1 INTRODUCTION

A radiation scheme plays an important role in global atmospheric models. As not only its accuracy but also its computing efficiency is important, Japan Meteorological Agency (JMA) developed a more accurate and efficient radiation scheme for a global atmospheric model, as a part of the RR2002 project funded by MEXT (Ministry of Education, Culture, Sports, Science and Technology).

2 CHANGES IN LONGWAVE RADIATION SCHEME

2.1 Outline of changes

The following refinements were carried out based on Chou et al. (2001), in order to calculate radiative flux accurately both in the troposphere and in the stratosphere.

First refinement is on calculation method of transmittance for line absorption. K-distribution method and table look-up method are newly used instead of statistical band model.

Secondly, treatment of water vapor continuum is revised. Parameterization used in the previous scheme is based on Roberts et al. (1976) which takes account of only self broadening (e-type) absorption. In the new scheme, effect of foreign broadening (P-type) absorption is introduced based on Zhong and Haigh (1995). Variation of absorption coefficient due to water vapor mass change is also considered.

Thirdly, longwave spectrum is divided into 9 bands instead of previous 4 bands. Radiative flux is calculated in each band separately, in order to improve accuracy of band-averaged transmittance. In addition, water vapor absorption are taken into account in entire longwave spectrum. Effects of absorption by trace gases such as CH₄, N₂O and 3 CFCs are also introduced. Figure 1 shows spectral ranges for these bands and absorbers involved in each band.

2.2 K-distribution method

Transmittance in most of spectral bands are calculated by k-distribution method which has advantage of computing efficiently. The basic assumption of this method is that an integration over wavenumber ν can be replaced by an integration over the absorption coefficient k, for a narrow spectral interval where the Planck function can be considered almost constant. If the normalized probability distribution function for k is given by f(k), transmittance can be expressed by

\[ T = \int_{0}^{\infty} f(k) \exp \left[ -k \frac{u}{\bar{\mu}} \right] dk = \int_{0}^{1} \exp \left[ -k(g) \frac{u}{\bar{\mu}} \right] dg, \]

(1)

where u is absorber amount, 1/\( \bar{\mu} \) is diffusivity factor, and g(k) is a cumulative probability density function. This integration can be replaced by a finite sum of exponential terms.

Considering a homogeneous atmosphere in a spectral band, transmittance is expressed as

\[ T(p, \theta, u) = \sum_{n} \exp \left[ -\frac{E_{n}(p, \theta) u}{\bar{\mu}} \right] \Delta \lambda_{n}, \]

(2)

where \( \Delta \lambda_{n} \) is a cumulative probability density function weighted by the Planck function.

For calculation for a nonhomogeneous atmospheric path, a pressure scaling method is adopted. We introduce scaled absorber amount defined by

\[ \tilde{u} = \int \left( \frac{p'}{p} \right)^{m} h(\theta, \theta_{r}) du', \]

(3)

where p' and \( \theta_{r} \) are the reference pressure and temperature, m is an empirical constant, and h(\( \theta, \theta_{r} \)) is temperature scaling factor given by

\[ h(\theta, \theta_{r}) = 1 + \alpha (\theta - \theta_{r}) + \beta (\theta - \theta_{r})^2, \]

(4)

where \( \alpha \) and \( \beta \) are regression coefficients. Using this scaling method, a nonhomogeneous atmosphere is regarded as a homogeneous atmosphere with pressure p', temperature \( \theta_{r} \), and absorber amount \( \tilde{u} \).
2.3 Table look-up method

K-distribution method described above is a very efficient method, but its accuracy in the upper stratosphere is not enough because pressure scaling technique cannot deal with effects of Doppler absorption adequately. In order to compute transmittance in the upper stratosphere accurately, a pre-computed table look-up technique is used for spectral bands where radiative cooling in the stratosphere is significant.

Transmittance in a homogeneous layer is calculated in advance for some combinations of pressure, temperature and absorber amount by line-by-line method. Temperature dependency is expressed in a form of quadratic fit. Transmittance is given by

\[ T(p, θ, u) = A(p, u) + B(p, u)(θ - 250) + C(p, u)(θ - 250)^2. \]  

(5)

Coefficients of the tables \((A, B, C)\) are determined using HITRAN2000 (Rothman et al. 2003) as a line parameter database andLBLRTM (Clough et al. 1992, Clough and Iacono 1995) as a line-by-line model.

Transmittance in a nonhomogeneous layer with pressure and temperature varying with height is computed as a homogeneous layer with an effective pressure and temperature defined by

\[ p_{\text{eff}} = \frac{\int p \, du}{\int du}, \quad θ_{\text{eff}} = \frac{\int θ \, du}{\int du}. \]  

(6)

where \(u\) is the absorber amount.

2.4 Parameterization of water vapor continuum absorption

Parameterization of water vapor continuum absorption is based on Zhong and Haigh (1995). Optical depth by water vapor continuum in a spectral band is described as

\[ τ_c = \overline{K}(\overline{w}) \overline{w} + K^p \left( \left( \frac{p - u}{p - e} \right) \frac{w(p - e)}{p} \right), \]  

(7)

where \(\overline{w}\) and \(\frac{w(p - e)}{p}\) are scaled water vapor mass for \(e\)-type and \(P\)-type absorption respectively, defined as

\[ \overline{w} = \int e^f (\theta') \, du' \]  

(8)

\[ \frac{w(p - e)}{p} = \int (p' - e') f^p (\theta') \, du'. \]  

(9)

In the equations above, \(e'\) and \(p'\) are water vapor partial pressure and total pressure respectively, \(f^e\) and \(f^p\) represent temperature dependency described as

\[ f^e(θ) = \exp \left[ θ \left( 1 - \frac{θ}{296} \right) \right] \]  

(10)

\[ f^p(θ) = \frac{296}{θ}. \]  

(11)

where \(θ\) is temperature in K, \(\Theta\) is a constant defined for each spectral band using CKD model (Clough et al. 1989). \(\overline{K}\) and \(K^p\) are absorption coefficients when temperature is 296 K and are functions of scaled water vapor mass. These are fit by

\[ \overline{K} = a^e \left[ 1 + e^c \overline{w} \right] + d^e, \quad K^p = a^p \left[ 1 + e^c \frac{w(p - e)}{p} \right] + d^p. \]  

(12)

where \(a^e, b^e, c^e, d^e, a^p, b^p, c^p\) and \(d^p\) are fitting parameters determined by comparison with calculation by MT-CKD model. An example of fitting is shown in Figure 2.
3 CHANGES IN SHORTWAVE RADIATION SCHEME

Shortwave scattering and absorption are modeled by a two-stream formulation using the delta-Eddington approximation. Absorptions by O₃, CO₂ and O₂ are refined in order to improve forecast for temperature in the stratosphere based on Freidenreich and Ramaswamy (1999).

For O₃ absorption, the number of spectral bands is increased from 8 to 15 and we use newer absorption cross section data.

For CO₂ and O₂, absorption bands are added. All absorptions in near-infrared spectrum for CO₂ and absorption in Schumann-Runge band in the ultraviolet spectrum for O₂ are taken into account. In addition, optical depth parameterization is also refined. Although the old scheme does not express variation of absorption coefficient with height sufficiently, the new scheme is able to take account of this effect more adequately. These changes will be more important when the uppermost level in the model will be higher to the mesosphere in the near future.

4 CHARACTERISTIC OF THE SCHEME

Figure 3 shows the effect of P-type absorption to heating rate by longwave radiation. Calculation which takes account of only e-type absorption (×) overestimates radiative cooling in the lower troposphere and underestimates that in the upper troposphere. With the effect of P-type absorption, calculated cooling rate profile is quite similar to the line-by-line calculation.

Figure 4 shows the longwave heating rate profiles calculated for the midlatitude summer profile. The old scheme underestimates the cooling around the stratopause (near 1hPa), and the new scheme reduces the error (Figure 4(a)). This changes were brought mainly by taking account of the Doppler absorption effect properly. Heating rate profiles for
the troposphere are shown in Figure 4(b). The old scheme underestimates the cooling in the middle troposphere and overestimates that near the surface. These errors are reduced by the revision of transmittance calculation of water vapor line absorptions and the introduction of P-type continuum absorption.

5 FORECAST PERFORMANCE OF THE MODEL

Figure 5 shows a difference in downward longwave radiative flux at the surface between forecasts and the Surface Radiation Budget (SRB). We used averages of SRB data from 1984 to 1994 as a verifying climatology. The old scheme underestimates the downward longwave flux at the surface over the nearly whole globe. Flux expressed by the new scheme increases especially over the tropical region and over land. A difference between forecasts and SRB is smaller than 10 W/m² over most area.

Figure 6 shows vertical profile of temperature bias against sonde observations at the Northern hemisphere (20°N–90°N) in August 2004. Colored lines in the figure represent errors for each forecast time (FT00–216 hours). It is obvious that the new scheme improves temperature forecast in the stratosphere. In the troposphere, bias near 300, 700 hPa and the surface are reduced. In addition, though bias near the surface is increased at the beginning of forecast with the old scheme, the new scheme almost reduces this characteristic. This means that imbalance between initial field and forecast field is reduced.

6 SUMMARY

JMA developed a more accurate and efficient radiation scheme for a global atmospheric model. In this new radiation scheme, a longwave spectrum is divided into 9 bands. Considering a trade-off between accuracy and efficiency, gaseous transmittance is computed using three different approaches depending on the absorber and the spectral band. These are a k-distribution method and a precomputed table look-up method for line absorption, and a parameterization for water vapor continuum absorption. Effects of absorption by trace gases are also introduced. In
addition to above changes in the longwave scheme, the parameterization of absorption coefficient is refined in the new shortwave scheme.

By taking account of the Doppler absorption effect properly, errors in longwave cooling around the stratopause are reduced. Errors in cooling of the troposphere are also reduced by improvement of transmittance calculation of line absorption and introduction of P-type absorption of water vapor continuum. Accuracy of downward longwave flux at the ground expressed with the new scheme is also improved. A difference between forecasts and data derived from satellite observations is less than 10 W/m² over most area.

REFERENCES


