Development of a revised longwave radiation scheme for an atmospheric general circulation model

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SUMMARY

This paper describes the development of a new version of the longwave part of the radiation scheme used in the Meteorological Office 11-layer atmospheric general circulation model. The work was initiated when comparisons with other radiation schemes revealed systematic errors in the longwave fluxes. A detailed investigation of these errors was carried out by examining the sensitivity of the scheme to many of the details of its formulation. Various improvements were made, notably to the treatment of the temperature dependence of the Planck function and the water vapour continuum absorption. It is demonstrated that the fluxes are extremely sensitive to the formulation of the continuum absorption and suggested that more observations are needed to refine the values of the absorption coefficients. Special attention was paid to the treatment of carbon dioxide absorption, as the model is being used to continue research on the effect on climate of increasing CO₂ concentrations. A simple scaling of the absorber amounts is applied in order to include the temperature dependence of the CO₂ absorption. It is demonstrated that fluxes from the new version of the scheme and the sensitivity of the fluxes to changing CO₂ concentrations in realistic atmospheres are in good agreement with those from more detailed models.

1. INTRODUCTION

One of the most important components of an atmospheric general circulation model (AGCM) is the radiation scheme, which computes both the field of shortwave heating due to the absorption of the incoming solar radiation and the field of longwave cooling from the compensating emission back to space. It is important that such a scheme should not only be numerically fast but also as accurate as possible, especially when the model is to be used for investigating the response of climate to a radiative perturbation, such as that due to increasing carbon dioxide concentrations, and particularly when an interactive ocean surface is employed. It is thus fortunate that the radiation scheme is the only component which may be run independently of the rest of the model and checked against more detailed schemes.

A large number of papers describing new radiation schemes have appeared in the last few years. Until recently, no systematic intercomparison of these schemes had been made in order to understand the differences in the modelled fluxes and to identify systematic errors. Limited comparisons were performed as part of the U.S. carbon dioxide research program (Luther 1983). A much broader international effort, known as the Inter-Comparison of Radiation Codes used in Climate Models (ICRCCM), has recently started, the first stage being a detailed comparison of longwave fluxes under cloud-free conditions (Luther 1984).

In this paper, comparisons with several other schemes are used to guide the development of a revised version of the longwave part of the radiation scheme in the Meteorological Office 11-layer AGCM. The work was originally motivated by the need to remove certain systematic errors, which are discussed in section 3. These errors were removed by making changes to the treatment of the Planck function and the spectral resolution (section 4) and of the water vapour continuum absorption (section 5). In addition, a simple parametrization of the temperature dependence of carbon dioxide absorption is presented in section 6 and compared with the more detailed models developed by Kiehl and Ramanathan (1983). The results are not specific to the 11-layer model, but are relevant to a wide range of radiation schemes, particularly in their application to the carbon-dioxide/climate problem.
The work reported here concentrates on cloud-free atmospheres, because these provide the simplest and most controlled conditions for detailed comparisons between radiation schemes. Clouds can of course dominate the radiation fields, but it is sensible first to consider the clear-sky case before proceeding to cloudy conditions. Details of the methods used to represent clouds will be given in a subsequent paper.

2. ORIGINAL VERSION OF THE LONGWAVE RADIATION SCHEME

A brief description is given here of the original version of the longwave part of the radiation scheme used in the 11-layer model. A comprehensive account of the revised version is contained in the model handbook (Slingo 1985). Seven spectral divisions are used to represent the complex wavelength dependence of atmospheric absorption and emission, these being grouped into five distinct intervals as shown in Fig. 1. The first interval treats both the near-infrared vibration/rotation band and the far-infrared rotation band of water vapour. The second and third intervals deal with the overlap between water vapour and the 15 μm band of carbon dioxide. The final two intervals cover the contributions in the atmospheric window from weak water vapour lines, the 9-6 μm ozone band and the water vapour continuum absorption. Note that the continuum treatment only partially overlaps the CO₂ band, ending at 700 cm⁻¹.

The equations for the downward and upward longwave fluxes at pressure \( p \) are:

\[
F \downarrow (p) = B(0) \cdot \varepsilon(0, p) - \int_p^0 a(p', p) \left( \frac{dB(p')}{dp'} \right) dp' \\
F \uparrow (p) = B(p) + \int_p^0 a(p', p) \left( \frac{dB(p')}{dp'} \right) dp'
\]

![Figure 1. Band limits and absorbers taken into account in the Roach and Slingo (1979) longwave radiation scheme and the original and new versions of the 11-layer model scheme. The numbers identify the spectral bands of the former scheme and the separate contributions to the total flux from each absorber for the latter.](image)
where \( B(p) \) is the Planck flux for the temperature of the air at pressure \( p \), \( B(0) \) is thus the Planck flux for the top of the atmosphere, which is assumed to be the same as that for the top model level, and \( B(p_r) \) is that for the surface. This formulation assumes that the air close to the surface is at the same temperature as the surface itself, which is a reasonable approximation in calculating the fluxes. \( \varepsilon(0,p) \) is the slab emissivity of the atmosphere from the top down to pressure \( p \), and \( a(p',p) \) is the slab absorptivity from the dummy pressure \( p' \) to \( p \). Equations (1) and (2) are essentially the same as Eqs. (2) and (3) of Ramanathan et al. (1983), except for slight differences in nomenclature. The fluxes are calculated at each of the layer boundaries and the net fluxes are differentiated to give the layer cooling rates. The integrals are approximated by a trapezoidal rule, except that the layer adjacent to the level at which a flux is required is divided into two, in order to arrive at a more accurate estimate of the large local contribution in regions of high absorption. The Planck fluxes are calculated at the 11 atmospheric levels and at the surface and are assumed to vary linearly between these levels. The vertical coordinate of the model is sigma (pressure divided by the surface pressure) and the layer boundaries are situated at sigma values of 1, 0.975, 0.9, 0.79, 0.65, 0.51, 0.37, 0.27, 0.195, 0.125, 0.06 and 0 (as illustrated by Fig. 4 of Slingo (1980) and also by Figs. 2 and 3 of this paper).

The emissivity and absorptivity in the above equations are for the entire longwave spectrum and are calculated in a separate subroutine in which the contributions from each spectral band are added:

\[
\varepsilon(0,p) = \sum_{j=1}^{N} \varepsilon_j(0,p) \tag{3}
\]

\[
a(p',p) = 1 - \sum_{j=1}^{N} \tau_j(p',p) \tag{4}
\]

where \( \varepsilon_j \) and \( \tau_j \) are the emissivity and transmissivity in the spectral band \( j \), and \( N \) is the number of bands. In this version, each \( \varepsilon_j \) and \( \tau_j \) is normalized (by the fraction of the Planck flux in that band and by the fraction of the derivative of the Planck flux with respect to temperature in that band, respectively) to ensure that \( \varepsilon \) and \( a \) vary between zero and unity. For a band in which water vapour is the only absorber, the emissivity and transmissivity in Eqs. (3) and (4) are simply those for water vapour, calculated for the absorber amounts for the given path by interpolation from look-up tables stored in the program. For bands with two or more absorbers the emissivities and transmissivities for each gas are combined by making the usual assumption that the transmissivities may be multiplied together to give the overlapped values. The look-up tables were calculated by applying the version of the Goody random band model described by Hunt and Mattingly (1976) to the spectroscopic data of McClatchey et al. (1973) with a spectral resolution of typically 40 cm\(^{-1}\). The emissivities and transmissivities are stored for a temperature of 263 K and the temperature dependence is ignored. The absorber amounts are scaled to take account of the pressure dependence of the line half-widths, by a factor \( p^{0.9} \) for water vapour and \( p^{0.4} \) for ozone. The continuum treatment is based on the data of Bignell (1970) and depends on the water vapour partial pressure, but the temperature dependence is ignored. The mass mixing ratios of the gases are defined at the model levels and are assumed to be constant within each layer. The mixing ratio of \( \text{CO}_2 \) is taken to be \( 4.9 \times 10^{-4} \) throughout the model, corresponding to 323 parts per million by volume (p.p.m.v.).

The relative contribution of each spectral band to the total flux depends on the
fraction of the Planck flux in that band at a given temperature. The contributions thus change with increasing temperature as the peak of the Planck function moves to shorter wavelengths. However, in the original version of the scheme this effect was ignored. It will be shown later that this is an unnecessarily restrictive assumption which contributes to the errors discussed in the next section.

3. Systematic Errors in the Longwave Fluxes

A survey of observed and calculated longwave fluxes for the cloud-free tropical atmosphere showed that the scheme described in the previous section underestimates the downward longwave fluxes in the lower troposphere by up to about 30 W m$^{-2}$ (Rowntree 1981). This is illustrated in Fig. 2, which shows upward and downward longwave fluxes for the tropical profile of McClatchey et al. (1971) as given by the 11-layer model, the Roach and Slingo (1979) scheme (RS) and a recent version of the Ellingson and Gille (1978) scheme (EG), incorporating minor changes. The EG scheme is a spectrally-detailed model which was shown by them to produce radiance spectra in very good agreement with satellite observations. The fluxes were calculated for the same vertical grid as the profile data, without interpolation, and were kindly provided by Dr R. G. Ellingson. For the other two schemes the data were interpolated; in the case of the 11-layer model to the same vertical grid used in the AGCM and for RS to 50 levels, uniformly spaced in pressure from the surface to the top of the atmosphere.

Figure 2 shows that in the lower troposphere the fluxes from RS are within 5 W m$^{-2}$ of those from EG, although in the upper troposphere and stratosphere there are larger systematic deviations. Downward fluxes from the 11-layer model are significantly smaller than those from the other schemes in the lower troposphere, the largest difference being over 30 W m$^{-2}$ at 800 mb. At the surface the difference is about 20 W m$^{-2}$, so that the net

![Graph showing comparison of downward and upward longwave fluxes from different models.](image-url)
surface longwave cooling of 60 W m\(^{-2}\) given by the other schemes is overestimated by about 30 per cent. The first three entries in Table 1 show the fluxes at the top and bottom of the atmosphere from each scheme for all the five standard atmospheres listed by McClatchey et al. (1971). The downward fluxes at the surface from RS are larger than those from EG, but the biggest difference is only 6·3 W m\(^{-2}\), whereas the 11-layer model fluxes are from 16·3 W m\(^{-2}\) to 21·6 W m\(^{-2}\) lower than the EG values. The upward fluxes at the top of the atmosphere are much closer, but as shown by Fig. 2 the divergence of the upward flux is always much less than that of the downward flux so the better agreement here is not surprising.

The effect of these flux errors on the longwave cooling rates is illustrated in Fig. 3 for the tropical and subarctic winter atmospheres. In the mid-troposphere the original version of the scheme underestimates the cooling rates given by EG by up to 0·5 K/day. The underestimate continues to the surface in the subarctic winter atmosphere, whereas in the tropical atmosphere there is an equally large overestimate of the cooling below 800 mb.

The good agreement between RS and EG demonstrates that insufficient spectral resolution is not the reason for the errors in the 11-layer model fluxes, as RS has even fewer spectral intervals, as shown on Fig. 1. The spectral line data in RS come from the same compilation as the 11-layer model and were obtained using the same band model, although in other respects there are many differences between the schemes. It was decided to investigate the errors in the 11-layer model fluxes by progressively changing the model to remove the major differences in formulation compared with RS. It must be appreciated that the RS scheme was not treated as an absolute reference but merely as a convenient tool for carrying out the investigation.

Firstly, code was added to the 11-layer model to break the fluxes down into the contributions from each spectral band, so that the role of each band could be determined.

Figure 3. Comparison of longwave cooling rates from the Ellingson and Gille (1978) scheme (continuous profiles), the original version of the 11-layer model scheme (dotted square profiles) and the new version (solid square profiles) for two cloud-free atmospheres.
<table>
<thead>
<tr>
<th>Version</th>
<th>Notes</th>
<th>Downward flux at surface</th>
<th>Upward flux at top of atmosphere</th>
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<tr>
<td>Ellingson and Gille (1978) scheme</td>
<td></td>
<td>396-7</td>
<td>347-0</td>
</tr>
<tr>
<td>2</td>
<td>= 1 but new spectral data</td>
<td>379-8</td>
<td>328-0</td>
</tr>
<tr>
<td>Effect of new spectral data</td>
<td>= 2 plus Planck function temperature dependence</td>
<td>379-9</td>
<td>328-0</td>
</tr>
<tr>
<td>3</td>
<td>= 2 plus Planck function temperature dependence</td>
<td>382-8</td>
<td>332-0</td>
</tr>
<tr>
<td>4</td>
<td>= 2 with no continuum term</td>
<td>368-4</td>
<td>319-0</td>
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<tr>
<td>Effect of no continuum term</td>
<td>= 4 but new spectral bands</td>
<td>373-5</td>
<td>323-7</td>
</tr>
<tr>
<td>Effect of new spectral bands</td>
<td>= 5 plus Planck function temperature dependence</td>
<td>377-3</td>
<td>328-9</td>
</tr>
<tr>
<td>Effect of Planck function temperature dependence</td>
<td>= 6 but RS window continuum</td>
<td>396-3</td>
<td>347-4</td>
</tr>
<tr>
<td>Effect of RS window continuum</td>
<td>= 7 but revised window continuum</td>
<td>19-0</td>
<td>18-5</td>
</tr>
<tr>
<td>Effect of revised window continuum</td>
<td>= 8 plus 15 µm continuum</td>
<td>402-1</td>
<td>350-9</td>
</tr>
<tr>
<td>Effect of 15 µm continuum</td>
<td>= 9 but additional 20 µm band</td>
<td>13-0</td>
<td>11-8</td>
</tr>
<tr>
<td>Effect of additional 20 µm band</td>
<td>= 10 plus 20 µm continuum</td>
<td>402-1</td>
<td>351-0</td>
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<td>= 11 but no K1 continuum term</td>
<td>405-6</td>
<td>355-7</td>
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<td>= 11 but with minor changes (see text)</td>
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<td>355-7</td>
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<td>Effect of CO2 temperature dependence</td>
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<td>0-3</td>
</tr>
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</table>

**KEY:** TROP. (tropical), M.I.S. (mid-latitude summer), S.A.S. (subarctic summer), M.I.W. (mid-latitude winter) and S.A.W. (subarctic winter)
Secondly, the calculation of the absorber amount in each layer was checked by temporarily changing the pressure and temperature scaling in RS to match that in the 11-layer model. This showed that there were no significant differences between the schemes in this calculation.

The following three sections describe the changes to the 11-layer model scheme and examine the effect on the fluxes. The results are presented in Table 1.

4. CHANGES TO THE SPECTRAL DATA, PLANCK FUNCTION AND SPECTRAL BANDS

(a) Spectral data

The first change was to re-calculate the emissivity and transmissivity tables using the more recent compilation of spectral line data described by Rothman (1981). The fluxes from this version (2 in Table 1) show only small changes compared with the original. Except close to the surface in the tropical profile, the atmospheric emission is reduced, so the downward fluxes are lower (by up to 2.4 Wm\(^{-2}\) at 375 mb in the tropical profile, with smaller changes at the surface) and the upward flux at the top of the atmosphere is larger.

(b) Planck function

As described earlier, in the original version of the 11-layer model the temperature dependence of the fractions of the Planck flux in each spectral band was ignored, whereas in RS this is accounted for. To include this effect the fractions were first calculated by numerical integration of the Planck function across each band, using 1 cm\(^{-1}\) spectral resolution for 5 K temperature intervals from 180 to 320 K. These data were then fitted with a polynomial in temperature and the coefficients stored in the program. In the tropical profile the fluxes from this version (3) show an increase by 7.8 Wm\(^{-2}\) at 658 mb, decreasing to 2.9 Wm\(^{-2}\) at the surface. In the colder profiles the level of maximum increase moves to lower levels, so that in the subarctic winter profile it is at the surface, where the increase of 9.2 Wm\(^{-2}\) removes about half the disagreement with the RS and EG schemes.

The reason for this response is that at 263 K the fraction of the Planck flux in the first spectral band (0-500, and greater than 1200 cm\(^{-1}\)) is smaller than at the lower temperatures more typical of the upper troposphere, whereas for the atmospheric window bands it is larger. The importance of the far-infrared rotation band of water vapour, which provides most of the downward longwave flux from the upper troposphere, is thus reduced when the temperature dependence is ignored so that the downward fluxes are too low. The underestimate increases from the top of the atmosphere down to the level where the air temperature is about 263 K and thereafter decreases, so the level of maximum change moves from the mid-troposphere in the warmest profiles to the surface in the subarctic winter profile.

(c) Spectral bands

Further comparisons between the 11-layer model and RS were made difficult by the different configurations of the spectral bands, in particular the fact that the 11-layer model had a single band covering both the 0-500 and the greater than 1200 cm\(^{-1}\) regions. It was also felt that dividing the CO\(_2\) band into two at 700 cm\(^{-1}\), close to the centre of the band, might not be justifiable and that the assumption of random overlap between CO\(_2\) and water vapour lines might be questionable in the 500-700 cm\(^{-1}\) region, because CO\(_2\) absorption is strongest near 660 cm\(^{-1}\) (where the water vapour line absorption is much weaker) and is weak below 600 cm\(^{-1}\) (where the water vapour line absorption is
stronger) (Rowntree 1981), as for example shown by Fig. 1 of Kiehl and Ramanathan (1983). It was therefore decided to change the spectral resolution in these regions to be closer to that of RS, leaving the treatment of the atmospheric window unchanged. Given that RS does not include water vapour continuum absorption outside the window, a proper comparison first required removal of the overlap term 9 from the 11-layer model (Fig. 1). The effect is shown by version 4 compared with 2 in Table 1. As expected, there is a large response at the surface for the tropical profile (−11.5 W m⁻²) which decreases rapidly with height and is also much smaller in the colder profiles. This demonstrates the importance of the continuum term outside the window, which is examined more closely in the next section.

Three major changes to the band configuration were made for version 5. Separate water vapour bands covering 0-560 cm⁻¹ (corresponding to RS bands 1 and 2) and 1200 cm⁻¹ upwards (roughly equivalent to RS band 5) and a water-vapour/CO₂ overlap band covering 560-800 cm⁻¹ without a continuum overlap term (corresponding to RS band 3) were included. The effect is to increase the downward fluxes in the lower troposphere, the largest response being at the surface and varying from 5-1 W m⁻² to 2.3 W m⁻², with a very small reduction at upper levels. When the temperature dependence of the fraction of the Planck flux in each band is added to produce version 6 there is a slightly larger response compared with that from the version with the original spectral bands (3). The downward flux at the surface in the subarctic winter profile is now even closer to that given by RS and EG, but there is still a large discrepancy for the warmer profiles.

The reason for most of the remaining discrepancy compared with RS for the tropical profile was found by comparing the fluxes for particular spectral regions. For the bands outside the 10μm window, there was no evidence for more than a few W m⁻² underestimate by the 11-layer model. In the window, however, the 11-layer model uses a wider spectral interval than RS, as shown by Fig. 1. To be consistent with RS, the downward fluxes should thus be larger but in fact they are about 10 W m⁻² lower. In this spectral region there is absorption by ozone, weak water vapour lines and the water vapour continuum. Ozone makes only a small contribution to the downward flux at the surface and comparisons with other schemes (not shown here) indicate that the treatment of this band is adequate. The remaining discrepancy must therefore be mainly due to differences in the treatment of the water vapour continuum, which provides most of the downward flux in the window in clear tropical atmospheres. In the following section, a revised treatment of the continuum in the window and at longer wavelengths is described.

5. Changes to the treatment of the water vapour continuum

(a) Window continuum

The existing continuum treatment was first replaced by that of section 3(b) of RS, which follows Bignell (1970) and is similar to that used by EG. There are two contributions to the continuum absorption: a ‘foreign broadened’ coefficient k₁, arising from broadening of water vapour lines by collisions with other gases, and an ‘e-type’ coefficient k₂. The latter is often attributed to water vapour dimers, although there is evidence that it may be caused by absorption in the far wings of distant, self-broadened water vapour lines (Burch and Gryvnak 1980). The values of k₁ and k₂ and their temperature dependence were taken from RS. The effect of this change is shown by the fluxes from version 7 compared with version 6. There is a substantial increase in the downward fluxes, the surface value increasing by 19 W m⁻² for the tropical profile and by 2.7 W m⁻² for the subarctic winter profile. The downward flux at the surface is now within a few W m⁻² of
that from both RS and EG. However, this apparent agreement is misleading as there are still differences between the schemes. For example, RS ignores the effect of local water vapour lines in the window while EG includes a continuum term not only in the window but across the CO₂ band to end at 400 cm⁻¹. In this section the effect of a revised continuum treatment for the 11-layer model which also covers this range will be examined.

Two aspects of the continuum treatment described by RS were changed. Firstly, there seems to be little evidence to support the weak T¹⁻⁵ temperature dependence for the foreign broadened coefficient k₁, so this was removed. Secondly, the temperature dependence for the e-type coefficient k₂ was changed to that described by Roberts et al. (1976), using their best estimate of T₀ = 1800 K for the temperature dependence parameter:

\[ k_2(T) = k_2(296 \text{ K}) \exp \{ \frac{T_0}{T} - \frac{T_0}{296} \}. \]  

At the new reference temperature of 296 K the values of the continuum coefficients were taken to be k₁ = 0.05 g⁻¹cm²atm⁻¹ and k₂ = 10 g⁻¹cm²atm⁻¹ for both bands 4 and 5 in the window. The ratio of k₁ to k₂ is thus 0.005, which was also used by EG. The effect of these changes (version 8) is to weaken the window continuum compared with RS, the largest flux change being -8.3 W m⁻² at the surface for the mid-latitude summer profile.

(b) 15 μm continuum

In section 4(c) it was shown that removal of the continuum term overlapping CO₂ in the 700–800 cm⁻¹ region reduced the surface downward flux by up to 11.5 W m⁻². Such a term thus makes an important contribution in this region and when it is extended to cover the entire 15 μm band it significantly reduces the sensitivity of the net surface flux in moist atmospheres to increased CO₂ concentrations (Kiehl and Ramanathan 1982). Both Bignell (1970) and Roberts et al. (1976) show that the e-type continuum is stronger at these wavelengths than in the 10 μm window. From Bignell's data the mean value of k₂ in the 560–800 cm⁻¹ interval was taken to be 30 g⁻¹cm²atm⁻¹ with the same temperature dependence as in the window and with k₁/k₂ = 0.005. The 15 μm continuum was included in version 9 as an overlap term in addition to the terms from water vapour and CO₂ lines. The effect is to increase the downward fluxes by up to 13 W m⁻² for the tropical profile at the surface and by smaller amounts in the other profiles. The effect on the sensitivity to doubled CO₂ concentrations will be examined in section 6.

(c) 20 μm continuum

Bignell (1970) and Roberts et al. (1976) show that the strength of the continuum absorption continues to increase beyond the 15 μm band to at least 400 cm⁻¹ (25 μm wavelength). There seems little point in including a continuum term at longer wavelengths because the strong absorption by the far-infrared rotation band of water vapour ensures that fluxes are already close to the Planck values in this spectral region in the lower troposphere. However, there is a weak window at about 20 μm where the continuum might be important. The 0–560 cm⁻¹ band was therefore divided into two, as in RS, and the continuum included as an overlap term with water vapour lines in the 400–560 cm⁻¹ region. The effect of dividing the band before adding the continuum term is given by comparing versions 10 and 9 in Table 1. The effect at the surface is small but it increases with height to a maximum of 1.8 W m⁻² at 375 mb in the tropical profile and 2.4 W m⁻² at 517 mb in the subarctic winter profile. These are the levels where the flux divergence in the rotation band, and hence the cooling rate, is greatest and it is therefore not surprising to find a sensitivity when improved spectral resolution is incorporated.
The mean value of $k_2$ in the 400–560 cm$^{-1}$ band was taken from Bignell’s data to be 70 g$^{-1}$ cm$^2$ atm$^{-1}$ with the same temperature dependence and ratio of $k_1$ to $k_2$ as in the window and at 15 µm. The final configuration of the spectral bands and overlaps used in this version (11) is shown on Fig. 1. The response to this term is significant and justifies its inclusion. In the tropical profile the downward flux increases by 7.1 W m$^{-2}$ at 800 mb and by 3.5 W m$^{-2}$ at the surface. In the other profiles the maximum increase moves towards the surface so that in the subarctic summer profile the surface flux increases by more (5.8 W m$^{-2}$) than in the tropical profile, while in the subarctic winter profile the maximum is at the surface itself but smaller in magnitude (3.4 W m$^{-2}$).

(d) Discussion

It is well known that the water vapour continuum term makes a substantial contribution to the net longwave flux at the surface in warm, moist atmospheres. For example, if all the continuum terms are removed from version 11 the surface downward flux in the tropical profile drops by 87.2 W m$^{-2}$, thus enhancing the surface longwave cooling by over two and a half times. This emphasizes the accuracy which is required in calculating this term, although there is still no clear consensus on the magnitude of the absorption coefficients and their variation over wide ranges of temperature. For example, the somewhat arbitrary ratio $k_1/k_2 = 0.005$ has been used here, whereas Bignell (1970, Fig. 8) shows evidence that $k_1/k_2$ is much larger than this at about 20 µm, although Roberts et al. (1976) suggest that it is much smaller and that $k_1$ should be ignored at all wavelengths. The effect of removing $k_1$ altogether in all the continuum bands but retaining $k_2$ is shown by comparing versions 12 and 11. In the tropical profile the largest response is at 912 mb ($-9.7$ W m$^{-2}$) and the surface flux drops by almost as much ($9.3$ W m$^{-2}$). Most of the change at the surface ($8.7$ W m$^{-2}$) is due to the window bands (800–1200 cm$^{-1}$) but at higher levels the 15 µm and 20 µm contributions are as important. In the other profiles the maximum response is at the surface, varying from $-10.5$ W m$^{-2}$ for the mid-latitude summer to $-4.0$ W m$^{-2}$ in the subarctic winter profiles. These changes are of similar magnitude to those resulting from the inclusion of the 15 µm continuum and underline the need for more reliable information on the magnitude of this term as well as of $k_2$.

Version 11 of the scheme was now optimized for efficient execution in the full model on the Cyber 205 computer. It was found convenient to alter the subroutine which calculates $\epsilon$ and $a$ to calculate directly the $B(0).\sigma(0,p)$ and integral terms in Eqs. (1) and (2), thus calculating the flux contributions from each band and each layer. The differences between the fluxes from this ‘intermediate’ version (13) and version 11 are very small, the largest difference being $-0.4$ W m$^{-2}$ for the upward flux at the top of the atmosphere from the tropical profile.

6. Changes to the Treatment of Carbon Dioxide

One of the most important applications of the 11-layer model is to continue work on the effect of increasing carbon dioxide concentrations on climate (Mitchell 1983). It is obviously important that the radiative effects of CO$_2$ applied to the model should be as accurate as possible. Results from the model are here compared with the work of Kiehl and Ramanathan (1983) (hereafter KR), who carried out a detailed comparison of fluxes from a new wide band scheme, designed for fast computation in climate models, with those from Goody and Malkmus narrow band models. They showed that as regards accuracy there was little to choose between the three schemes, although the best
agreement with measured absorptances was obtained with the Malkmus and wide band models.

In the simplest comparison, fluxes for isothermal atmospheres at 200 K and 300 K in which CO$_2$ is the only radiatively-active gas were calculated for CO$_2$ concentrations of 320 and 640 p.p.m.v. Results for the downward flux at the surface for the models studied by KR and versions of the present scheme are shown in Table 2. At 200 K, the

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<th>Kiehl and Ramanathan (1983)</th>
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<td></td>
<td>Goody</td>
<td>Malkmus</td>
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<td>$T = 200$ K</td>
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<td>CO$_2$ = 320 p.p.m.v.</td>
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<td>13·2</td>
</tr>
<tr>
<td>CO$_2$ = 640 p.p.m.v.</td>
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<td>14·3</td>
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<td>640' - 320</td>
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<td>1·09</td>
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</tr>
<tr>
<td>CO$_2$ = 320 p.p.m.v.</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>CO$_2$ = 640 p.p.m.v.</td>
<td>97</td>
<td>97</td>
</tr>
<tr>
<td>640' - 320</td>
<td>6·98</td>
<td>6·96</td>
</tr>
</tbody>
</table>

fluxes and sensitivity to changing CO$_2$ from the original version of the present scheme are overestimated compared with KR, whereas at 300 K there is good agreement. The intermediate version (13 in Table 1) shows improved fluxes and sensitivity at 200 K, but at 300 K both are too low. The pattern of the differences between this version and KR suggested that they might be reduced by including the temperature dependence of the CO$_2$ absorption. This has long been known to be significant, with emissivities which increase steadily with increasing temperature (e.g. Liou 1980, Fig. 4.8), such that using values for 263 K at all temperatures (as in this version) would be expected to overestimate emissivities at lower temperatures and underestimate them at higher temperatures. Figure 4 shows curves of the normalized emissivity of CO$_2$ in the 560–800 cm$^{-1}$ band as a function of the absorber amount $u$ for various temperatures $T$, as given by the band model (at 40 cm$^{-1}$ resolution). The shape of the curves, which diverge steadily with increasing $u$, suggested that a reasonable approximation to the emissivity at any temperature could be obtained by using the curve for 263 K as before, but in addition scaling the absorber amounts with a temperature-dependent factor which is itself a function of absorber amount. After some experimentation, it was found that the following scaling of the absorber amount in each layer, $\Delta u$, was adequate:

$$\Delta u_{\text{SCALED}} = \Delta u \cdot (T/263)^{\text{POWER}}$$  \hspace{1cm} (6)

where

$$\text{POWER} = 8·5 + 2 \log_{10}(\Delta u)$$  \hspace{1cm} (7)

and $T$ is the layer temperature. At small $\Delta u$, POWER is forced to be zero rather than become negative. The dots on Fig. 4 show the effective emissivities at the layer boundaries for a CO$_2$ concentration of 320 p.p.m.v., obtained by using this scaling for temperatures of 203 and 323 K, which demonstrates the excellent fit to the data. Note that the dependence of the scaling on the absorber amount results in a shift of the effective emissivity curves as the CO$_2$ concentration is increased, but the effect on the sensitivity of the scheme to changing CO$_2$ amounts is very small.
This scaling represents the final change to create the new version of the radiation scheme (14). Table 2 shows that the fluxes and sensitivity to doubled CO$_2$ for this version are in excellent agreement with KR at 200 K. At 300 K the fluxes are also in good agreement although the sensitivity to doubled CO$_2$ is still low. Fluxes using this version are also entered in Table 1. As expected, the scaling reduces the downward fluxes at upper levels and increases the outgoing longwave flux, with smaller changes at the surface.

Although results for isothermal atmospheres are useful in studying the temperature dependence, it is also important to check the CO$_2$ fluxes for more realistic atmospheres. Table 3 shows a comparison of the sensitivity to doubling CO$_2$ of the original and new versions of the scheme with that of the schemes used by KR, for three atmospheres in which CO$_2$ is the only absorber. In addition, results when the overlaps of the CO$_2$ band by water vapour line and continuum absorption are also included, are shown in brackets for the wide band and 11-layer models. The values for the wide band model are different from those given by KR as they come from a more recent version (Kiehl, in preparation). This employs a new vertical finite difference scheme to determine the mean temperature used in the calculation of the CO$_2$ absorption, leading to fluxes which are in better agreement with the narrow band model results when CO$_2$ is the only absorber. There is also a revised formulation of the mean water vapour absorption across the wide band. Neither change affects the results shown in Table 2.

The change in the downward flux at the surface for the new version of the scheme is lower than in KR for all three atmospheres when CO$_2$ is the only absorber, while the original version gives values which are closer to KR. However, the agreement between
the new version and the wide band model is much better when the overlapping by water vapour is included. In the tropical profile, all the models now predict a much smaller change because the lower troposphere becomes much more opaque in this spectral region. This effect is weakest in the original version of the 11-layer model scheme because the continuum term does not cover the entire CO₂ band but only the 700–800 cm⁻¹ region (see Fig. 1). It is much stronger in the new version of the scheme and the essential result that the change in the surface flux is reduced to a low value agrees well with KR. Similar comments apply to the results for the mid-latitude summer case, where the lower water vapour mixing ratios lead to a slightly larger change in the surface flux compared with the tropical profile. The largest change is now found for the subarctic winter atmosphere, but even in this much drier atmosphere all the schemes predict a significant reduction in the sensitivity of the downward longwave flux to doubled CO₂, compared with the case when CO₂ is the only absorber.

The response of the climate system to increased CO₂ concentrations is controlled more by the change in the net upward flux at the tropopause than by that at the surface (e.g. Ramanathan 1981). Table 3 shows that for this parameter when CO₂ is the only absorber the original version of the 11-layer model scheme gives values for the two warm profiles which are larger than those obtained by KR, whereas the values from the new version are closer. All five schemes show good agreement for the winter profile. When the water vapour overlaps are added the agreement between the values from the new version and the wide band model is extremely good, the biggest difference being only 0.18 W m⁻². It is thus reasonable to conclude that the new version shows a sensitivity to changing CO₂ concentrations in realistic atmospheres which compares very favourably with the schemes developed by KR.

7. DISCUSSION

Figure 2 shows that the changes described in the previous sections to create the new version of the 11-layer model longwave radiation scheme have reduced substantially the systematic errors in the fluxes from the original version. Compared with the EG scheme, there is still evidence that the downward fluxes in the middle troposphere are too low,

<table>
<thead>
<tr>
<th>Profile</th>
<th>Flux</th>
<th>Goody</th>
<th>Malkmus</th>
<th>Wide band</th>
<th>11-layer model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Original version 1</td>
</tr>
<tr>
<td>Tropical</td>
<td>ΔF ↓ (S)</td>
<td>6.80</td>
<td>6.85</td>
<td>7.00 (0.10)</td>
<td>6.69 (1.17)</td>
</tr>
<tr>
<td></td>
<td>ΔF ↑ NET(T)</td>
<td>-6.43</td>
<td>-6.40</td>
<td>-6.74 (-5.33)</td>
<td>-7.42 (-6.15)</td>
</tr>
<tr>
<td>Mid-latitude</td>
<td>ΔF ↓ (S)</td>
<td>6.37</td>
<td>6.42</td>
<td>6.55 (0.42)</td>
<td>6.19 (1.54)</td>
</tr>
<tr>
<td>summer</td>
<td>ΔF ↑ NET(T)</td>
<td>-6.09</td>
<td>-6.15</td>
<td>-6.35 (-5.30)</td>
<td>-6.56 (-5.63)</td>
</tr>
<tr>
<td>Subarctic</td>
<td>ΔF ↓ (S)</td>
<td>3.79</td>
<td>3.86</td>
<td>3.93 (2.77)</td>
<td>3.65 (2.50)</td>
</tr>
<tr>
<td>winter</td>
<td>ΔF ↑ NET(T)</td>
<td>-3.63</td>
<td>-3.72</td>
<td>-3.69 (-3.50)</td>
<td>-3.67 (-3.53)</td>
</tr>
</tbody>
</table>

For the Goody and Malkmus models, the flux change when CO₂ is the only absorber is entered. For the other models, this is followed by brackets the value obtained when the overlaps by water vapour line and continuum absorption are added. The fluxes from the wide band model differ from those given by Kiehl and Ramanathan as they come from a more recent version. See text for details. ΔF ↓ (S) is the change in downward flux at the surface and ΔF ↑ NET(T) is the change in the net upward flux at the tropopause.
but by at most 10 W m$^{-2}$ compared with 30 W m$^{-2}$ previously. At the surface, the new scheme gives a downward flux which is 9.2 W m$^{-2}$ larger than EG, compared with 16.9 W m$^{-2}$ smaller for the original version. However, the net upward flux at the surface is now 53.5 W m$^{-2}$, which is much closer to the value of 45$\pm$22 W m$^{-2}$ for the cloudless tropical atmosphere studied in GATE (Feigelson et al. 1982). For the other profiles, the downward fluxes at the surface are also much larger than before and are in better agreement with those from EG, especially for the colder atmospheres (Table 1). The changes in the upward fluxes at the top of the atmosphere are much smaller, so that for all five profiles the smaller longwave cooling of the surface is compensated by enhanced atmospheric cooling. The vertical structure of the atmospheric cooling is much closer to that from EG, as shown by Fig. 3.

It has been shown that the surface fluxes are extremely sensitive to the formulation of the water vapour continuum absorption. Clearly, more data are needed to refine the values of the continuum absorption coefficients and in particular to establish the validity of the temperature dependence assumed for the e-type component over a wider range of temperature and wavenumber and to confirm or disprove the existence of the foreignbroadened component. The problem with the continuum is that it cannot be studied in isolation from the water vapour lines, because it is defined as the excess absorption which is not accounted for by the known water vapour lines with simple theoretical line shapes. If the excess can indeed be explained by reasonable adjustments to the line shapes (so that dimers do not need to be invoked), as suggested by Burch and Gryvnak (1980), then for consistency the emissivity and transmissivity tables used here should also be changed. This could be done by incorporating the new line shapes into the band model, or into a line-by-line calculation, which would provide the more accurate results.

At this stage, having made substantial improvements, it was decided to terminate the work on the radiation scheme and concentrate on the problem of cloud prediction in the full AGCM. It is of course recognized that further improvements could be made. For example, it would be advantageous to include the temperature dependence of the water vapour line absorption, perhaps in a similar way to that employed for carbon dioxide (section 6). However, for the investigations being carried out with and planned for the model it is believed that the revised scheme represents a reasonable balance between accuracy and numerical speed. The entire radiation scheme (shortwave plus longwave calculations) takes on average only 0.9 ms per profile on a Cyber 205 computer, which allows it to be called several times per model day (at present eight times) for each grid point in order to resolve the diurnal cycle of radiative forcing.

This study has demonstrated the value of detailed comparisons between radiation schemes to establish the reasons for differences in the predicted fluxes. While some modellers may wish to pursue even small flux differences to provide a complete explanation, the authors’ experience is that this is a time-consuming process. There comes a point in developing an AGCM where that time is best spent on other more uncertain areas of the model. The AGCM modeller thus needs to know how the flux differences of the magnitude studied here affect the quality of simulations with the model, in order to assess the impact and importance of flux errors on the model’s climate. The effect of these and other radiation scheme changes on the climate of the 11-layer AGCM is currently being investigated.
ACKNOWLEDGMENTS

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