atmosphere of about 2 K in the tropics and sub-tropics, an enhanced warming occurs at higher latitudes. This is attributed to changes in surface reflectivity of the snow and ice, and to the trapping of warm air in the near surface layer. Changes are produced in other meteorological variables, such as energy transport, precipitation and water storage in the surface layer, all of which have potential climatic, economic and sociological implications. Since CO_2 in the atmosphere is expected to double from its preindustrial value by the middle of next century, owing to fossil fuel burning and the clearing of land, an important inadvertent climatic change may occur. Apart from analogues of unknown value to past years of warmer conditions (Wrigley *et al.* 1980), the only way the geographical consequences of this climatic effect can be assessed realistically is via general circulation models.

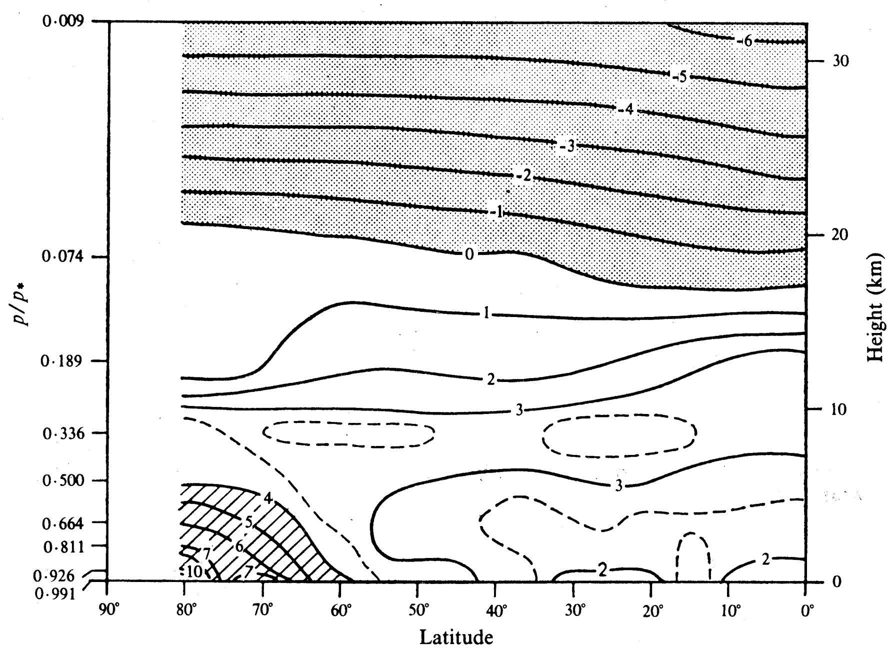

Fig. 4. Computed temperature change (K) produced by doubling the carbon dioxide content of the atmosphere. The left-hand ordinate is the local pressure p normalized by the surface pressure p_*. [From Manabe and Wetherald (1975).]

The second example concerns the climatic impact of large volcanic eruptions which influence the climate by depositing fine particles in the stratosphere, where they reflect the incoming solar radiation. Fig. 5 shows that a cooling of about 0·5 K is produced at low latitudes by a tropical eruption, and that subsequently a cooling at higher latitudes occurs. Such small temperature changes are important climatically, and a very large volcanic eruption could have a marked depressing effect on food production.

Many other aspects of climatic modelling have not been discussed here. Foremost among these are atmospheric–oceanic coupling, as attempted by Manabe *et al.* (1975) and Bryan *et al.* (1975). Another important factor concerns the cryosphere, and Parkinson and Washington (1979) have recently developed a numerical model of sea ice, while Budd (1975) has modelled the detailed dynamics of a glacier. Much scope exists for ingenuity in these and other aspects of large scale climatic modelling.

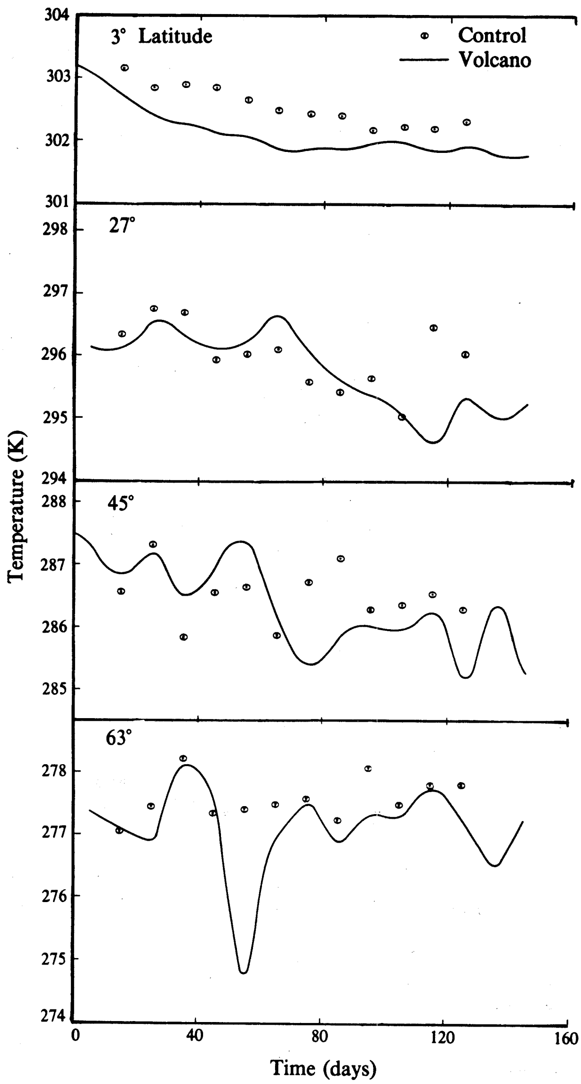

Fig. 5. Temperature changes produced at the indicated latitudes as a function of time attributed to a volcanic eruption such as Krakatoa. The control temperatures are those obtained from a model experiment without the volcanic eruption. [From Hunt (1977).]

3. Radiative Convective Equilibrium Models

These are one-dimensional (height) models, normally extending from the surface to about 40 km, which were introduced by Manabe and Strickler (1964) and Manabe and Wetherald (1967). Basically these models compute a 'global mean' atmospheric temperature profile, from a balance between incoming solar radiation and outgoing terrestrial radiation, for specified water vapour, ozone, carbon dioxide and cloud distributions. A convective adjustment mechanism is incorporated into the model which, subject to energy conservation requirements, ensures that unrealistic temperature changes with height are not obtained. A number of variants of this approach have now been developed, and this modelling technique has recently been comprehensively reviewed by Ramanathan and Coakley (1978).

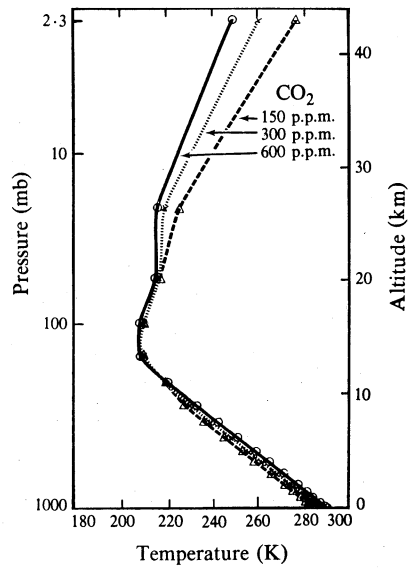

Fig. 6. Temperature profiles for three CO_2 amounts computed with a radiative convective equilibrium model. [From Manabe and Wetherald (1967).]

Although these models might seem unduly simplistic, they have proved to be extremely valuable in a number of situations. For example, the global mean temperature changes resulting from a doubling of atmospheric CO_2 amount obtained by Manabe and Wetherald (1967) (see Fig. 6) have essentially been verified by subsequent general circulation models (see Fig. 4). Radiative convective models have also been used to assess the potential climatic impact of other atmospheric perturbations such as particulate increases, either volcanic or anthropogenic, ozone variations attributable to chlorofluorocarbons, and changes in surface reflectivity. Variations in atmospheric composition associated with such gases as methane and nitrous oxide, which also interact with the Earth's radiative budget, have similarly been studied. A very useful role of these models is that of sensitivity analysis. In this role an arbitrary perturbation is made in some atmospheric component, like cloud amount or height, and the subsequent impact on the atmospheric temperature is computed. This permits the relative importance of the various atmospheric components to be determined, and highlights the accuracy to which changes in these components need to be measured, or the detail in which they need to be specified in more comprehensive models.

Since the models can also be marched forward in time, as opposed to generating equilibrium solutions, the time scales over which certain climatic effects should be felt can be determined. In this regard it is of value to know, for example, whether the thermal capacity of the oceans will greatly delay the temperature rise caused by a doubling of atmospheric CO_2. Hunt and Wells (1979) coupled a radiative convective model to a simple mixed layer model of the ocean and integrated the model for various growth rates in atmospheric CO_2, until the CO_2 amount doubled. Fig. 7 shows the resulting time variations. For each of the CO_2 growth rates it was found that including the oceans in the calculation gave a respite of only eight years in the time taken to reach an equilibrium temperature appropriate to a doubled CO_2 content. This is not a particularly encouraging result but it is the only estimate available to date.

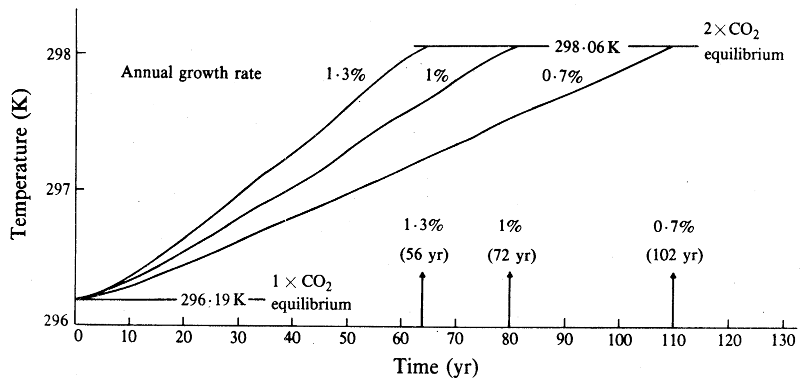

Fig. 7. Temporal variation of sea surface temperatures at 35° latitude for the annual CO_2 growth rates indicated. The upper and lower temperature limits of 298·06 and 296·19 K correspond to equilibrium values for fixed double and normal CO_2 amounts respectively. The vertical arrows on the abscissa identify the years in which sea surface temperatures of 298·06 K were first obtained for the indicated growth rates. The corresponding times taken to double the CO_2 amount in the atmosphere are also given (in parentheses). [From Hunt and Wells (1979).]

Radiative convective models are clearly a very useful and economic tool for investigating certain aspects of the climatic scenario, and will no doubt continue to be used creatively in the future.

4. Energy Balance Models

There are numerous variants of the basic energy balance model which is one-dimensional and computes a longitudinally averaged surface temperature profile as a function of latitude, obtained as a balance between incoming solar radiation and outgoing terrestrial radiation. The original form of this model derives from Budyko (1969) and Sellers (1969). Their models have been widely used because of the ease with which they can be generated, their modest computational demands, and the rather surprising results which both Budyko and Sellers obtained. This type of model embodies the equation

$$R + \mathrm{div}\,\boldsymbol{F} = 0,$$

where R is the net radiation for a column of the atmosphere at a given latitude, and $\mathrm{div}\,\boldsymbol{F}$ is the divergence of the net energy flux by atmospheric motions for that latitude. The net radiation is

$$R \equiv Q(1-\alpha)-\Delta I,$$

where Q is the annual mean solar energy, α the planetary albedo (reflectivity) and ΔI the net terrestrial radiation to space, all for a given latitude. Various empirical formulae are available for ΔI which relate the radiative flux to the surface temperature (the only computed variable in the model). The albedo is also empirically related to the surface temperature, and it is this empiricism which is responsible for many of the surprising results. The flux divergence term for the atmospheric energy transport is also specified empirically, normally by an arbitrary diffusion coefficient times the latitudinal gradient of the surface temperature. Since these models do not explicitly represent the individual radiative terms, experiments such as doubling CO_2 or varying the ozone amount cannot be performed.

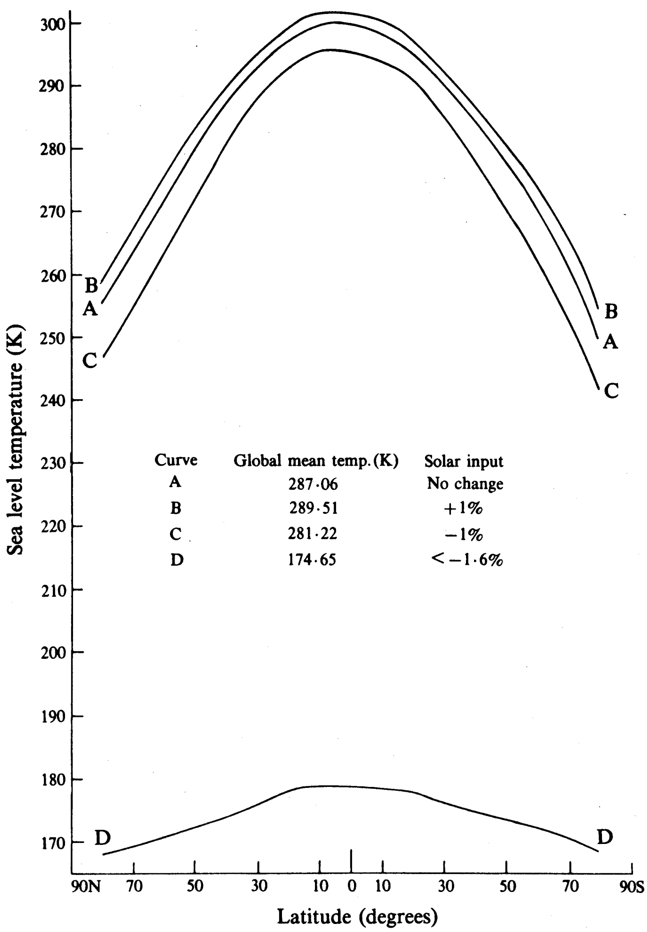

Fig. 8. Latitudinal temperature distribution calculated for various solar constant values. [From Schneider and Gal-Chen (1973).]

Clearly these models are heavily parametrized and their results must be viewed with caution. Nevertheless they have served to highlight the sensitivity of the climatic system to model specifications, thus encouraging more realistic approaches to be developed. The extreme sensitivity of the model solution to solar perturbations is illustrated in Fig. 8 taken from Schneider and Gal-Chen (1973). This figure shows that quite realistic latitudinal surface temperatures are produced by the model, and that for $\pm 1\%$ solar intensity variations the 'climate' changes in the expected sense, For a solar intensity reduction of more than 1·6% (curve D) an ice covered Earth is produced. This is an unrealistic result (see the Wetherald and Manabe 1975 general circulation experiment), attributable to the parametrization used for the albedo in the model. Budyko (1969) and Sellers (1969) also used their models to speculate about the possible consequences of removing the polar ice, and the impact of waste heat or volcanic activity on the climate.

Recently Thompson and Schneider (1979) have extended this type of model by including an underlying ocean, thus increasing the potential of this approach. They have used this coupled model to demonstrate the time lag that arises in the response of the climatic system to imposed disturbances, as well as investigating seasonal variability.

Perhaps the most important aspect of the Budyko–Sellers model has been the greatly increased interest in climatic problems that it has aroused.

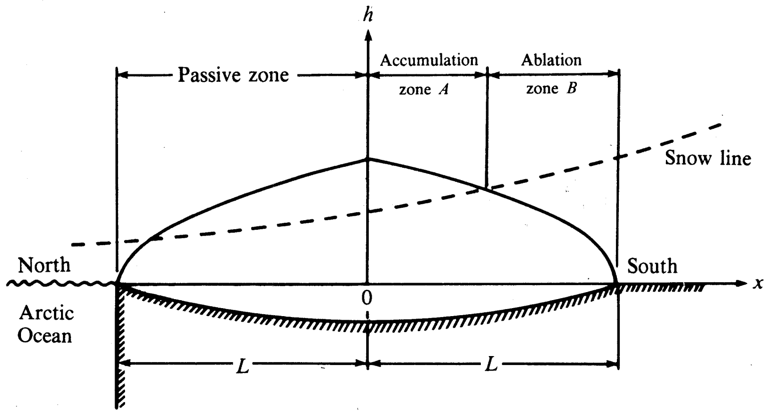

Fig. 9. Schematic cross section of a model ice sheet (see text).

5. Glacier, Ocean and Atmospheric (GOA) Models

In their simplest form these GOA models are only another variant of energy balance models. In fact the model used by Suarez and Held (1976) to investigate the Milankovitch theory of climate represents a reasonable bridge between those two types of model. The distinguishing feature of a GOA model is the explicit incorporation of long response times associated with oceanic and ice sheet dynamics into the usual atmospheric climatic system. This permits a number of interesting output signals to be obtained. Prior to discussing the complete model it is useful to consider the ice sheet dynamics separately.

A very simple ice sheet model has been developed by Birchfield (1977) and Birchfield and Weertman (1978). A cross section of the ice sheet is shown in Fig. 9. From conservation of mass, with given accumulation rate a and ablation rate b, a prediction equation for the half-width $L(t)$ can be obtained (see Birchfield 1977) as

$$\mathrm{d}L/\mathrm{d}t = \tfrac{1}{3}\lambda^{-\frac{1}{2}}Lb(EA-B), \qquad E \equiv a/b,$$

where A and B are the latitudinal extents of the accumulation and ablation zones respectively (see Fig. 9), and λ is a model parameter containing the yield stress of the ice. In Fig. 10 the response of the ice sheet to a periodically displaced snow line for two different periods is illustrated. Although the model is extreme in its simplicity the results are interesting nevertheless. For a short period of snow line variability (10 700 years) a periodic response of the ice sheet is obtained, with nonglacial intervals between glacial episodes (Fig. 10*a*). A relatively small ice sheet is also produced. For a longer forcing period (21 000 years) the ice sheet tends towards an equilibrium state without nonglacial intervals, and only an oscillatory response to the varying snow line (Fig. 10*b*). These results simply reflect that for a given set of model input parameters a model ice sheet has a unique characteristic time, which generates different responses depending upon the interrelation of this time with the forcing period. Clearly the existence of such a characteristic time for an ice sheet can have a strong impact on the evolution of a climatic system.

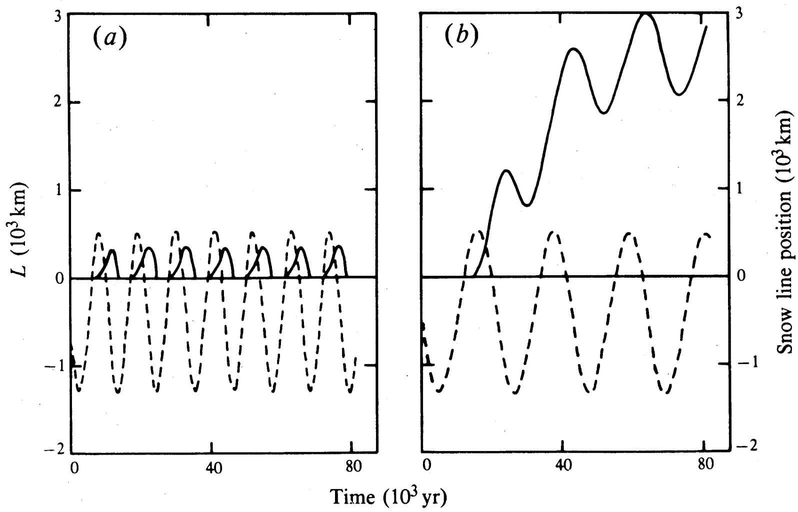

Fig. 10. Ice sheet half-width L (solid curve) and position of the snow line at sea level with respect to the northern edge of the continent (dashed curve) are shown for periods of (*a*) 10 700 yr and (*b*) 21 000 yr. [From Birchfield (1977).]

Returning to the GOA model, we find the inclusion of the oceanic response in this model adds another long characteristic time which permits further interactions in the climatic system. Kallen *et al.* (1979) have described a rather simple GOA type model, while Sergin (1979) has given a detailed account of a much more advanced and complicated model. Very briefly, the models consist of differential equations expressing the time variation of the height of the ice sheet, a hemispheric mean surface temperature, the equator to pole temperature difference and the ice sheet volume. Only longitudinally averaged fields are considered. The coupling of the various physical processes in the model involves much parametrization, and the specification of characteristic times for coupling between the individual atmospheric, oceanic and ice sheet components. Although these models lack most of the internally generated variables of a general circulation model, and are constrained by their parametrizations, they are still capable of producing fascinating results. They *suggest* that the climatic system is capable of undergoing long term fluctuations (auto-oscillations) without any external forcing being necessary. Thus ice ages could be explained by natural variability rather than recourse to external events such as solar input fluctuations as is currently the prevailing opinion. A particularly interesting result of Sergin (1979) was that while a model of only the northern hemisphere could undergo auto-oscillations, a southern hemispheric model did not. This difference was attributed to the possibility of continental ice sheets being formed in the northern hemisphere, while in the southern hemisphere the maximum size of the ice sheet was constrained by the surrounding oceans, and its stable environment prevented sharp decreases in the ice sheet. However, when the two hemispheres were coupled the auto-oscillations of the northern hemisphere caused a similar response in the Antarctic ice sheet, in the form of periodic decreases in its size. This example is illustrated in Fig. 11. Prior to coupling the hemispheres the southern ice sheet volume in Fig. 11*b* was essentially time invariant.

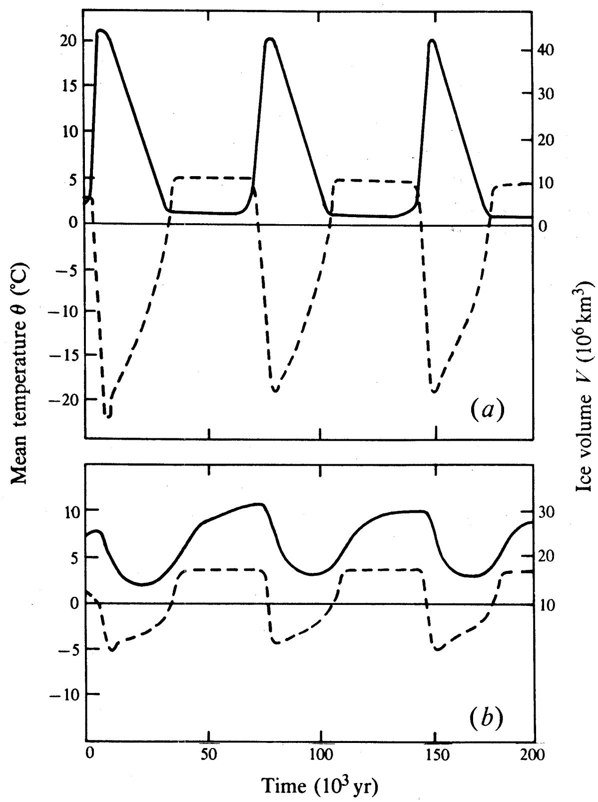

Fig. 11. Continental ice volume V (solid curve) and hemispheric mean temperature θ (dashed curve) are shown for (*a*) the northern and (*b*) the southern hemispheres. [From Sergin (1979).]

Although much developmental work remains to be done with GOA models they represent a very useful tool for examination of many long term problems of climatic interest.

6. Concluding Remarks

This review has attempted to highlight some of the techniques currently being used in climatic simulation and the problems which concern climatologists. The models selected by no means exhaust all the approaches being developed, and those discussed here were largely chosen because of their potential interest to physicists. Apart from the general circulation models no detailed knowledge of meteorology is required to experiment with the models described, and much scope exists for creative research in climatology using these tools. Because of the complexity of the subject, the primitive state of much of our knowledge, and the pressing need for some form of credible climatic prediction method, climatic research has become a growth area of science and will offer challenging career opportunities for many years ahead.

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Manuscript received 7 August 1980, accepted 19 September 1980