Large-scale atmospheric models as an experimental tool

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(Manuscript received November 1981)

The utility of large-scale numerical models for exploring the properties of the atmosphere is discussed. Thus the assessment of model simulations of the atmosphere is not of concern here, but rather the application of the models to clarify why the atmosphere actually has its observed characteristics. In addition the possibility of performing null experiments with the models in order to evaluate links in a physical hypothesis is emphasised. The technique is illustrated with examples from experiments involving a sun-weather mechanism, a rotation rate variation, removal of mountains, and modifications to cloud amounts. Considerable potential exists for exploitation of this technique in the future.

Introduction

A ‘model’ can range from a loose description of some process or idea to complex sets of mathematical equations which essentially define the potential activities of the phenomenon under consideration. The models to be considered here are so-called general circulation models (GCM) of the atmosphere which fall into the latter category. Despite the undoubted contributions made by one and two-dimensional and more conceptual models they will not be considered here for brevity.

The mathematical equations governing a general circulation model are the modified Navier Stokes equations incorporating a rotating frame of reference, the thermodynamic equation, the hydrostatic approximation, the continuity equation and the equation of state. For a specified initial state of the atmospheric variables, wind, temperature, pressure etc. it is possible to integrate the controlling partial differential equations forward in time for a chosen spatial representation of these variables, and thus obtain a new initial state. By continuing this process for many thousands of time steps of say 10 to 30 minutes, it is possible to simulate the evolution of the large-scale properties of the atmosphere. It is the numerical output from such a simulation that constitutes the data base from which insight into the behaviour of the actual atmosphere may be obtained.

The general circulation models are, of course, considerably more complex than the above brief description suggests. Many physical processes, such as radiative transfer, surface hydrology, dissipation, evaporation, convective mechanisms, snowfalls etc., have to be incorporated with the governing equations. The representation of such processes is normally referred to as ‘parameterisation’ and constitutes a major aspect of model formulation and evaluation. The difficulties involved in this procedure can be readily appreciated when it is realised that these small-scale processes have to be parameterised in terms of the large-scale model variables forecast by the governing equations.

It is hoped that the above brief description will establish in the mind of the reader the very firm physical basis of GCM.

An indication of the current ability of GCM to simulate the atmosphere is given in Fig. 1 (from Hunt 1981a). The comparison indicates that the computed results are in satisfactory agreement with observation at most heights, implying that the associated wind fields and other meteorological processes should also be acceptable.

A further point that needs to be considered in assessing model experiments is the signal-to-noise ratio of the model output. The model simulation contains ‘noise’ in the same way as does an observed atmospheric data set, and for similar reasons. It is against this natural noise level that any perturbation introduced into a GCM experiment has to be evaluated. For some of the experiments considered here this is not a problem because of the very large changes induced in the model.

Why use models?

Can models tell us anything about the atmosphere that could not be obtained from observations (specifically enhanced observations if necessary)? The answer is undoubtedly ‘yes’. Although not germane to the main thrust of this article probably
the most publicised example of the utility of a GCM to date is the forecast of a future global warming associated with the anthropogenically-induced CO₂ increase in the atmosphere (see Manabe and Stouffer (1980) for example).

Of principal concern here, however, is the philosophy of using a GCM in such a way as to provide insight into why and how the atmosphere behaves in its observed manner. There are a number of components to such a philosophy. One of the most obvious is to use a GCM to try to understand the basis for an observed correlation between two atmospheric variables such as Darwin pressure and Victorian rainfall (Nicholls and Woodcock 1981). Is this a casual relationship with no underlying interacting mechanism? If not, which is cause and effect and what initiates the observed variation? The ability to 'roll back the atmosphere' in a GCM experiment involving such a relationship and repeat it with selected modifications, such as enhanced output of data or changed initial conditions, is an attribute which observational meteorologists must greatly envy.

Again, in examining some particular atmospheric phenomenon it may be possible to develop a hypothesis that appears satisfactory but in which detailed mechanistic linkages are unobtainable. This limitation also exists in GCM simulations, but there it is possible to conduct alternative tests or even null experiments that can hopefully clarify the issues. Such experiments are probably impossible to perform in the actual atmosphere. It is also possible with models to modify a fundamental physical property, such as the acceleration due to gravity, so that some special feature of the atmosphere is enhanced, thereby greatly clarifying its role in some mechanism.

The utility of performing experiments with numerical models that involve 'unrealistic' changes to the properties of the atmosphere is not generally appreciated or, in fact, approved of. Such experiments can give great insight into the functioning of the atmosphere and explain why certain physical regimes are preferred over others. The reservations concerning the use of atmospheric models in this way should be contrasted with the general approval of performing rotating dishpan experiments over very extensive parameter ranges, and then endeavouring to interpret them in terms of atmospheric behaviour. At best these dishpans are a modest analogue of the actual atmosphere compared to the far higher accuracy represented by a GCM. Hence it is difficult to understand the lack of support for exploring wide parameter ranges with a GCM.

Some experiments designed to illustrate the above approaches will now be considered. This discussion is not concerned with simulation of the atmosphere per se, or with geophysical experiments where volcanic eruptions, ice perturbations etc. are explored, but with using a GCM to probe the atmosphere.

Examples of this modelling technique

Sun weather experiment

Although this was a geophysical rather than a probing experiment it illustrated an important model option. The experiment (Hunt 1981b) consisted of inserting a 'hole' in the model climatological ozone distribution in the high latitude mid-stratosphere similar to that observed by satellite following a solar proton event (Heath et al. 1977). Since the principal tropospheric-stratospheric dynamical coupling also occurs at high latitudes, it was hypothesised that the radiative changes induced by the ozone perturbation would affect the transmissivity of the stratosphere to upwards-propagating long-meteorological waves, and thus affect the tropospheric synoptic systems which determine these waves. The experiments certainly showed that changes were produced in the troposphere, in particular the mean zonal wind in
the mid-latitude upper troposphere was enhanced by about 25 per cent, but it proved impossible to identify a clear mechanistic linkage relating stratospheric transmissivity changes to perturbations in the high latitude upwars-propagating long waves. To clarify this situation a 'null' experiment was performed which was designed to violate one aspect of the original hypothesis. The philosophy behind this experiment was that if such a modification was made to a crucial component of the overall mechanism, and the previously obtained tropospheric response did not materialise, then this would tend to corroborate the original hypothesis.

In the null experiment the high latitude ozone hole was moved to 45° latitude where the maximum tropospheric response was obtained previously. Thus if this response was due to a direct radiative effect, then locating the ozone hole at 45° should enhance the response. If on the other hand the response was caused by a modification to the upwars-propagating long waves which maximised at high latitudes, as surmised in the original hypothesis, then a 45° latitude ozone hole should be ineffective. Figure 2 compares the tropospheric response for these two situations and clearly illustrates that a mechanistic linkage via the high latitude long waves is a tenable part of the hypothesis. Since the high latitude 'waveguide' is a concept rather than a reality, leakage occurs so that the tropospheric response for the 45° ozone hole is not zero, but it is markedly reduced in amplitude and quite different in character.

Presumably more critical tests of the hypothesis could have been performed in order to evaluate potential paths of the mechanistic linkage between the ozone hole and the tropospheric mid-latitudes, but the above experiment highlights the utility of a GCM in providing insight into what is clearly a very subtle relationship. This potential has been only modestly used to date.

**Variable rotation rate experiment**

In this experiment the earth's rotation rate was increased and decreased by a factor of 5 (Hunt 1979). The objective of the exercise was to try to understand some fundamental features of the atmosphere. Why does the atmosphere have such a marked subtropical jet? What determines the number and location of jets in a planetary atmosphere? On earth the subtropical jet is located at the upper conjunction of the Hadley and Ferrel cells; is this inconsequential or causal? In a similar vein what determines the number and latitudinal extent of the mean meridional cells in the atmosphere? One might surmise that such fundamental problems had long ago been identified, resolved and documented in the literature. This is certainly not the case, as an examination of a typical meteorological textbook will confirm. The most detailed, but inconclusive, discussion is given by Lorenz (1967) who provides much background information on this problem.

An answer to some of the above questions was attempted by Hunt (1976) as part of the analysis of a 'standard' GCM simulation. The essential point which emerged was that the intensity and location of the subtropical jet are apparently controlled by local east-west pressure torques. These are required to prevent excessive latitudinal shears of the zonal winds from being produced. (An examination of the mean zonal wind distribution in the atmosphere readily reveals the existence of a marked latitudinal shear in this wind in the vicinity of the subtropical jet core.) Such shears result from the generation of west winds, owing to conservation of absolute angular momentum, because of the mean polewards drift of air associated with the upper arm of the Hadley cell (see Fig. 3). Since the magnitude of the theoretically possible mean zonal wind computed from conservation of absolute angular momentum increases very rapidly with latitude, extremely large wind shears would result if the Hadley cell extended further polewards for the earth's current rotation rate. The pressure torques which prevent the occurrence of unreasonable shears are created by the descent of the polewards components of the Hadley cell, which thus produce local regions of high surface pressure in the subtropics. This implies that the poleward extent of the Hadley cell is determined by the need to produce such pressure.

**Fig. 2** Absolute values of the differences for the control run minus SWE2, control run minus SWE3 and control run minus noise, mean zonal wind profiles at 45° latitude for a 4-day averaged period near the time of maximum response. SWE2 had a stratospheric ozone deficit at high latitudes, SWE3 had the same ozone deficit at 45° latitude. The noise experiment is included to indicate the likely magnitude of the natural variability of the model.
Fig. 3 Mean zonal wind distributions and mean meridional streamfunctions are shown on the left and right of the figure respectively. Fast (5 times), normal and slow (1/5) rotation rate results are given in the top, middle and bottom panels respectively. For the mean zonal wind hatched areas are regions with east winds; units m s$^{-1}$. For the streamfunction; units 10$^{11}$ kg s$^{-1}$. 
torques. The basis of this idea is due to Exner (see Lorenz 1967). Hence there should be a unique relationship between the location of the subtropical jet core, the corresponding surface pressure maximum, the polewards extremity of the Hadley cell and the earth's rotation rate via the conservation of absolute angular momentum.

As a simple test of this uniqueness the model was run with the earth's rotation rate increased and decreased by a factor of 5, since the rotation rate was deemed to be the crucial controlling factor. Figure 3 reveals that the jet stream characteristics and the structure of the mean meridional circulations change dramatically with rotation rate. In particular note that the latitudinal extent of the Hadley cell varies inversely with the rotation rate, as the higher the rotation rate the smaller is the polewards traverse needed to produce a given west wind intensity. Examination of the figure shows that in each case the subtropical jet core was located at the conjunction of the Hadley and Ferrel cells, as surmised above. A unique relationship also existed between the region of descending air and the surface pressure high for each rotation rate. This implies that the pressure torques were responding also to the variation in rotation rate. Of particular importance was the finding that in each case the maximum latitudinal shear of the mean zonal wind at the height of the jet core attained the same critical value. Such a shear should be a function of the basic atmospheric properties, viscosity, density etc., and should be expected to be independent of rotation rate. That this is so is extremely encouraging and adds to the confidence that can be placed in the analysis. In fact this critical shear appears to be such a crucial feature of the atmosphere that it can be used to determine the latitude of the subtropical jet for any reasonable rotation rate for non-summer conditions (see Hunt 1979). Various other aspects of the general circulation were discussed in Hunt (1979), but it suffices here to note that the experiment undoubtedly illustrates the potential for GCM to be used to explore fundamental problems of the atmosphere and to provide insight into such problems.

Experiments with and without mountains

The most detailed account of an experiment investigating the influence of mountains on the general circulation is that of Manabe and Terpstra (1974). Even though it represented an unattainable change to the boundary conditions of the model, the experiment was not just of academic interest. It helped to quantify the relative contributions of thermal effects (land-sea contrast) and orography in determining the observed features of the atmosphere. This type of information is valuable in assessing the potential influence of, say, changes in thermal contrast on the climate. Such changes could result from any CO₂ induced warming owing to the use of fossil fuels, or from natural variability altering the characteristics of a large-scale ocean current such as the Gulf Stream. The simulations also revealed that the Icelandic and Aleutian lows are attributable to land-sea contrast, while the winter Siberian high is topographically controlled. In a separate experiment Manabe and Hahn (1975) have found that not only the geographical extent but also the timing of the Asian monsoon is sensitive to the presence of the Tibetan plateau.

The importance of orographically-induced standing waves was found to increase with height in the stratosphere, an effect which presumably continues into the mesosphere and above. Given the stronger orographic forcing in the northern hemisphere compared to the southern hemisphere this may explain why sudden stratospheric warmings are a more dominant feature in the former hemisphere (see Schoeberl 1978). Similarly, other differences might be expected in the general circulation of the stratosphere and mesosphere of the two hemispheres. This experiment should also help to interpret the differences in the climates of the two hemispheres by identifying the relative contributions of land-sea contrast and orography. Such insights would be valuable in assessing possible future climatic responses of the hemispheres to perturbing functions.

Manabe and Terpstra (1974) also highlighted the influence of orography on cyclogenesis, indicating that it preferentially occurs in the lee of mountain chains, while for the no-mountain case there appeared to be little selectivity. This information is useful when interpreting climatic statistics as it implies that some 'order' exists.

A final point is that comparison of mountain/no-mountain simulations can be useful in identifying model deficiencies, and can thus focus attention on areas requiring improvement.

The role of clouds

Clouds are one of the most dominant atmospheric variables of which we are conscious in our daily life. Their precise role in determining the overall characteristics of the atmospheric general circulation is far from clear. Clouds interact with the atmosphere both radiatively and dynamically — which is the more important? As regards the radiative properties of clouds which are dominant? Are the detailed transient and spatial characteristics of clouds crucial, or would some average value suffice? How important are the various types of clouds, their height distribution, albedo, absorptivity etc? Is the atmosphere essentially buffered against individual cloud perturbations because automatic compensation occurs at another level? On the dynamical side is the water vapour flux and subsequent release of latent heat in a cloud more important than the radiative effects of that cloud? How much mass, momentum, sensible heat and water vapour are transported vertically by clouds compared with the large-scale motions?
Answers to the above questions are difficult to obtain, but considerable clarification could result from well-conceived experiments with GCM. A number of preliminary experiments have been performed. For example, Hunt (1978) removed all clouds from a GCM and, apart from the expected overall warming, found very little difference compared to a control experiment with fixed, zonally-averaged clouds. This experiment suggests that perhaps the single most important radiative function of cloud is in maintaining the observed atmospheric temperature range. The possibility of radiative perturbations associated with variable cloud cover inducing dynamical changes could not be assessed by this experiment, but recent work by Gordon (personal communication) does not seem to support such coupling. His experiment consisted of using a control model which forecast its own cloud cover to generate a time-averaged, zonal mean cloud distribution. This distribution was then used to replace the forecast clouds in the model and a new set of climatic statistics was produced. Comparison of these statistics with those of the control revealed very little difference as regards the zonal mean properties of the general circulation. An indication of the difference in synoptic characteristics is shown in Fig. 4. The essential result indicated in this particular example is that over the majority of the globe synoptic cloud variability made very little difference to the lower-tropospheric temperature in the model. Statistically the warmings over Australia and South America are probably significant, but those at high latitudes are doubtful in view of the large natural variability in these regions. However, the warming over northern Siberia may be an exception, related to the poor forecast of cloud by the model in this locality.

Most other cloud-related GCM experiments have been concerned with just predicting cloud amounts, and many facets of this subtle problem have still to be explained (see for example Schneider et al. 1978 and Roads 1978). Clearly, much remains to be done.

Conclusions
A number of examples have been given where GCMs have been used to try to understand why the atmosphere exhibits its observed characteristics. This type of experimentation is quite distinct from the normal role of using a GCM to simulate the atmosphere per se, or to investigate some geophysical perturbation. These ‘probing’ type experiments can provide much insight into the mechanics of the general circulation, which in turn can be of great assistance in interpreting the output of conventional GCM experiments. This results from the expansion of one’s horizons, which occurs because it is necessary to explore and analyse a situation outside of its normal frame of reference. Such an exercise provides considerable intellectual stimulus which can result in useful concepts for additional experiments.

In principle very subtle problems can be explored by suitably modifying model properties or boundary

Fig. 4 Temperature difference (K) at 750 mb between a control experiment with self-generated cloud, and a model rerun using time and zonally averaged clouds from the control experiment. Results are for January conditions and have been time averaged over days 31-80 of the experiment. Double hatched areas are regions where the control run was more than 2K warmer than the model with fixed clouds. The single hatched areas are where it was 1K colder. (Figure kindly supplied by Dr H. B. Gordon of ANMRC.)
conditions. Some future experiments might involve
examination of linear/non-linear aspects of the
governing equations, interactions between different
scales of motion and the reasons for observed scale
selectivity. No doubt the reader can identify other
appropriate problems. The potential of the
technique has hardly been appreciated as yet, so
much remains to be done and many opportunities
for imaginative science exist.

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