

4.1. Introduction

Climate models attempt to simulate the behavior of the climate system. The ultimate objective is to understand the key physical, chemical and biological processes that govern climate. Through understanding the climate system, it is possible to: obtain a clearer picture of past climates by comparison with empirical observation, and; predict future climate change. Models can be used to simulate climate on a variety of spatial and temporal scales. Sometimes one may wish to study regional climates; at other times global-scale climate models, which simulate the climate of the entire planet, will be desired.

There are three major sets of processes that must be considered when constructing a climate model:

- 1) radiative - the transfer of radiation through the climate system (e.g. absorption, reflection);
- 2) dynamic - the horizontal and vertical transfer of energy (e.g. advection, convection, diffusion);
- 3) surface process - inclusion of processes involving land/ocean/ice, and the effects of albedo, emissivity and surface-atmosphere energy exchanges.

The basic laws and other relationships necessary to model the climate system are expressed as a series of equations. These equations may be empirical in derivation based on relationships observed in the real world, they may be primitive equations that represent theoretical relationships between variables, or they may be a combination of the two. Solving the equations is usually achieved by finite difference methods; it is therefore important to consider the model resolution, in both time and space i.e. the time step of the model and the horizontal/vertical scales.

4.2. Simplifying the Climate System

All models must simplify what is a very complex climate system. This is in part due to the limited understanding that exists of the climate system, and partly the result of computational restraints. Simplification may be achieved in terms of spatial dimensionality, space and time resolution, or through parameterization of the processes that are simulated.

The simplest models are zero order in spatial dimension. The state of the climate system is defined by a single global average. Other models (see [section 4.4](#)) include an ever-increasing dimensional complexity, from 1-D, 2-D and finally to 3-D models. Whatever the spatial dimension of a model, further simplification takes place in terms of spatial resolution. There will be a limited number of, for example, latitude bands in a 1-D model, and a limited number of grid points in a 2-D model. The time resolution of climate models varies substantially, from minutes to years depending on the nature of the models and the problem under investigation.

In order to preserve computational stability, spatial and temporal resolution has to be linked. This can pose serious problems when systems with different equilibrium time scales have to interact as a very different resolution in space and time may be needed.

Parameterization involves the inclusion of a process as a simplified (sometimes semi-empirical) function rather than an explicit calculation from first principles. Subgrid-scale phenomena such as thunderstorms, for example, have to be parameterized as it is not possible to deal with these explicitly. Other processes may be parameterized to reduce the amount of computation required.

Certain processes may be omitted from the model if their contribution is negligible on the time scale of interest. For example, there is no need to consider the role of deep ocean circulation whilst modeling changes over time scales of years to decades. Some models may handle radiative transfers in great detail but neglect or parameterize horizontal energy transport. Other models may provide a 3-D representation but contain much less detailed radiative transfer information.

Given their stage of development, and the limitations imposed by incomplete understanding of the climate system and computational constraints, climate models cannot yet be considered as predictive tools of future climate change. They can, however, offer a valuable window on the workings of the climate system, and of the processes that have influenced both past and present climate.

4.3. Modeling the Climatic Response

The ultimate purpose of a model is to identify the likely response of the climate system to a change in any of the parameters and processes that control the state of the system. The climate response occurs in order to restore equilibrium within the climate system. For example, the radiative forcing may perturb the climate system associated with an increase in carbon dioxide (a greenhouse gas) in the atmosphere. The aim of the model is then to assess how the climate system will respond to this perturbation, in an attempt to restore equilibrium.

The nature of the model can be one of two modes. In equilibrium mode, no account is taken of the energy storage processes that control the evolution of the climate response with time. It is assumed that the climate response occurs instantaneously following the system perturbation. The inclusion of energy storage processes allows the model to be run in transient mode, simulating the development of the climate response with time. Generally, both equilibrium and transient models will be run twice, once in a control run with no forcing, then over the test run including forcing and perturbation of the climate system.

The climate sensitivity and the role of feedback are critical parameters whatever the model formulation. In the most complex models, the climate sensitivity will be calculated explicitly through simulations of the processes involved. In simpler models this factor is parameterized by reference to the range of values suggested by the more complex models.

This approach, whereby more sophisticated models are nested in less complex models, is common in the field of climate modeling.

4.4. The Climate Models

It is often convenient to regard climate models as belonging to one of four main categories:

- 1) energy balance models (EBMs);
- 2) one dimensional radiative-convective models (RCMs);
- 3) two-dimensional statistical-dynamical models (SDMs);
- 4) three-dimensional general circulation models (GCMs).

These models increase in complexity, from first to last, in the degree to which they simulate the particular processes and in their temporal and spatial resolution. The simplest models permit little interaction between the primary processes, radiation, dynamics and surface processes, whereas the most complex models are fully interactive.

It is not always necessary or beneficial to the analysis, however, to invariably choose the more sophisticated models. The choice of model depends upon the nature of the analysis. For example, the simpler models, unlike the 3-D GCMs, may be run many times in sensitivity studies which test the influence of modeling assumptions. For simulation experiments, which require complex modeling of the physical, chemical and biological processes inherent in the climate system, more sophisticated models may indeed be more appropriate. Computational cost is always an important factor to consider when choosing a climate model.

4.4.1. Energy Balance Models

Energy balance models (EBMs) simulate the two most fundamental processes governing the state of the climate:

- a) the global radiation balance (i.e. between incoming solar and outgoing terrestrial radiation), and;
- b) the latitudinal (equator-to-pole) energy transfer.

EBMs are usually 0-D or 1-D in form. In 0-D EBMs, the Earth is considered as a single point in space, and in this case only the first process listed above is modeled. In 1-D models, the dimension included is latitude. Temperature for each latitude band is calculated using the appropriate latitudinal value for the various climatic parameters (e.g. albedo, energy flux etc.). Latitudinal energy transfer is usually estimated from a linear empirical relationship based on the difference between the latitudinal temperature and the global average temperature. Other factors that may be included in the model equation are the time-dependent energy storage and the energy flux into the deep ocean.

4.4.2. Radiative-Convective Models

Radiative-convective models (RCMs) are 1-D or 2-D, with height the dimension that is invariably present. RCMs simulate in detail the transfer of energy through the depth of the atmosphere, including:

- a) the radiative transformations that occur as energy is absorbed, emitted and scattered, and;
- b) the role of convection, energy transfer via vertical atmospheric motion, in maintaining stability.

2-D RCMs also simulate horizontally averaged energy transfers.

RCMs contain detailed information about the radiation streams or energy cascades - the fluxes of terrestrial and solar radiation - that occur throughout the depth of the atmosphere. By considering parameters such as surface albedo, cloud amount and atmospheric turbidity, the heating rates of a number of atmospheric layers are calculated, based on the imbalance between the net radiation at the top and bottom of each layer. If the calculated vertical temperature profile (lapse rate) exceeds some stability criterion (critical lapse rate), convection is assumed to take place (i.e. the vertical mixing of air) until the stability criterion is no longer breached. This process is called the convective adjustment.

As with EBMs, time-dependent calculations (energy storage and fluxes into the deep ocean) may be made, depending on the nature of the analysis. RCMs are most useful in studying forcing perturbations that have their origin within the atmosphere, such as the effects of volcanic pollution.

4.4.3. Statistical-Dynamical Models

Statistical-dynamical models (SDMs) are generally 2-D in form, with usually one horizontal and one vertical dimension, though variants with two horizontal dimensions have been developed. Standard SDMs combine the horizontal energy transfer modeled by EBMs with the radiative-convective approach of RCMs. However, the equator-to-pole energy transfer is simulated in a more sophisticated manner, based on theoretical and empirical relationships of the cellular flow between latitudes.

Parameters such as wind speed and wind direction are modeled by statistical relations whilst the laws of motion are used to obtain a measure of energy diffusion as in an EBM. Hence the description statistical-dynamical. They are particularly useful in investigations of the role of horizontal energy transfer, and the processes which disturb that transfer directly.

4.4.4. General Circulation Models

General circulation models (*GCMs*) represent the most sophisticated attempt to simulate the climate system. The 3-D model formulation is based on the fundamental laws of physics:

- a) conservation of energy;
- b) conservation of momentum;
- c) conservation of mass, and;
- d) the Ideal Gas Law.

A series of primitive equations describing these laws are solved, resulting in an estimate of the wind field, which is expressed as a function of temperature. Processes such as cloud formation are also simulated.

To compute the basic atmospheric variables at each grid point requires the storage, retrieval, recalculation and re-storage of 10^5 figures at every time-step. Since the models contain thousands of grid points, *GCMs* are computationally expensive. However, being 3-D, they can provide a reasonably accurate representation of the planetary climate, and unlike simpler models, can simulate global and continental scale processes (e.g. the effects of mountain ranges on atmospheric circulation) in detail. Nevertheless, most *GCMs* are not able to simulate synoptic (regional) meteorological phenomena such as tropical storms, which play an important part in the latitudinal transfer of energy and momentum. The spatial resolution of *GCMs* is also limited in the vertical dimension. Consequently, many boundary layer processes must be parameterized.

In summary, *GCMs* can be considered to simulate reasonably accurately the global and continental-scale climate, but confidence is lacking in the regional detail.

4.5. Confidence and Validation

Although climate models should aid understanding in the processes that control and perturb the climate, the confidence placed in such models should always be questioned. Critically, it should be remembered that all climate models represent a simplification of the climate system, a system that indeed may ultimately prove to be too complex to model.

Given that many of the processes that are modeled occur over time scales so long that it is impossible to test model results against real-world observations, it is also arguable that climate modeling is, in some respects, philosophically suspect. Model performance can be tested through the simulations of shorter time scale processes but short-term performance may not necessarily reflect long-range accuracy.

Climate models must therefore be used with care and their results interpreted with due caution. Margins of uncertainty must be attached to any model projection. Uncertainty margins can be derived by the comparison of the results of different model experiments or

through sensitivity studies, in which key assumptions are altered to determine the role they play in influencing the final climatic response.

Validation of climate models (testing against real-world data) provides the only objective test of model performance. As far as *GCMs* are concerned, validation exercises have revealed a number of deficiencies in their simulations of present-day conditions:

- a) modeled stratospheric temperatures tend to be lower than equivalent instrumental observations;
- b) modeled mid-latitude westerlies tend to be too strong; easterlies are too weak;
- c) modeled sub-polar low pressure systems in winter tend to be too deep and displaced east, and;
- d) day-to-day variability is lower than in the real world.

Finally, it has been observed that some models suffer from climate drift. The background climate shifts as the simulation proceeds, despite the absence of any climate forcing.

4.6. Conclusion

Through much of the history of climate modeling, division between modeling and observational studies has hampered the development of both sides. The coupling of these theoretical and empirical disciplines, to test both model accuracy and understanding gained from analysis of observational data, has only recently been addressed. Much of the discrepancy between the climate model and real world is the result of this division. Such a divide must be bridged if accurate forecasts of future climates are to be produced.