Dynamical Climatology

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1. Introduction

This note summarises a number of improvements which have been implemented in the radiation scheme used in the Meteorological Office 11-Layer General Circulation Model (GCM). This model is under development in the Dynamical Climatology Branch as part of an integrated model of the earth's climate system, which will also include an ocean GCM and a sea-ice model, for studying the physical basis of climate and its response to natural or man-induced perturbations.

Changes to the longwave part of the radiation scheme are described first, followed by revised surface shortwave albedos and cloud radiative properties. A brief description of the present configuration of the 11-layer model is followed by preliminary results from integrations with the new radiation scheme.

2. Longwave Radiation Scheme

A survey of observed and calculated longwave fluxes for the cloud-free tropical atmosphere, carried out by our colleague, Dr P R Rowntree (1981), showed that the radiation schemes in the 5 and 11-layer GCMs under-estimated the downward longwave fluxes in the lower troposphere by up to about 30 Wm^{-2}. This underestimate is evident in comparisons with the Ellingson and Gille (1978) scheme (EG) and the Roach and Slingo (1979) scheme (RS), as shown in Table 1. The fluxes from the EG scheme were kindly provided by Dr R G Ellingson. The RS scheme has a similar number of spectral bands to the 11-layer model scheme and was used to determine the reasons for the discrepancy by progressively removing the various differences between the two schemes. It was found that two differences were responsible for much of the discrepancy. The 11-layer model scheme ignored the temperature dependence of the fraction of the black body flux allocated to each spectral band, the fraction being fixed for a reference temperature of 263K. There was also a contribution from the different methods used to treat the water vapour continuum absorption. The treatment of both effects has been changed to formulations similar to those used by RS, except that the treatment of the water vapour continuum has been extended to 400 cm^{-1}, thus completely overlapping the CO_2 15μm band. This leads to a substantial reduction in the sensitivity of the downward longwave flux at the surface in moist atmospheres to changing CO_2 concentrations, due to absorption by the continuum of the emission from higher levels (e.g. Kiehl and Ramanathan 1983). Other changes include a different band structure in the 0-800 cm^{-1} region and the use of more recent spectral line data.

Special attention was paid to the treatment of carbon dioxide (CO_2) absorption, as the model will be used to continue research on the effect of increasing CO_2 concentrations on climate. Comparisons with the work of Kiehl and Ramanathan (1983) and others showed that there was a significant overestimate of the longwave fluxes in a pure CO_2 atmosphere at low temperatures. Some of this overestimate was removed by the changes outlined above and the remainder by including the temperature-dependence of the CO_2 absorption. This was achieved by introducing a scaling of the CO_2 absorber amounts to allow for the change in shape of the emissivity and transmissivity curves with temperature.

Following all these changes, the longwave fluxes are in much better agreement with those from the other schemes, as shown in Table 1. A complete description of this work is in preparation (Slingo and Wilderspin 1984).

3. Surface Shortwave Albedos

In the original version of the 11-layer model, the shortwave albedos for snow-free land, snow-covered land and sea-ice were fixed at 0.2, 0.5 and 0.8 respectively. More realistic values have now been incorporated. Firstly, the global dataset of land cover and soils data compiled by Wilson and Henderson-Sellers (1984) was used to create a geographical distribution of the snow-free land albedo. This dataset has formed the basis of a series of experiments to determine the sensitivity of the model to the land surface albedo (Wilson 1984). Secondly, the albedo of snow-covered land is now a function of the snow-depth, through a formulation similar to that employed in the 5-layer model (J. M. Slingo 1982). This is designed to take account of the fact that as the mean snow-depth increases, not only does the snow more completely cover any surface irregularities but also the area of the grid box which is snow-free is likely to decrease. Finally, the sea-ice albedo is now a function of the ice temperature, such that above 268K the albedo drops linearly from 0.8 to a value of 0.5 at 273K. This crudely represents the tendency for leads to open through the ice and for melt ponds to form on the surface as the temperature increases.

4. Cloud Radiative Properties

In early integrations of the model described below, it was found that, with imposed zonally-meaned clouds from published climatologies, the globally-averaged shortwave albedo was over-estimated compared with satellite data and the outgoing longwave radiation was also slightly too high. As a result, the net incoming radiation averaged over the year was significantly less than zero. Investigation showed that the most likely cause of the first problem was that the reflectivities for low and convective cloud used in the radiation scheme were too high. They were therefore reduced from 0.7 to 0.6, which brings them into closer agreement with the range of values obtained in recent observational and theoretical studies. The emissivity which is assumed for high cloud was also increased from 0.5 to 0.75, which reduces the outgoing longwave radiation and leads to a reflectance-emissivity relationship which is in good agreement with the results summarised by Stephens and Webster (1981). The complete set of cloud radiative properties in the new version of the model are summarised in Table 2.

5. The 11-layer Model

The 11-layer model is a global finite-difference GCM which is similar in many respects to the 5-layer model described by Corby et al (1977). The vertical coordinate is sigma (pressure divided by its surface value) and the 11-layers are irregularly distributed in the vertical to provide enhanced resolution near the surface and in the upper troposphere (see Figure 4 of J M Slingo (1980)). A limited-area version was used in the GATE experiment (Lyne et al 1976) and for experiments with a cloud parametrization scheme (J M Slingo 1980). The model was re-programmed for efficient execution on a Cyber 205 computer and is now usually integrated on a regular 2.5 x 3.75 degree latitude-longitude grid (72 x 96 points) with a 10 minute time-step. The land-sea mask was chosen to enable the model to be coupled to dynamical ocean and sea-ice models which are also being developed (Gordon and Bottomley 1984). Multipoint filtering in the E-W direction of the increments for the 17 rows nearest to each pole maintains computational stability at high latitudes (Hills 1982). Non-linear diffusion (to control grid-point noise) is applied to a linear combination of temperature and potential temperature, designed to have a small variation in each sigma surface for a horizontally homogeneous atmosphere, rather than to potential temperature as previously. This produces a better formulation near steep topography and removes a part of the global-mean cooling of the model when integrated from real data. The dynamical routines now use virtual temperatures in order to include the effect of the moisture content on the air density.

Physical processes are modelled in four sub-routines, which deal with boundary layer and surface exchanges, convection, large scale precipitation and finally radiation and clouds. The boundary layer is assumed to occupy the lowest three model layers in all conditions and transfers of heat, moisture and momentum between the layers are modelled by an eddy diffusivity approach (Carson 1982). The treatment of the surface is similar to that used in the 5-layer model (J M Slingo 1982) with interactive soil moisture and snow depth. Evaporation is limited for soil moisture less than 5 cm of water and runoff occurs to prevent the soil moisture from exceeding 15 cm. The convection scheme treats both unsaturated and saturated convection as it penetrates the vertical grid of the model (Rowntree 1984). Large-scale precipitation, in the form of rain or snow, is formed whenever the relative humidity exceeds 100%. Apart from the changes outlined earlier, the radiation scheme is that of J M Walker (1977), which is similar to that for the 5-layer model described by J M Slingo (1982).

One novel feature of the model is the use of a 360-day year, made up of twelve months each of 30 days, which leads to a considerable simplification of the logic required to run the model and produce diagnostics. The small error thus introduced into the incoming solar radiation is minimised by a slight adjustment to the date of perihelion (Slingo 1982). The diagnostics are passed through a high-speed link to the front-end IBM computers for off-line processing.

6. Experiments with the improved radiation scheme

An integration of the revised model with imposed zonally-meaned clouds and a parallel integration using a version of the cloud-prediction scheme described by J M Slingo (1980) have recently begun. These are intended to run for several simulated years to examine the effect of the radiation changes and of interactive cloud on the climate of the model. The cloud parametrization scheme has been modified to overcome a tendency to predict too much cloud in the boundary layer, especially over the oceans (Slingo 1984). In this version, convective cloud is still obtained from the saturated mass flux calculated in the convection scheme, as described by J M Slingo (1980). The dependence of the low cloud amount on the lapse rate has been removed, however, so that layer cloud is now determined solely by relative humidity. This relative humidity is an adjusted value which takes account of the fact that some of the moisture is associated with convective cloud and therefore should not be included when predicting the layer cloud amounts.

Some results from the first August of these integrations are shown in Table 3. The modifications to the cloud scheme lead to a globally-averaged cloud cover which is in close agreement with the climatological value used in the imposed-cloud integration. The radiation budget is also very similar and agrees reasonably well with that given by Stephens et al (1981). The modelled net radiation appears to be too low, but it is close to the value to be expected at this time of year if the annual-mean net radiation is to be zero, which should be the case. If the annual-mean of 9

Wm^{-2} obtained by Stephens et al (1981) is subtracted from their value of 4 Wm^{-2} for August, then the corrected value is close to those from the model integrations.

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Table 1 - Clear-sky downward fluxes (Wm^{-2}) at 800 mb and at the surface for the McClatchey Tropical profile. (McClatchey et al. 1971).

SCHEME	$F_{800}^{\downarrow}$	$F_S^{\downarrow}$
Ellingson and Gille (1978)	283	396
Roach and Slingo (1979). 50 levels	283	402
Original 11-layer model scheme	249	380
New 11-layer model scheme	281	406

Table 2 - Cloud radiative properties for the new version of the model (R = Reflectance, A = Absorptance, T = Transmittance and ϵ = emissivity).

CLOUD	SHORTWAVE			LONGWAVE
TYPE	R	A	T	ϵ
High	0.2	0.05	0.75	0.75
Medium	0.6	0.1	0.3	1.0
Low	0.6	0.1	0.3	1.0
Convective	0.6	0.1	0.3	1.0

Table 3 – Some results from the first August of two integrations with the improved radiation scheme. The observed results are from Stephens et al (1981). *See text for discussion.

Parameter	Integration: Imposed clouds	Integration: Interactive clouds	Observed
Global Albedo (%)	30.2	30.1	29*
Outgoing longwave flux (Wm^{-2})	241.1	240.1	235*
Net incoming radiation (Wm^{-2})	-7.1	-5.8	4*
Total cloud cover (%)	53.9	53.6	–