GREENHOUSE MODELLING IN BMRC

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1. INTRODUCTION

The Bureau of Meteorology Research Centre (BMRC) is the research division of the national weather service, and at present there are six research groups in BMRC. The group activities are on short range prediction, medium range prediction, climate, remote sensing, tropical meteorology, and greenhouse modelling. All the groups involve numerical modelling to some extent. Thus the work of the greenhouse modelling group is incremental to a comprehensive climate research program in BMRC. The work is carried out under the Federal Government greenhouse research program in cooperation with CSIRO and funded through the Department of Arts, Sport, the Environment, Tourism and Territories.

Climate research in BMRC consists of several components: studies of the natural variability of climate, climate model development, greenhouse modelling, and observational studies. The work involves collaboration across the research groups, such that the same global model is used by all groups. Cooperation with other units of the Bureau of Meteorology is vital for the successful implementation of operational models and techniques, and for the execution of large-scale field programs to support model development.

Meteorology, particularly global modelling, is big science and so it is best conducted in a cooperative fashion. Nationally BMRC has special ties with Monash and Macquarie Universities, and international links are well developed. For example, there is a formal memorandum of understanding between BMRC and the USA National Center for Atmospheric Research (NCAR) covering a number of common research areas, including global modelling.

2. DEVELOPMENT OF THE BMRC GLOBAL MODEL

The global atmospheric model in BMRC has been developed over the last twenty years through the combined efforts of many individual scientists. The model provides a numerical solution for the equations for the conservation of mass, momentum, energy and moisture. The horizontal distribution of the dependent variables is represented by a truncated set of spherical harmonics, and this spectral method of solution was pioneered in the early 1970s. The method was first demonstrated with the shallow water equations (Bourke [1]) which led to the implementation in Australia in 1976 of the first operational spectral numerical weather prediction model. This technique is now commonly used for global weather and climate modelling throughout the world.

International cooperation has always played a significant role in model development. For example, the radiation code in the BMRC model has been developed through interaction with the USA Geophysical Fluid Dynamics Laboratory (GFDL). In 1978 an early version of the BMRC model was transferred to NCAR where it was integrated on the Cray 1 supercomputer and became the basis of the initial NCAR Community Climate Model. The model was vectorized in 1984 for use on the CSIRO Cyber 205 supercomputer, and it was recently adapted for the Bureau's ETA10 supercomputer. Over the last five years the model has been developed considerably to improve its basic climatology and so enhance its capability for general circulation studies (Hart et al., [5]). A primary application of the model is for numerical weather prediction, and since July 1989 the model has been run each day to produce a five-day global weather prediction.

The detailed characteristics of the model are described by Bourke [2]. The equations of motion are approximated by a spectral representation with rhomboidal truncation in wave number space. A semi-implicit method is used for the time integration to allow the computations to be efficient yet accurate. It is necessary to take into account not only the adiabatic motion of the atmosphere but also the effects of various diabatic processes. Most of these processes act on scales smaller than the resolution of the model grid. Thus there is a need to parameterize sub-grid scale processes.

Parameterization is the representation of the effects of a sub-grid scale process in terms of the resolved variables. This is generally achieved through a blend of empirical studies and approximations to the equations of motion. Field (or process) studies are often conducted in order to improve our understanding of these processes. For example, an objective of the Australian Monsoon Experiment (AMEX) was to acquire data to assist in the validation of numerical models and in the development of improved parameterizations of tropical convection (Holland et al., [6]).

Much of the development on the model over the last five years has been on the refinement of the parameterization of sub-grid scale processes. Such development requires the identification of a deficiency in the model, the implementation of an appropriate parameterization, and then testing of its impact against the background of all the other processes in the model. The work therefore requires great care.

Turbulent mixing is included to ensure that the transport of heat, moisture and momentum across the surface of the earth is accounted for. The parameterization is based on Monin-Obukhov similarity theory and tuning to empirical data (Louis, [7]). The effects of radiative heating are implemented through approximate solutions to the full equations of radiative transfer (Fels and Schwartzkopf, [4]). This task is complex since the atmosphere is inhomogeneous and multiple scattering cannot be neglected, especially in clouds.

The interaction between cloud and radiation is a critical determinant of global climate and so there is continuing work on methods to estimate fractional cloud cover in the model.

The global model itself is only one component of the software suite needed to do effective climate modelling research. Integration of the model yields a vast amount of output; for
example, with resolution of about 5 x 3 degrees horizontally and 9 levels in the vertical, the model generates about 200,000 numbers each time step. Using a typical time step of 20 minutes leads to the output of many millions of numbers for a long integration. Through cooperation with NCAR, BMRC has acquired and modified the NCAR diagnostics processor which takes model output and readily generates fields of useful statistical properties. Thus the processor allows the model output to be analysed efficiently. Further development of the processor will proceed in cooperation with NCAR. The graphical display of the processor is linked to the NCAR Graphics V3.0 package.

3. MODEL APPLICATIONS

A major application of the global model is to numerical weather prediction (NWP). Accurate NWP requires the model to have as realistic a climatology as possible, otherwise systematic errors arise in model predictions. Research on systematic errors in global models has shown that the structure of these errors is different at the low resolutions (e.g. rhomboidal wavenumber 15) used for many climate studies from that at higher wavenumbers (e.g. rhomboidal 31) used for NWP. This result is an incentive for climate modelling to be carried out at higher resolution.

The performance of the BMRC model is similar to that of other major NWP centres around the world. For example, the average mean-sea-level pressure is found to be generally well simulated in the northern hemisphere, but there are some discrepancies in the southern hemisphere. The intensity of the main storm tracks near 60 S and the strength of the Antarctic trough are found to be underestimated. Some of these deficiencies can be reduced by the introduction of parameterizations of processes such as gravity wave drag, which arises from the dissipation of waves forced by the flow over high orography.

An important aspect of NWP is data assimilation in which observational data are combined in a dynamically consistent manner to provide initial conditions for a model integration. This process involves statistical interpolation procedures using the model to apply constraints on the solution. Because real data are invariably noisy and irregularly spaced in time and space, useful climate data sets must also be generated by data assimilation procedures, and a major task for the future will be the application of accurate global models to this task.

The global model can be used like a laboratory model to examine the nature of the atmospheric circulation. Some component of the model can be perturbed and the resulting solution compared with that from a control run with the unperturbed model. For example, Puri [10] has used the BMRC model to investigate some aspects of teleconnections, that is the response of the atmosphere at one location on the earth to forcing at another. He imposes sea-surface temperature anomalies in order to consider the response of the model to diabatic heating in the tropics. By applying a special filter as the model is integrated in time, he shows that the divergent flow produced by such heating and causing disturbances at higher latitudes is carried by low-frequency gravity waves.

Recent studies have shown that the rainfall at particular locations around the world can be influenced by the global distribution of sea-surface temperature. For example, Nicholls [8] demonstrates that the two main principal components of Australian rainfall are associated with distinct sea-surface temperature patterns. One component corresponds to the well-known link between rainfall in eastern Australia and the temperature of the Pacific Ocean; this is the El Nino-Southern Oscillation response. However, the other rainfall component is correlated with the difference in sea-surface temperature between the central Indian Ocean and the Indonesian region. This principal component represents a band of rainfall extending from the north-west to the south-east, resembling the effects of the north-west monsoon rainbands. The global model is now being run with appropriately specified sea-surface temperature anomalies in order to investigate the physical nature of these correlations.

Sea-surface temperatures are important determinants of climate because the oceans are the major moisture source and because they also have much greater thermal inertia than the atmosphere; that is, the oceans provide a long-term memory for the climate system. Thus sea-surface temperatures represent forcing for the atmosphere on time scales of weeks and months. As part of the World Climate Research Programme, a project called Tropical Ocean Global Atmosphere (TOGA) has been set up to investigate this cause of seasonal variations in climate. In collaboration with CSIRO Division of Oceanography, a statistical interpolation scheme has been developed in BMRC to analyse the upper ocean in the tropics using real-time data from expendable bathythermographs (XBTs) deployed from ships of opportunity in the Pacific and Indian Oceans (Smith [11]). That work is now being extended to combine the ocean analyses with ocean models for data assimilation and prediction studies.

4. GREENHOUSE MODELLING STUDIES

In order to use the global model for climate change studies, it is necessary to enhance the representation of processes that become relevant at decadal time scales. Two particular areas that have been improved in the BMRC model are the upper ocean and sea ice. The simplest model of the ocean is a swamp model; that is, the ocean temperature is determined by a local energy balance such that the ocean has no heat capacity (Washington and Meehl, [12]). This representation can only be used for equilibrium studies and so the climate is forced by a fixed solar constant corresponding to the annual average. The advantage of this simple model is that it reaches a statistical equilibrium after a very short integration period of tens of days, rather than the tens of years required for a fully-coupled ocean-atmosphere model. It can therefore be used readily to test the sensitivity of the atmospheric model to various modifications. It makes a suitable test-bed at the start of a comprehensive modelling study.

Calculations have been carried out with the BMRC atmospheric model coupled to a swamp ocean in order to study the effects of a doubled concentration of carbon dioxide in the atmosphere. The results have been compared with those of Washington and Meehl [12] using the NCAR Community Climate Model. The integrations demonstrate the importance of positive feedback between surface temperature and sea-ice coverage. Because the albedo of sea ice is greater than that of open water, an increase in surface temperature leads to a reduction in sea-ice coverage, which in turn causes more solar radiation to be absorbed and so increases the surface temperature. The BMRC results are consistent with the NCAR results, showing an essentially linear trend between the increase in global surface temperature and reduction in sea-ice coverage.

It is worth noting that the parameterization of sea ice is rather crude in global climate models. Stand-alone models of sea ice have been developed in great detail, but they tend to be too complex to be integrated in conjunction with a full climate model. The nature of sea ice in Antarctica also tends to be different from that in the Arctic because the Southern Ocean is open so that the sea ice is greatly influenced by wind stress. There is therefore a particular justification for an Australian research effort on the investigation and parameterization of sea ice for climate models.

While climate change integrations are a necessary part of the work of the greenhouse modelling group in BMRC, there is an equally important task of improving the credibility of the model. A major part of the work of the group has been on participation in an international model intercomparison experiment being organized by the USA Department of Energy (DOE). This intercomparison is a continuing program, but the first stage has now been completed. The objective of this stage was to determine whether differences in the representation of the feedback between cloud and radiative transfer are a significant factor in causing differences in the results of greenhouse simulations in climate models. It should be noted that the marked differences in the results of the global models are somewhat surprising when we consider the strong interaction between the different modelling groups around the world. The DOE experiment is a simplified simulation of a double carbon dioxide experiment. The solar forcing is fixed at a mean July value, and the sea-ice coverage is fixed. These assumptions reduce the number of possible feedback processes and allow equilibrium results to be obtained after a short integration period. The change in forcing is produced by undertaking two integrations with specified sea-surface temperatures differing by precisely 4 K; this may be viewed as an effective 4 K greenhouse warming. The model results are analysed in terms of the calculated feedback between the forced change in radiative forcing at the top of the atmosphere and the change in global surface temperature. Thus all the model output is condensed to two parameters representing this feedback and the radiative forcing due to clouds in the atmosphere (Cess and Potter, [3]).

The result of the intercomparison demonstrates that the differences in the representation of cloud-radiation feedback does indeed cause major differences in the results of climate models, and so much more work is required to improve the parameterization of this process. Some recent work by the UK Meteorological Office suggests that even the microphysical properties of clouds should be included in climate models (Mitchell et al. ,[9]).

5. FUTURE PLANS

There is clearly a large amount of research and development required before we can produce credible simulations of climate change on the scale demanded by policy makers. A full global climate model will have at least six major components:

atmospheric dynamics,
ocean dynamics,
land surface processes,
atmospheric chemistry,
marine biochemistry, and
terrestrial ecosystems.

At present the BMRC model, as for most climate models throughout the world, has parts of only the first three of these components. For the short term, the emphasis is expected to remain on these components, with the work on land surface processes being carried out particularly in collaboration with Macquarie University. The main focus in BMRC will be on the development of a coupled ocean-atmosphere model. Work on the transport of atmospheric constituents needs to commence not only because it is relevant to greenhouse climate change but also because it is necessary for the operational needs of the Bureau on the behaviour of stratospheric ozone and the transport of atmospheric pollutants.

The BMRC would look to support projects associated with the development and testing of all components of the overall climate system. The last components are the particular focus of IGBP, which complements the work of the World Climate Research Programme centred at present on dynamics and physics.

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