NMRF/UMTD/1/2013

TECHNICAL DOCUMENT

Description of the Radiation Scheme in NCMRWF Unified Model

Liji Mary David, John P. George and E. N. Rajagopal

December 2013

National Centre for Medium Range Weather Forecasting
Earth System Science Organisation
Ministry of Earth Sciences
A-50, Sector 62, NOIDA – 201 309, INDIA

Description of the Radiation Scheme in NCMRWF Unified Model

National Centre for Medium Range Weather Forecasting
Ministry of Earth Sciences
A-50, Sector 62, NOIDA-201 309, India

Abstract

A description of the shortwave and longwave radiation schemes used in the Unified Model implemented at NCMRWF is given in this document. The document presents the theoretical details of the radiation scheme as well as the description about various inputs, including climatology and constants, and outputs of the radiation scheme. It also includes details of the spectral files used for the shortwave and longwave radiation computations.

Contents

1. Introduction

The radiation from the sun is the source of energy for the Earth system, which is mainly in the shorter wavelength (< 4 μm) of the electromagnetic spectrum. This radiation is generally referred to as the shortwave (SW) radiation in the atmospheric models. The Earth-atmospheric system emits radiation according to its temperature, mainly in the infra-red (IR) wavelengths (>3.0 μm), which is referred as the longwave (LW) radiation. In the Unified Model (UM), the radiation code used for both SW and LW computation consists of a common core.

Solar radiation is in the wavelength range 0.2-5 μm with a peak at 0.55 μm. The absorption of SW wavelengths by ozone (O_3) in the stratosphere and absorption of wavelengths longer than 0.7 μm by water vapour are important. The absorption by carbon dioxide (CO_2) and oxygen (O_2) are smaller in magnitude but are of importance. Rayleigh scattering (where the size of the particle is smaller than the wavelength of light used) by molecules, aerosols and water droplets and ice crystals in clouds are considered in the SW along with the reflection from surface.

There are differences in the absorptive characteristics of atmospheric constituents at LW wavelengths, which give LW radiation a different character from SW radiation. Water vapour absorbs strongly outside the range 8-12 μm. CO_2 absorbs strongly around 15 μm and O_3 absorbs at 9.6 μm. Scattering by cloud particles in the infrared (IR) region has a different character from the solar region. The IR radiative transfer is dominated by absorption and emission.

The following sections discuss the details of the radiation scheme in the UM (version 7.9) operational at NCMRWF. The UM documentation paper Nos. 23 (Edwards et al., 2003) and 23a (Manners et al., 2012) has been referred to compile the present document.

2. Formulation of the core radiation scheme

The radiation code is used to calculate the radiative fluxes from which heating rates and related quantities are determined. In this radiation scheme, the fluxes are determined using a two-stream approximation (in which the angular variation of the diffused radiance field is represented simply by an upward and a downward flux). The spectral data used for the parameterizations are stored in a spectral file, which has been discussed in detail in Appendix-I. It is to be noted that radiation parameterizations that require spectrally dependent data may be selected only if such data are present in the spectral files. The spectral files are independent of the spatial resolution of the model.

2.1. Calculation of monochromatic fluxes

The atmosphere is divided into N homogeneous layers. The boundaries of these layers, which are referred to as levels and numbered from 0 to N, starting from the top; such that the i^{th} level marks the base of the i^{th} layer as shown in Figure 1. The interior boundaries correspond to ρ (levels $2,...,N$); the first ρ level is omitted on the physics grid. Increments to the heating rates are applied on θ (layers $1,...,N$). The upward flux (U), total downward (diffuse+direct) flux (V) and direct solar flux (Z), are taken as the primary variables in the solar radiation region to reduce the execution time. The net flux is given as $N=U-V$. The flux in a column consisting of homogeneous layers is given as:

$$U_{i-1} = T_i U_i + R_i V_{i-1} + S_i^+ \tag{1}$$

$$V_i = T_i V_{i-1} + R_i U_i + S_i^- \tag{2}$$

$$Z_i = T_{0i} Z_{i-1} \tag{3}$$

where,

i = Layer of the atmosphere
T = Diffuse transmission
R = Deflection coefficients
T_0 = Direct transmission coefficient
S = Source term

Since there is no incident diffuse flux at the TOA in the shortwave region, the boundary condition for solar radiation is such that direct solar flux is equal to the downward flux,

$$V_0 = Z_0 = \Phi_0 / \chi_0 \tag{4}$$

where,

Φ_0 = Solar irradiance at the TOA
χ_0 = Solar zenith angle

In the longwave computation, the boundary condition is $V_0 = 0$ (i.e. no incoming radiation).

The boundary condition on the SW fluxes at the surface is given as:

$$\begin{aligned} U_N &= (\alpha_s - \alpha_d) Z_N + \alpha_d V_N \\ U_N &= \alpha_s Z_N + \alpha_d (V_N - Z_N) \end{aligned} \tag{5}$$

In the longwave computation, the equation is given as

$$U_N = \alpha_d V_N + \varepsilon_* \pi B_* \tag{6}$$

where,

α_s = Surface albedo for direct radiation

α_d = Surface albedo for diffuse radiation

ε_* = Surface emissivity

B_* = Planck function

The source term (S) is related to direct solar flux or to variations in the Planck source function across the layer. In the SW it is defined as:

$$S_i^+ = c_{1i} Z_{i-1} \text{ and } S_i^- = c_{2i} Z_{i-1} \tag{7}$$

where, c_j depends on the properties of the layer.

In the longwave computation, the source function is given as:

$$S_i^+ = c_{1i}\Delta_{1i} + c_{2i}\Delta_{2i} \text{ and } S_i^- = -c_{1i}\Delta_{1i} + c_{2i}\Delta_{2i} \tag{8}$$

where, Δ_1 and Δ_2 are related to the first and second derivative of the Planck function (B) across the layer. Δ_2 is present only if the Planck source function varies quadratically across the layer. Explicitly,

$$\Delta_{1i} = B_i - B_{i-1} \tag{9}$$

$$\Delta_{1i} = 2\left(B_i - B_{i-1} - 2B_i^{(m)}\right) \tag{10}$$

where,

$B_i^{(m)}$ = Planck function at the middle of the i^{th} layer. B is given by a polynomial

$$B = \sum_{k=0}^{n} \beta_k \left(\theta/\theta_R\right)^k \tag{11}$$

where,

n = Order of the polynomial

β_k = Coefficient

θ_R = Reference temperature

For LW calculations, temperature on the edges of the layers is required. It is obtained by linear interpolation from θ-levels. The temperature at the top boundary of the model's atmosphere is set equal to the temperature in the middle of the top layer. The temperature of the air in contact with the ground is taken as the temperature of the air in the middle of the bottom layer, which is the surface temperature.

The heating rates are calculated from the net fluxes divergence at any level using the following equation:

$$\frac{d\theta}{dt} = \frac{g\left(N_{top\_level} - N_{base\_level}\right)}{c_p\left(P_{top\_level} - P_{base\_level}\right)} \tag{12}$$

Where, c_p = Specific heat of air at constant pressure

For coupling to ocean, it is necessary to calculate the net SW flux at the surface at wavelengths <0.69 μm, in addition to the spectrally integrated flux. This is because the penetration depth into the ocean is different for the two spectral ranges.

2.2. Calculation of fluxes in the absorbing-scattering medium

The fundamental single scattering properties of a layer are the optical depth(τ), single scattering albedo (ω) and asymmetry(g). The optical depth expresses the quantity of light removed from a beam by scattering or absorption during its path through a medium. If (I_0) is the intensity of radiation at the source and (I) is the observed intensity after a given path, then optical depth (τ) is defined by the following equation:

$$I = I_0 e^{-\tau} \tag{13}$$

Single scattering albedo is defined as the ratio of scattering efficiency (K_s) to total extinction efficiency (a sum of scattering and absorption(K_a)). A single-scattering albedo of unity implies that all particle extinction is due to scattering and a single-scattering albedo of zero implies that all extinction is due to absorption.

$$\omega = \frac{K_s}{K_s + K_a} \tag{14}$$

The asymmetry factor (g) describes the shape of the phase function; $g > 1$ indicates forward scattering and $g < 1$ indicates backscattering. It is a useful parameter for characterizing the phase function independent of scattering angle.

The two stream equations are expressed in terms of the diffuse fluxes, $F^{\pm}$ as:

$$\begin{aligned} \frac{dF^+}{d\tau} &= \alpha_1 F^+ - \alpha_2 F^- - Q^+ \\ \frac{dF^-}{d\tau} &= \alpha_2 F^+ - \alpha_1 F^- - Q^- \end{aligned} \tag{15}$$

where,

$Q^{\pm}$ = Source terms

s and d are defined as

$$s = \alpha_1 + \alpha_2;\ d = \alpha_1 - \alpha_2 \tag{16}$$

They are derived in five different ways as given below:

i) In the Eddington approximation,

$$s = \frac{3}{2}(1-\omega g);\ d = 2(1-\omega) \tag{17}$$

ii) In the approximation given by Zdunkowski et al. (1980) known as the Practical Improved Flux Method (PIFM85),

$$s = D - \frac{3}{2}\omega g;\ \ d = D(1-\omega) \tag{18}$$

where,

D = diffusivity factor, which is taken as 2 though 1.66 is used in the IR to agree with Elsasser's value.

iii) In the approximation given by Zdunkowski et al. (1980),

$$s = 2 - \frac{3}{2}\omega g - \frac{1}{2}\omega;\ d = 2(1-\omega) \tag{19}$$

iv) From discrete ordinates:

$$s = \sqrt{3}(1-\omega g);\ d = \sqrt{3}(1-\omega) \tag{20}$$

v) Under the hemispheric mean approximation

$$s = 2(1-\omega g);\ d = 2(1-\omega) \tag{21}$$

The Practical Improved Flux Method approximation is used in the current version of UM.

The overall diffuse transmission (T) and reflection coefficients (R) depend on the actual two stream approximation selected. Here, it is determined using the following equations:

$$\begin{aligned} T &= \frac{p(1-\Gamma^2)}{1-p^2\Gamma^2} \\ R &= \frac{\Gamma(1-p^2)}{1-p^2\Gamma^2} \\ &= \Gamma(1-pT) \end{aligned} \tag{22}$$

where,

$$\Gamma = \frac{s-\lambda}{s+\lambda};\ p = e^{-\lambda\tau};\ \lambda = \sqrt{sd}$$

In the longwave computations, the transmission and reflection equations are given as:

$$c_1 = \frac{1-T+R}{s\tau};\ c_2 = -\frac{1}{s\tau}\left(1+R+T-2\frac{1-T-R}{\tau d}\right) \tag{23}$$

These equations become indeterminate when $\tau \to 0$. This indeterminacy is removed by adding a small tolerance, which is the square root of the precision of the machine to $s\tau$, $d\tau$, $1-T+R$ and $1+T+R$. However, when τ is very small, the asymptotic form is used for the second term in c_2 given as:

$$\frac{1-T-R}{\tau d} \approx 2-\tau d \tag{24}$$

To define c_j in the solar region, the quantity ξ_0 is introduced, where

$$\xi_0 = \frac{3g}{2\chi_0} \tag{25}$$

The above equation is used for all the above two-stream approximations except the discrete ordinate approximation, for which

$$\xi_0 = \frac{\sqrt{3}g}{\chi_0} \tag{26}$$

In this spectral region,

$$f = \omega\frac{\chi_0}{2}$$

$$\begin{aligned} \upsilon_+ &= f\left(S-\chi_0-\xi_0\left(d-\chi_0\right)\right) \\ \upsilon_- &= f\left(S+\chi_0+\xi_0\left(d+\chi_0\right)\right) \end{aligned} \tag{27}$$

then,

$$\begin{aligned} c_1 &= \left(\upsilon_+ - R\left(1+\upsilon_-\right)\right)-\upsilon_+ TT_0 \\ c_2 &= T_0\left(1+\upsilon_- - R\upsilon_+\right)-\left(1+\upsilon_-\right)T \end{aligned} \tag{28}$$

2.3. Single scattering properties

The single scattering properties related to the physical sources are the mass extinction coefficient $\left(k^{(e)}\right)$, scattering coefficient $\left(k^{(s)}\right)$ and asymmetry $\left(k^{(g)}\right)$. The mass extinction coefficient is defined as the mass extinction cross-section (sum of mass absorption and mass scattering cross-sections) multiplied by the particle number density (cm^{-3}). The scattering coefficient is defined as the scattering cross-section (hypothetical area that describes the likelihood of the radiation being scattered by a particle) multiplied by the particle number density (cm^{-3}). The representation of single scattering properties for individual processes is given below.

i) Gaseous absorption

If there are M active absorbing gases, $j = 1,...,M$ in a band, each will enter a single quasi-monochromatic calculation with the effective mass extinction coefficient $K_j^{(g)}$, calculated at a reference temperature (θ_0) and pressure (p_0). The total contribution by all the absorbing gases to the mass extinction coefficient is then given as:

$$k^{(e,g)} = \sum_j^M K_j^{(g)} q_i f_i (p, \theta) \tag{29}$$

where,

q_j = Mixing ratio of the j^{th} gas

f_j = Scaling function, which allows variations in pressure (p) and temperature (θ)

The two forms of f allowed within the code are

$$f = \left(\frac{p+\Delta}{p_0+\Delta} \right)^{\alpha} \left(\frac{\theta}{\theta_0} \right)^{\beta}; \; f = \left(\frac{p+\Delta}{p_0+\Delta} \right)^{\alpha} \left[1 + A\left(\frac{\theta-\theta_0}{\theta_0} \right) + B\left(\frac{\theta-\theta_0}{\theta_0} \right)^2 \right] \tag{30}$$

The free parameters α, β, Δ, A and B are determined by giving a fit to the gaseous transmission data and are chosen such that when the value given to the free parameters is 0, then $f = 1$. Δ represents the effects of Doppler broadening. A different scaling function is used for each $k-$term, or a single value for a band. These values are determined from the data in the spectral files.

The model takes mixing ratios for water vapour and O_3 as spatially varying fields and for other gases as constant values. The constant values are used to fill an array of gaseous mixing ratios carrying values for each gas in each layer at each grid-point, as the code treats all gases as spatially non-uniform.

ii) Continuum absorption

Two continua, the self and foreign broadened continua of water vapour, are included in the radiative calculations. For the self-broadened continuum, the broadening species is water vapour and for the foreign broadened continuum it comprises all other species except water vapour. Their contribution to the mass extinction coefficient is given as:

$$k^{(e,c)} = K_f^{(c)} q_w f_f n_{bf} + K_s^{(c)} q_w f_s n_{bs} \tag{31}$$

where,

q_w = Mixing ratio of water vapour

f = Scaling function

n_b = Molar density of the appropriate broadening species

The subscripts f and s stand for the foreign and self-broadened continua, respectively. The coefficients $K_f^{(c)}$ and $K_s^{(c)}$ are determined externally by fitting and are determined from the spectral file.

iii) Absorption and scattering by aerosols

For the different species of aerosol present in each spectral band, the contributions to the total and scattering extinctions are given by the mass mixing ratio of the aerosol. The constant of proportionality and asymmetry are read from the spectral file. The variations in the shape of the size distribution are not considered within the model. Hence,

Mass extinction coefficient,

$$k^{(e,a)} = \sum_j K_j^{(e,a)} q_j \tag{32}$$

Scattering coefficient,

$$k^{(s,a)} = \sum_j K_j^{(s,a)} q_j \tag{33}$$

Asymmetry factor,

$$g^{(a)} = \sum_j K_j^{(s,a)} q_j g_j \Big/ k^{(s,a)} \tag{34}$$

It is to be noted that the summation is taken over all the aerosol species present and the mixing ratios are denoted by q_j. D. L. Robert's parameterization of the influence of humidity on the optical properties of hygroscopic aerosols is also included and read from the spectral file.

The radiative effects of atmospheric aerosols need to be considered for which the aerosol climatology is used. The different aerosol climatologies used in the UM is mentioned in Table 1 and shown in Figure 2. From the radiative point of view, it should be assured that the spectral file contains appropriate aerosol data.

iv) Rayleigh scattering

Rayleigh scattering is represented by adding a constant value to the scattering and total extinctions for each spectral band, determined externally and read from the spectral file. The asymmetry for Rayleigh scattering is zero.

v) Absorption and scattering by water droplets

The properties of water droplets are determined from the mass mixing ratio of liquid water (L) and the effective radius of the droplets (r_s) using an appropriate parameterization of Slingo and Schrecker (1982). Therefore,

Mass extinction coefficient,

$$k^{(e)} = L\left(a + b/r_e\right) \tag{35}$$

Scattering coefficient,

$$k^{(s)} = k^{(e)}\left(1 - c - dr_e\right) \tag{36}$$

Asymmetry factor,

$$g = e + fr_e \tag{37}$$

Where the constants a, b, c, d, e are determined externally and vary with the spectral band. Another parameterization is given by Ackerman and Stephens (1987) as:

Mass extinction coefficient,

$$k^{(e)} = L\left(a_1 r_e^{b2} + c_1\right) \tag{38}$$

Scattering coefficient,

$$k^{(s)} = k^{(e)}\left(1 - a_2 r_e^{b2} - c_2\right) \tag{39}$$

Asymmetry factor,

$$g = a_3 r_e^{b3} + c_3 \tag{40}$$

The a_j, b_j and c_j are determined externally by fitting and are read from the spectral file.

vi) Absorption and scattering by ice crystals

The scattering by ice crystals is similar to water vapour, but there are complexities because of the irregular shape of crystals. The parameterization similar to water droplets is used and given in equations (35) to (37). The modified anomalous diffraction approximation is a better scheme, in which the size of crystals is specified using the mean maximum dimension of the large mode $\left(\overline{D}_l\right)$. In this scheme, the (bi-modal) size distribution is characterized by $\overline{D}_l$, since once a particle shape is specified, there is a relationship between $\overline{D}_l$ and r_e. Also in this scheme $\overline{D}_l$ varies by over two orders of magnitude and hence, an elaborate fit is required. This has been done in two ways. The original form consists of two quartic polynomials for the small and large ranges of $\overline{D}_l$. Then,

Mass extinction coefficient,

$$k^{(e)} = I \exp\left(\sum_{j=0}^{4} a_j^{\pm} x^j \right) \tag{41}$$

Scattering coefficient,

$$k^{(s)} = k^{(e)} \left(1 - \sum_{j=0}^{4} b_j^{\pm} x^j \right) \tag{42}$$

Asymmetry factor,

$$g = \sum_{j=0}^{4} c_j^{\pm} x^j \tag{43}$$

where,

$$x = \log\left(\overline{D}_l / D_T \right)$$

$$x = log\left(\overline{D}_l / D_T \right)$$

a_j, b_j and c_j are constants and the sign is chosen according to $x > 0$ or $x < 0$, D_T is the transitional dimension.

Different crystal shapes may be represented with the same methodology, but the data in the standard spectral files are based on planar polycrystals. The spectral file contains data for a number of types of ice crystal and the types used is selected from the UM user interface. For a given type, the form of parameterization is determined by the spectral file.

2.4. Treatment of overlapping gaseous absorption

There is overlapping of the spectral lines when several gases absorb in a spectral band within few frequencies. The absorption is represented using $k-$terms, which considers the overlap of each $k-$term for one gas with each $k-$term for every other gas active in the band. The treatment of random overlap is available within the code and faster approximations are provided to it.

The equivalent extinction is defined as an extension of the method of exponential sum fitting (esft) in which the effects of minor gases are represented by a single absorption coefficient within the band. Here the coefficient is determined for the local atmospheric conditions by a subsidiary calculation. In the IR region, suppose that a minor gas has $k-$terms, K_r, $r = 1,...,n$ the net flux, N_r, including just absorption by the r^{th} $k-$term of

the gas (and any non-cloudy grey absorption) is calculated. The equivalent extinction is then given as:

$$\overline{K} = \sum_r w_r K_r N_r \Big/ \sum_r w_r N_r \tag{44}$$

where,

w_r = Corresponding weights

In this approximation the fluxes are calculated on levels, whereas the extinction coefficient is a representative value in a layer. More details are described in Edwards (1996).

To calculate the diffuse fluxes, it is assumed that the absorption by the minor gas falls into weak and strong parts, so that radiation that is scattered into the diffuse beam will be effectively denuded in parts where absorption is strong. The equivalent extinction for diffuse radiation is:

$$\overline{K} = \sum_r w_r K_r Z_{*r} \Big/ \sum_r w_r Z_{*r} \tag{45}$$

where,

Z_{*r} = Direct flux at the surface for the r^{th} $k-$term.

In the calculation of cloudy transmission and reflection coefficients, the direct flux is taken to vary from its actual value at the top of the layer with the effect of minor gases being represented by the direct transmission calculated from the equivalent extinction.

2.5. Clouds

Within an atmospheric layer, i, a fractional cloud cover, W_i, is specified. This cloud is divided into N_T types, each constituting a fraction, ϕ_j, of the total amount of cloud. Each of these sub-clouds is made up of various components. In UM, clouds are treated on the basis of ice and water clouds. Clouds consist of four components: stratiform water and ice and convective water and ice. The Monte Carlo Independent Column Approximation (McICA) is used in UM, which has been discussed in section 2.5.1. The radiative fluxes are affected by the cloud geometry.

The upward flux equation is given as:

$$\widehat{U}_{ij}^{+} = \sum_k u_{ijk} \breve{U}_{ik}^{+} \tag{46}$$

where, U_{ij} denotes the upward flux in the i^{th} region at the i^{th} level, with the circumflex

denoting a value just above the boundary. Similarly, the downward flux is given as:

$$\widehat{V_{ij}} = \sum_k v_{ijk} \breve{V}_{ij} \tag{47}$$

with an identical equation for Z. Then, it is given as,

$$u_{ijk} = Y_{ikj} / X_{i+1,j} \text{ and } v_{ijk} = Y_{ikj} / X_{i,j}$$

Y_{ijk} is determined from the overlap assumed. For random overlap

$$Y_{ijk} = X_{i,j} X_{i+1,k} \tag{48}$$

If maximum-random overlap is assumed, similar regions are maximally overlapped, but dissimilar ones are randomly overlapped as

$$\begin{aligned} Y_{ijj} &= \min\left(X_{i,j} X_{i+1,j}\right) \\ Y_{ijk} &= \frac{\left(X_{i,j} - Y_{ijj}\right)\left(X_{i+1,k} - Y_{ikk}\right)}{1 - \sum_k Y_{ikk}} \left(k \neq j\right) \end{aligned} \tag{49}$$

The model takes separate variables for convective and large-scale cloud. In the case of convective cloud, a total condensed water path $\left(L_C\right)$ and the top and bottom of the cloud are carried along with the cloud fraction. If the anvil scheme is not selected, the cloud fraction is taken as constant on all layers. In case the anvil scheme is selected, the array of cloud fractions is taken as three dimensional and the actual convective cloud fraction is held in that layer. In the case of large-scale cloud, the model carries grid-box mean values of the liquid and ice condensate separately, together with a cloud fraction that represents the fraction of large-scale cloud in that part of a grid-box which is not occupied by convective cloud. The total cloud fraction in a layer $\left(W\right)$ is given as:

$$W = W_C + W_L\left(1 - W_C\right) \tag{50}$$

where,

W_C = Convective cloud amounts

W_L = Large-scale cloud amounts

The function of the interfacing routine for clouds is to gather these fields and map them on to those required by radiation and assign sizes to water droplets and ice crystals. The size of water droplets are fixed in relation to the number of cloud condensation nuclei. The specification of the size of ice crystals is an area of uncertainty because of the crystal shape and the use of different measures of crystal size.

2.5.1. Monte Carlo Independent Column Approximation (McICA)

The McICA allow the radiative effects of sub-grid scale cloud water content variability to be represented. It has the advantage of separating the description of cloud from the radiation scheme. Each atmospheric column is represented by a field of sub-columns. Each layer in each sub-column is either overcast or cloud free (i.e. sub-columns cannot be partially cloudy) and when the sub-columns are averaged together they have the same properties as the original atmospheric column. The sub-column is randomly chosen for spectral integration and the resulting radiative profile is unbiased with respect to the full calculation. The sub-columns required for McICA are provided by a stochastic cloud generator based on Räisänen et al. (2004). The water content in each layer in each sub-column is a random sample from a gamma distribution with mean equal to the mean cloud water content and standard deviation determined by the fractional standard deviation (standard deviation divided by the mean). McICA is used for cloud representation by phase and not by type. The McICA method is used for cloud overlapping, more details of which are given in Barker et al. (2008).

2.6. Surface characteristics

The SW fluxes are influenced by the characteristics of the surface. The albedo, which is defined as the ratio of the reflected to the incident radiation, is the key factor. Hence, the albedo of land, sea and ice surfaces has to be given. Two spectral albedo fields is supplied to the radiation code depending on the form of land surface scheme adopted. The radiation code uses different albedo in each spectral band, so the specified albedos are mapped on to the bands of radiation scheme taking account of the fraction of the solar spectrum in each band.

The model considers the heterogeneity of the surface. A grid-box may contain open sea, land and sea-ice as the model includes the coastal tiling as an option, which has implications for the modelling of radiation.

The recommended values for the constants are as follows:

Snow-free ice albedo: 0.50

Deep melting snow albedo: 0.65

Deep cold snow albedo: 0.80

Temperature range: 2.00

The albedos are based on Ebert and Curry (1993). The modified Barker albedo and spectrally dependent sea albedos have been introduced. The Barker albedo is a formulation of the direct SW albedo for the open sea (Barker and Li, 1995). Spectrally dependent sea

albedos are used where the spectral file contains 6 SW bands. The land surface is prescribed a global emissivity of 0.97 regardless of the surface type (Walters et al., 2011).

2.7. Treatment of ozone

While most of the gases are well mixed in the atmosphere, water vapour and ozone exhibit strong spatial variations. Water vapour is carried as a model field but ozone is not modelled interactively in normal runs and ozone is specified as an ancillary field. Ozone is specified as zonal mean (latitude-height plane). The concentrations are high in the stratosphere but low in the troposphere. The latitude-height ozone climatology is shown in Figure 3.

3. Radiation subroutines in UM

In the UM, the code is split into three sections: (i) routines for SW radiation, (ii) routines for LW radiation and (iii) routines common to both SW and LW regions. To calculate the radiative fluxes the radiation code must receive the contents of the spectral file, which has the controlling options and fields that describe the state of the atmosphere and surface. All the required fields are not explicitly calculated by the model but further parameterization is required for a few to specify them, for example, the sizes of water droplets and ice crystals.

3.1. Algorithmic control and spectral files

The controlling options for the radiation code are specified in the namelist "RUN_Radiation" in the file CNTLATM created in the "umui_jobs" directory while processing through the UM user interface. Some of the variables, which are relevant outside the radiation, such as aerosol flags are specified in the namelist NLSTCATM. This information is read at the start of integration via the subroutine "readlsta", which calls "sw_control_struct" and "lw_control_struct" modules that declare the controlling structure for SW and LW calculations, respectively. Or else, it will call the modules, "sw_control_default" and "lw_control_default" to set the default values of the control structure for SW and LW calculations, respectively.

The spectral files are also read at the start of integration, after the controlling information has been read. The subroutine INITPHYS calls the subroutines required to read in the spectral files for the radiation scheme, which is explained in details in the next section.

3.2. Radiative control level

The calls to the radiation subroutines are made from the subroutine NI_RAD_CTL. It is an interface between the radiation code and the rest of the model. This is the top level radiation control subroutine and major book keeping is carried out here. Space for diagnostics is allocated, the astronomical calculations are made and spatial discretization is handled. This subroutine calculates the SW and LW radiative fluxes and heating rates on radiation time-steps. Radiation increments are applied on all physics time-steps.

The subroutine NI_RAD_CTL calls subroutines R2_SWRAD3C and R2_LWRAD3C separately, before the final call to the generic code. Several calls are made to each of these, each call comprising a fraction of the points, referred to as a segment. The above mentioned subroutines handle the mapping from fields defined at the control level to the quantities used in the radiation scheme. Generically, these operations comprise gathering over atmospheric points and inversion. The gathering is required because the radiation is not called at all the points. While arrays in the UM are indexed from the surface upward, those in the radiation code are indexed from the TOA downwards. There is provision for an extra layer in radiation, representing the part of the atmosphere between the explicit declared top and the TOA. The structure showing the calling of the spectral files and the calculation of radiation flux is shown in Figure 4. An explanation of the main program along with the subroutines and their importance is given below.

(1) One of the main programs is the flumeMain.

(2) It has a subroutine UM_SHELL, is the control subroutine for the atmosphere model. It acquires size information needed for dynamic allocation of configuration dependent arrays and calls “u_model” (the master control subroutine) to allocate the arrays and perform the top-level control functions and time stepping. The subroutine “u_model” acts as a dummy interface for alternative definitions of the same subroutine.

(3) This further calls two subroutines: U_MODEL_U_MODEL and U_MODEL_U_MODEL_4A. These are the high level control programs for the UM (master subroutine). It calls lower level control subroutines according to top level switch settings. It is called by top level subroutine UM_SHELL, which provides dimension sizes for dynamic allocation of data arrays.

(4) The subroutines U_MODEL_U_MODEL and U_MODEL_U_MODEL_4A call the subroutines INITIAL_INITIAL and INITIAL_INITIAL_4A. The purpose of this is to initialize the model and make it ready for integration/assimilation. This involves reading the model control files and setting up STASH (Storage Handling And Diagnostic System), reading the initial or restart dump, initialising the ancillary,

boundary and interface field control subroutines and updating the ancillary fields on restart, if time to do so, exchanging coupling fields and swapping dumps (if a coupled model), and initialising the assimilation package, if necessary. The subsidiary control subroutines are called to perform these functions. U_MODEL_U_MODEL and U_MODEL_U_MODEL_4A also call the subroutine ATM_STEP and "eg_atm_step", respectively, which are used to perform a one timestep integration of the atmosphere model. Both of these subroutines call the subroutine Atmos_Physics1.

(5) The subroutines INITIAL_INITIAL and INITIAL_INITIAL_4A have a subroutine INITPHYS, which calls the routines required to read in the spectral files for the radiation scheme. This calls the following modules/subroutines for the various purposes as mentioned below:

(a) The radiation modules, "sw_control_struct" and "lw_control_struct"

(b) spec_sw_lw: this module defines the LW and SW spectral file data for each call to radiation. It has two modules witihin it: MAX_CALLS_MAX_CALLS3C, which declares the maximum number of calls to the radiation code permitted on a single timestep and "dec_spec", which defines the elements of the structure for algorithmic control of the radiation code.

(c) ses_inisw and ses_inilw: for the initialisation of spectral parameters required in the Edwards Slingo SW and LW radiation scheme. It has a subroutine "ses_spectrum" to control reading of the spectral data file to the radiation code (interpolation version), which further calls the subroutine "ses_block" to control reading in of blocks of data using the following subroutines:

ses_block_0_0_0: reading the contents of block type 0

ses_block_0_0_1: reading the contents of block type 0

ses_block_1_0_0: reading the contents of block type 1

ses_block_2_0_0: reading the contents of block type 2

ses_block_3_0_0: reading the contents of block type 3

ses_block_4_0_0: reading the contents of block type 4, index numbers of absorbers in each band

ses_block_5_0_0: reading the contents of block type 5, exponential sum fitting terms

ses_block_6_0_0: reading the contents of block type 6, coefficients for source function in each band

ses_block_7_0_0: reading the contents of block type 7, surface albedo in each spectral bands

ses_block_7_1_0: reading the contents of block type 7, surface properties in each spectral band (subtype=1)

ses_block_7_2_0: reading the contents of block type 7, surface properties in each spectral band (subtype=2)

ses_block_7_3_0: reading the contents of block type 7, surface properties in each spectral band (subtype=3)

ses_block_7_4_0: reading the contents of block type 7, surface properties for sea water (subtype=4)

ses_block_7_4_1: reading the contents of block type 7, surface properties in each spectral band (subtype=4)

ses_block_8_0_0: reading the contents of block type 8, index numbers of continua in each band

ses_block_9_0_0: reading the contents of block type 9, exponential sum fitting terms

ses_block_10_0_0: reading the contents of block type 10, parameterized Mie scattering data

ses_block_10_0_2: reading the contents of block type 10, parameterized droplet scattering data

ses_block_11_0_1: reading the contents of block type 11, aerosol scattering data

ses_block_11_0_2: reading the contents of block type 11, aerosol scattering data

ses_block_11_1_0: reading the contents of block type 11, moist aerosol scattering data

ses_block_11_1_2: reading the contents of block type 11, moist aerosol scattering data

ses_block_12_0_0: reading the contents of block type 12, parameterized ice crystal scattering data

ses_block_13_0_0: reading the contents of block type 13, Doppler broadening terms

ses_block_14_0_0: reading the contents of block type 14, bands excluded from regions of the spectrum

ses_block_15_0_0: reading the contents of block type 15, mixed absorbing gas coefficients

ses_block_15_1_0: reading the contents of block type 15, moisture aerosols

ses_block_16_0_0: reading the contents of block type 16

(d) r2_sw_specin and r2_lw_specin: the subroutine is used to read SW and LW namelist, respectively, into a spectral array, the size of which is thereafter reduced to a manageable size.

(6) The subroutines INITIAL_INITIAL and INITIAL_INITIAL_4A has another subroutine INITDUMP, which reads the atmosphere dumps and calculates additional constants

based on the dump header information. This calls the following subroutines: READLSTA_READLSTA and READLSTA_READLSTA_4A, which reads the run-time control information from namelists for the atmospheric model. This further calls the modules “sw_control_struct”, “lw_control_struct”, “sw_control_default” and ‘lw_control_default”. The former two has been explained above. The latter two are used to set the default values of the control structure.

(7) Another main program is the “scm_shell”, which is the main calling program for the Single Column Model (SCM). It sets up the vertical level information read in from the UMUI and passes the information down to “scm_main” which then performs the run.

(8) It has a module “scm_cntl_mod” to declare variables and defines SCM namelist that is read from CNTLATM. The radiation modules: “sw_control_struct” and “lw_control_struct” are called. The subroutine “scm_main”, which is used to call the main part of the model, is called to run the SCM.

(9) “scm_main” calls the radiation modules, “run_init” to do initialization. This calls the radiation modules, “spec_sw_lw”, and the subroutines “r2_sw_specin”, “r2_lw_specin”, “ses_inilw”, “ses_inisw” and “Atmos_Physics1”.

(10) The subroutine “Atmos_Physics1” is the interface to atmospheric physics parameterizations before semi-Lagrangian (S-L) advection. It has a subroutine NI_RAD_CTL, which is an interface between “Atmos_physics1” and the radiation code. This glue routine has been inserted in order to manage the versions 3A, 3C, and 3Z of the radiation code. This calls a subroutine “glue_rad” which is an interface to atmospheric physics radiation code.

(11) The subroutine “glue_rad” calls the subroutines R2_SWRAD3C and R2_LWRAD3C, which are the respective SW and LW interface to the Edwards-Slingo radiation scheme. This routine prepares the call to the Edwards-Slingo radiation scheme. Principally, this routine transfers arrays into the correct formats. This further calls the subroutine FLUX_CALC to calculate radiative fluxes. The properties independent of the spectral bands are set. A loop over bands is then entered. Grey optical properties are set and an appropriate subroutine is called to treat the gaseous overlaps. The final fluxes are assigned. There are 62 calls made from FLUX_CALC for the calculation of the radiative flux.

4. Inputs used in the Unified Model

Table 1 lists the input that goes into the model run.

Table 1: The inputs used in the Unified Model for the calculation of SW and LW radiation fluxes.

Version	3Z General 2-stream and radiance code
Multiple calls to radiation	Time-stepping scheme along with incremental time-stepping for improved sampling of cloud
Shortwave radiation	
Solar constant	1365.0
Albedo of sea-ice	Minimum: 0.60 Maximum: 0.80
Temperature range over which the albedo varies linearly between maximum and minimum values	10
Equation of time in the astronomy	Included
Albedo for the open sea	Modified Barker albedo
Spectrally dependent sea albedos	Used when the number of SW band in the spectral file is 6
Orographic correction	Using the ancillary gradient fields
Transmission based solar zenith angle correction	Takes into account the change in optical path length through the atmosphere when correcting the surface and TOA fluxes for changes in solar zenith angle between radiation time-steps
Location of the SW spectral file	Directory: ${UM_RAD_SPECTRAL_GL}/ga3_1 Prognostic file: spec_sw_ga3_0_AOD Diagnostic file: spec_sw_cloud3_0
2-stream option	PIFM80 (Practical Improved Flux Method)
Treatment of overlapping for gaseous absorption	Equivalent extinction
Absorption by oxygen (SW) mass mixing ratio of oxygen	Included 0.2314
Longwave radiation	
Location of the LW spectral file	Directory: ${UM_RAD_SPECTRAL_GL}/ga3_1 Prognostic file: spec_lw_ga3_1_AOD Diagnostic file: spec_lw_cloud3_0
2-stream option	PIFM85 with D=1.66
Treatment of overlapping for gaseous absorption	Equivalent extinction
Absorption by methane mass mixing ratio of methane	Included 9.994e-07
Absorption by nitrous oxide mass mixing ratio of nitrous oxide	Included 4.925e-07

Absorption by CFC11 mass mixing ratio of CFC11	Included 1.129e-09
Absorption by CFC12 mass mixing ratio of CFC12 Absorption by CO_2 mass mixing ratio of CO_2	Included 2.225e-09 Simple method with fixed value 5.94100e-04
SW and LW radiation	
Option of climatological aerosols	Only stratospheric climatological aerosol components is used (Cusack et al., 1998)
Climatologies used (specified by ancillary files) (1) Biogenic aerosol climatology (2) Biomass-burning aerosol climatology (3) Black carbon aerosol climatology (4) Sea-salt aerosol climatology (5) Sulphate aerosol climatology (6) Dust aerosol climatology (7) Organic carbon (fossil fuel) aerosol climatology (8) Delta aerosol climatology (9) Mineral dust aerosol:Direct radiative effect (SW+LW)	All are included
Aerosol optical depths diagnostics	Enabled
Ozone treatment in radiation	Prescribed 2D field
Treating clouds in SW and LW radiation	Hogan solver for multiple regions
Option for overlapping clouds	McICA (Monte Carlo Independent Column Approximation) sampling of generated cloud
Deccorelation pressure scale for stratiform cloud	10000
Normalized cloud condensate standard deviation	0.75
McICA sampling method	2
Representation of clouds	Ice and water segregated for single cloud type
Partition convective cloud using the local	Yes
Types of droplets and ice crystals consistent with the spectral file: Number of water droplet in stratiform clouds Number of water droplet in convective clouds Type number for ice crystals in stratiform clouds Type number for ice crystals in convective clouds	 5 5 8 8
Cloud micro-physics	Included

5. Discussions

Figure 5 shows the mean (a) incoming and (b) outgoing SW radiation at the top of the atmosphere (TOA) for a particular day (01 April 2013). The upward and downward SW radiation at the surface is shown in Figure 6. The upward and downward LW radiation at the surface and outgoing longwave radiation at TOA (OLR) is given in Figure 7 for 01 April, 2013. The global mean for 01 April 2013 is calculated for the above seven components (four for SW and three for LW) along with the other fluxes and compared with the global mean values and shown in Table 2. The global mean value is taken from *Kiehl and Trenberth* (1997) and *Ohmura and Raschle* (2005). It is evident from the table that the mean flux values compare well with the global mean values available from observations. The slight differences in the values can be attributed to the single day in consideration. Otherwise, most of the flux values are in concordance with the global mean.

Table 2: Comparison of the global mean fluxes from UM with the observations

	Unified Model (W/m^2)	**Global Mean (W/m^2)**
Incoming SW (TOA)	341	342
Outgoing SW (TOA)	99	102
Downward SW (surface)	169	169
Upward SW (surface)	25	25
Downward LW (surface)	341	345
Upward LW (surface)	398	385
OLR	239	240
Sensible heat flux	18	19
Latent heat flux	79	85
SW reflected by clouds	52	77
SW reflected by aerosol and atmospheric gases	23	
SW absorbed by atmosphere	74	67
LW emitted by clouds	23	30
LW emitted by atmosphere	176	165

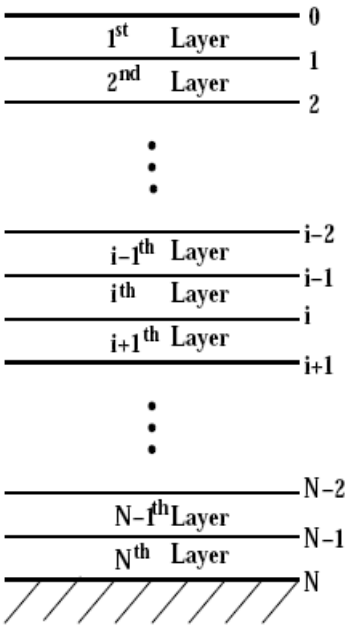
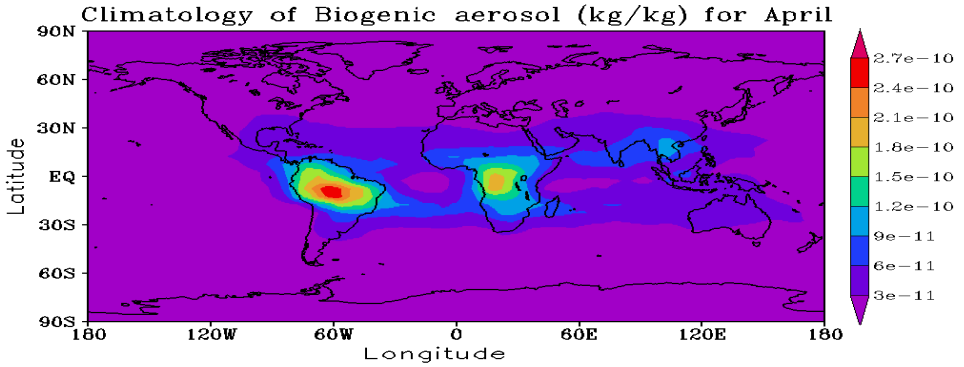
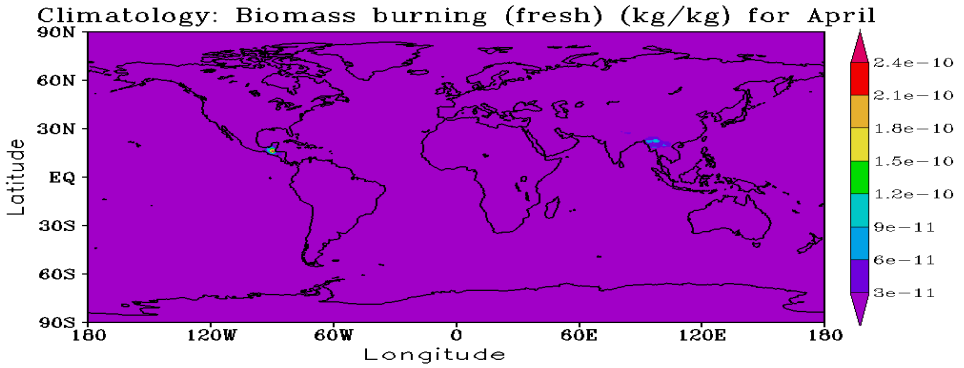


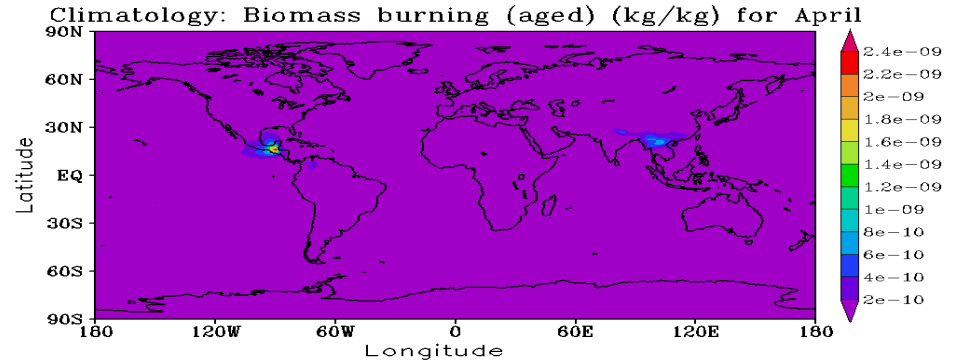
Figure 1: The vertical resolution of the atmosphere showing 1 to N homogeneous levels

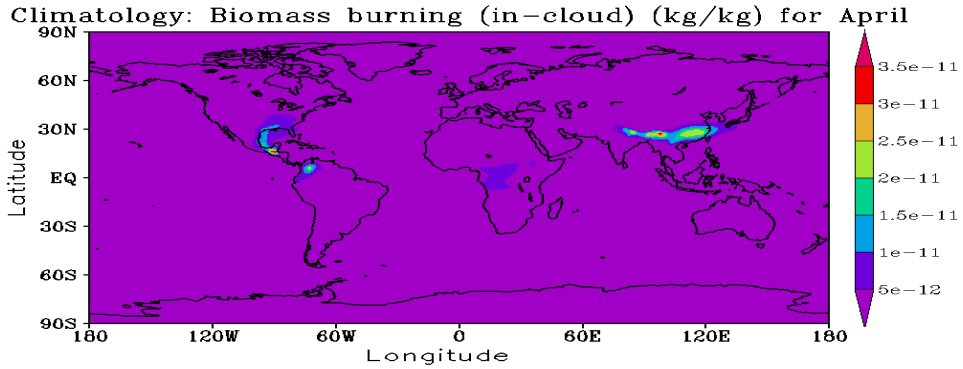
- **Biogenic aerosol climatology**



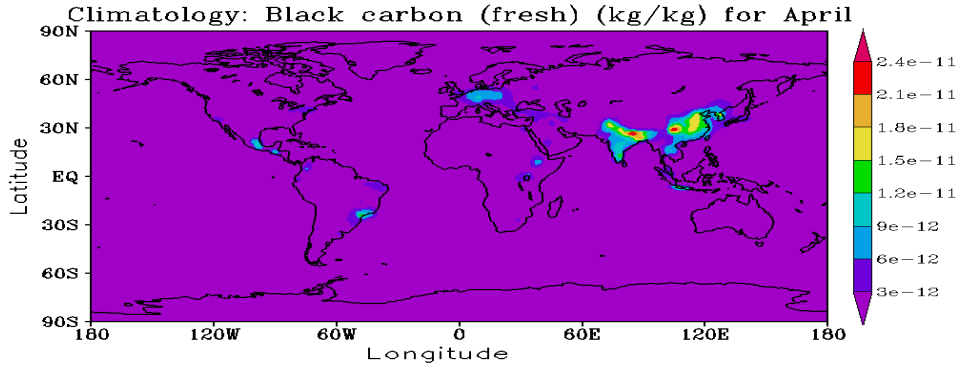
- **Biomass-burning aerosol climatology: fresh, aged and in-cloud**

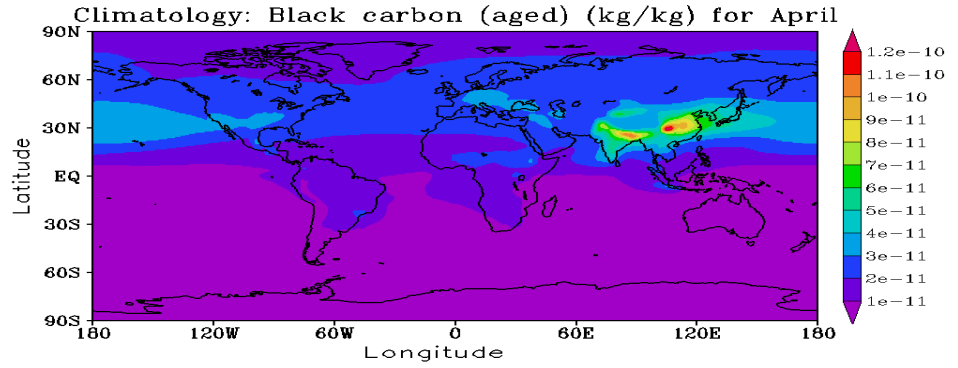




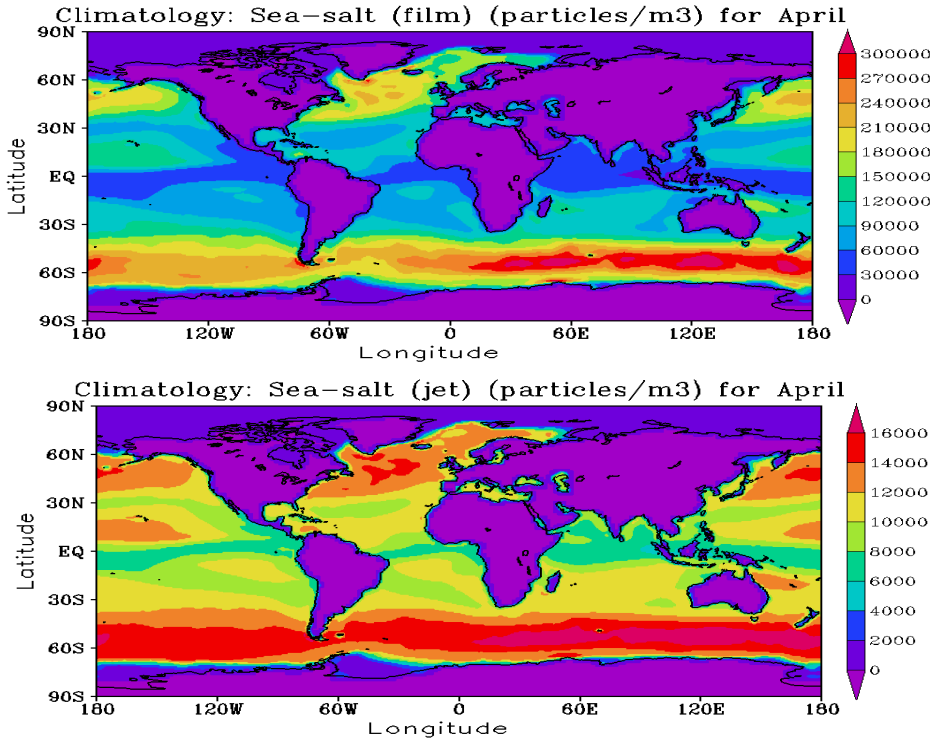


- **Black carbon aerosol climatology: fresh, aged**

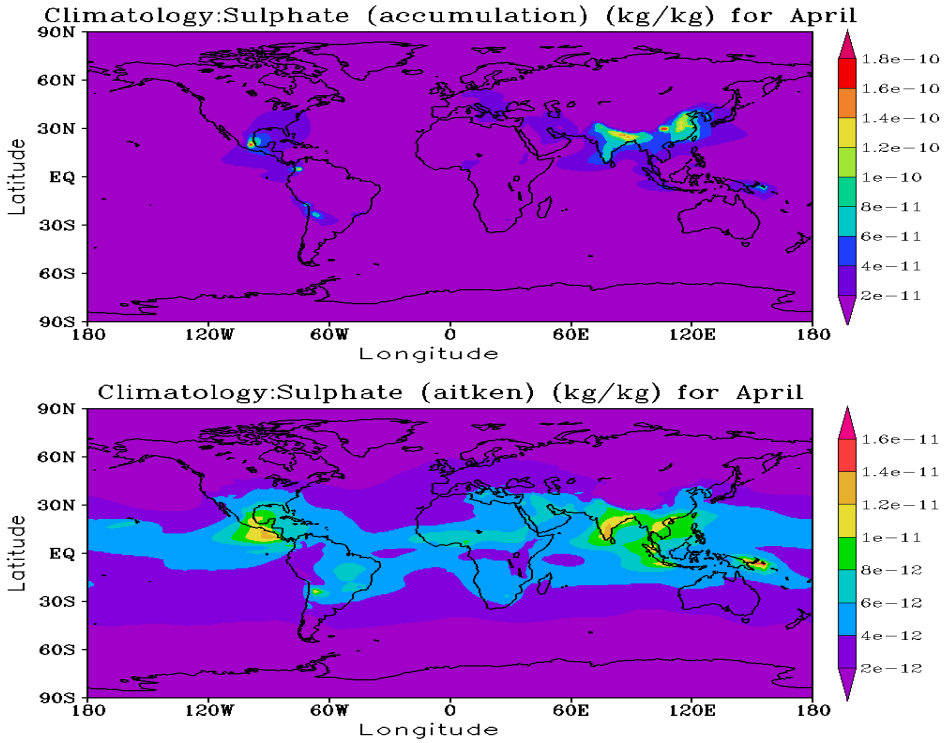


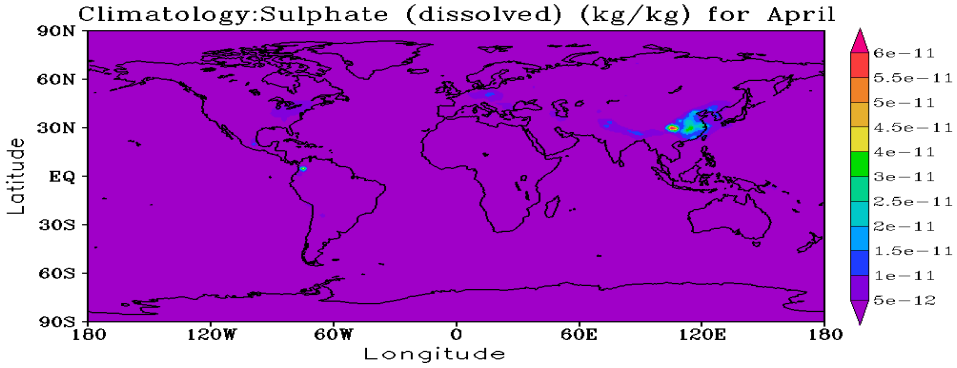


- **Sea-salt aerosol climatology: film mode, jet mode**

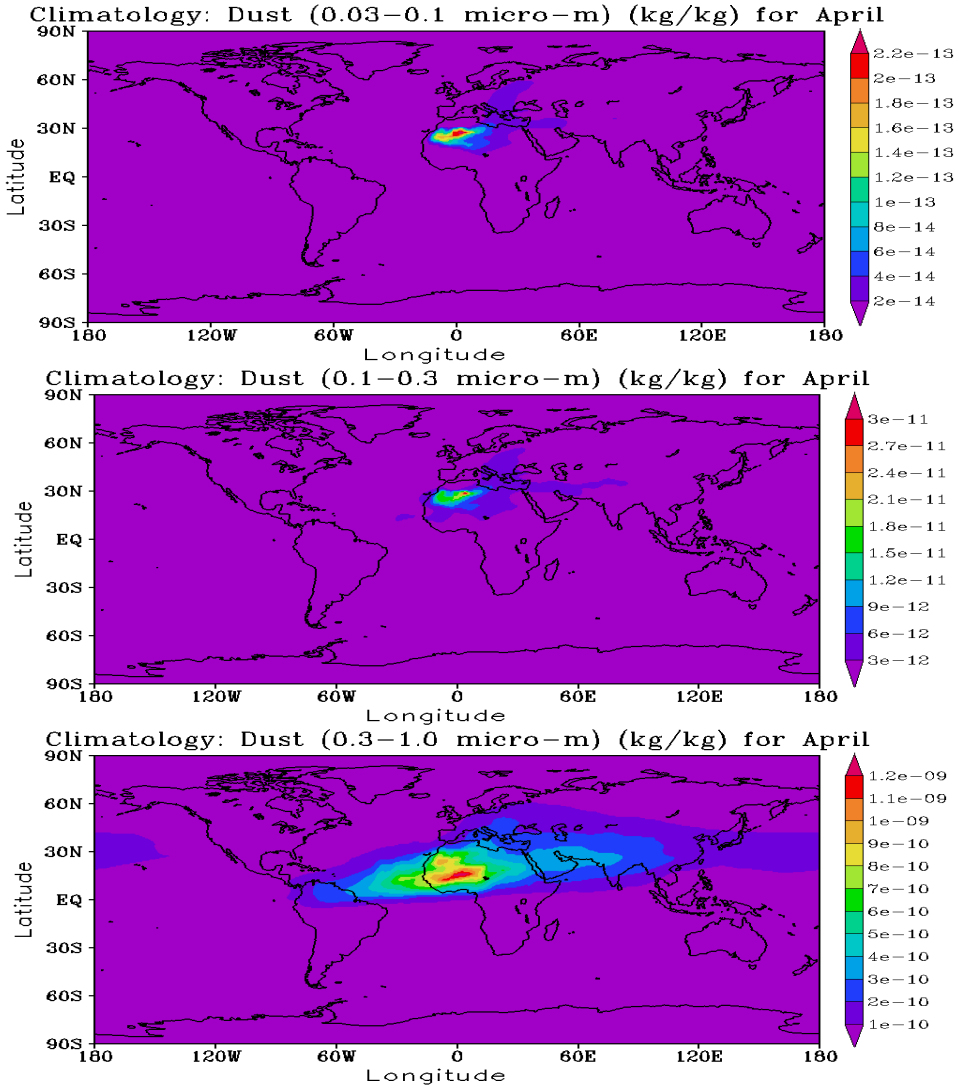


- **Sulphate aerosol climatology: accumulation, aitken, dissolved**

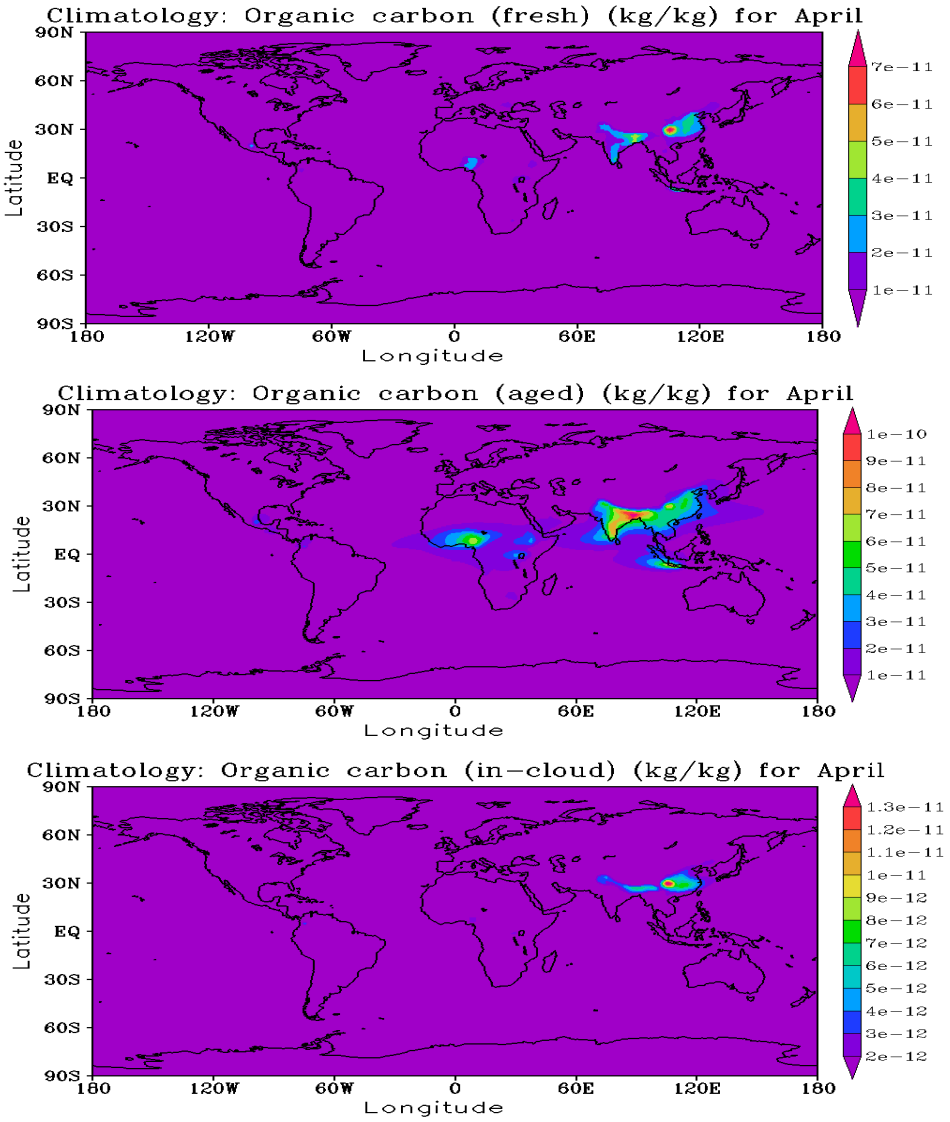




- **Dust aerosol climatology: 0.03-0.1, 0.1-0.3, 0.3-1.0**



- **Organic carbon (fossil fuel) aerosol climatology: fresh, aged, in-cloud**



- **Delta aerosol**

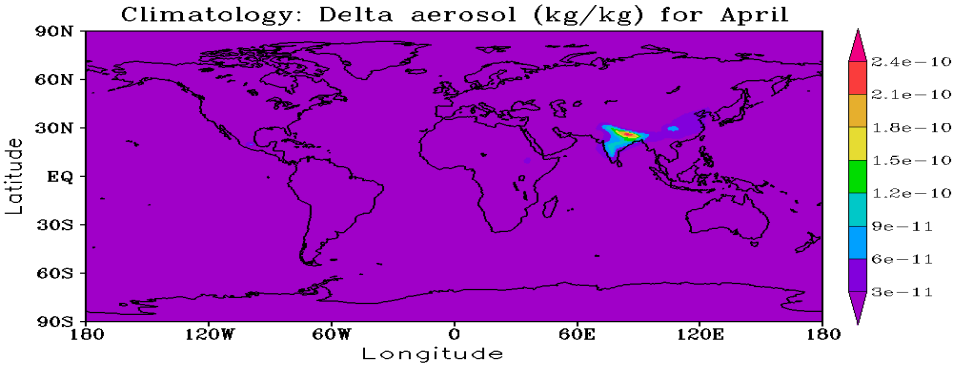


Figure 2: The different aerosol climatologies used in the Unified Model.

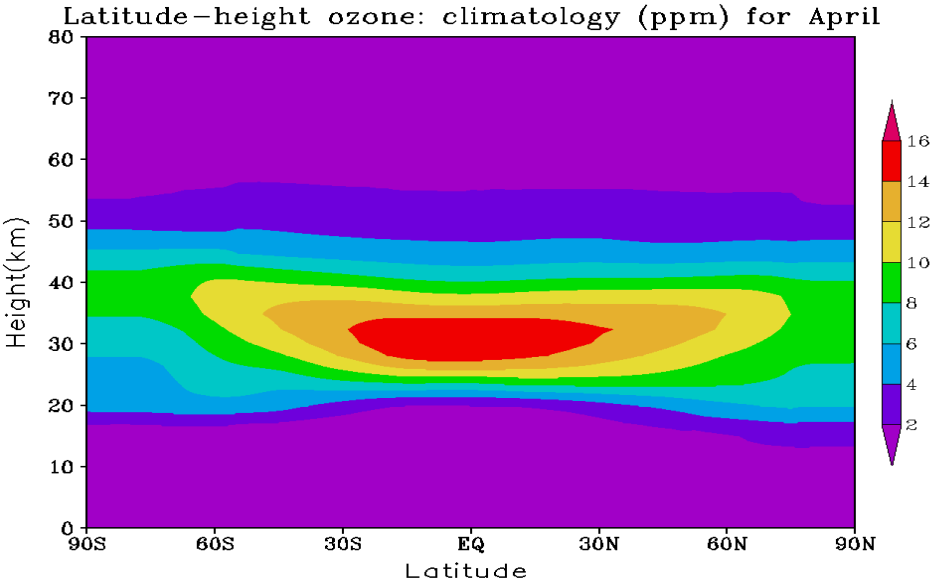
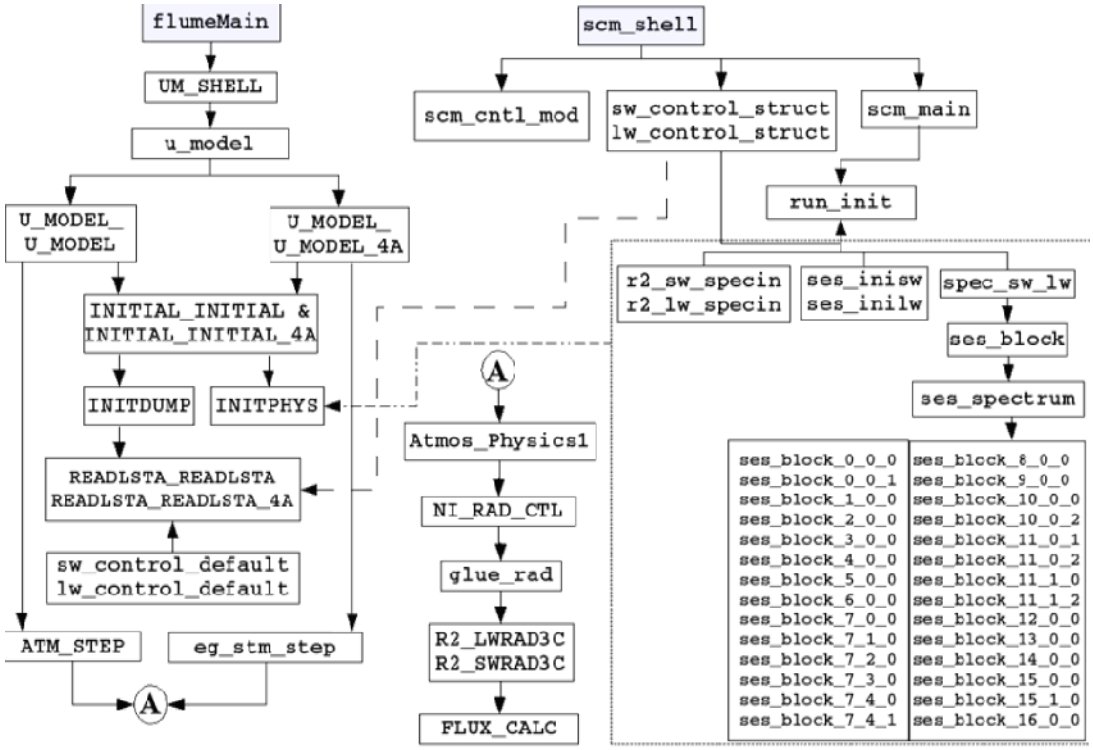
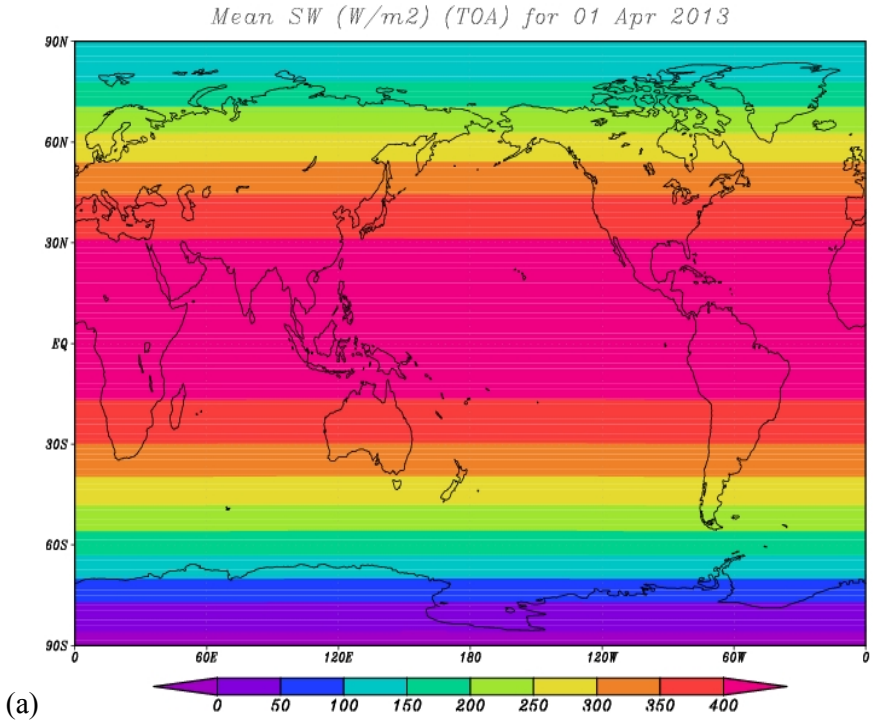


Figure 3: The latitude-height ozone climatology.

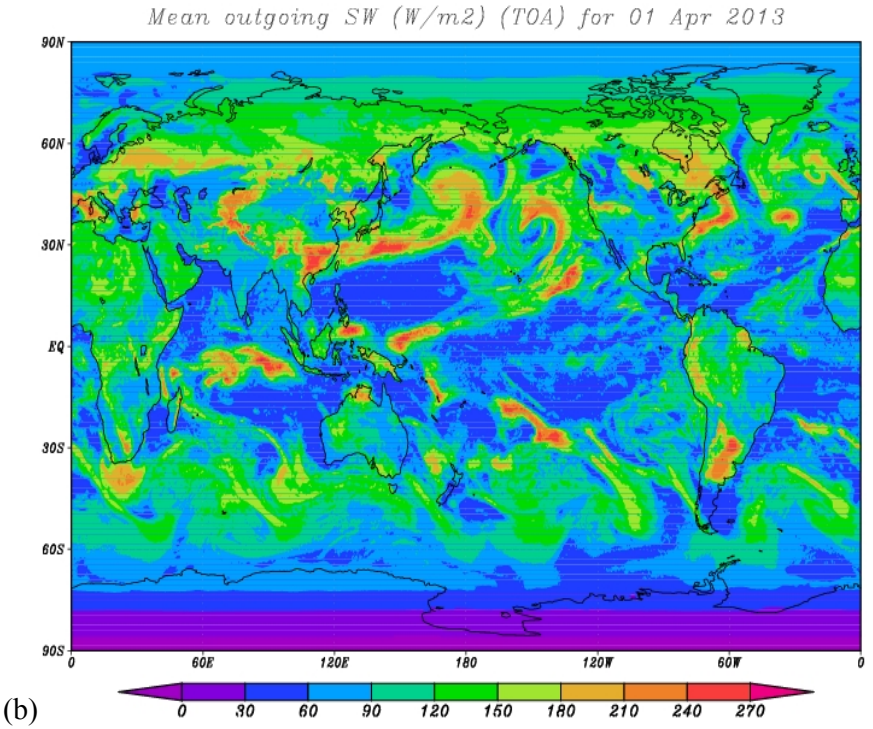
Figure 4: The flowchart showing the calling sequence of spectral files and the calculation of radiation fluxes in UM.



- flumeMain and scm_shell are the main FORTRAN programs
- UM_SHELL routine for the atmosphere model
- U_MODEL_U_MODEL & U_MODEL_U_MODEL_4A control the programs for the UM subroutine
- INITIAL_INITIAL & INITIAL_INITIAL_4A initialize the model and makes it ready for integration/assimilation
- INITPHYS calls the routines to read the spectral files for the radiation scheme
- sw_control_struct & lw_control_struct modules declare the controlling structure for SW and LW, respectively
- spec_sw_lw defines the LW and SW spectral file data for each call to radiation
- ses_inisw & ses_inilw for the initialisation of spectral parameters in the Edwards Slingo SW and LW radiation scheme
- ses_spectrum to control reading of the spectral data file to the radiation code
- ses_block to control reading in of blocks of data from the spectral files
- r2_sw_specin & r2_lw_specin used to read SW and LW namelist, respectively, into a spectral array
- INITDUMP reads the atmosphere dumps and calculates additional constants
- READLSTA_READLSTA & READLSTA_READLSTA_4A reads the run-time control information from namelists for the atmos model
- scm_cntl_mod to declare variables & scm_main used to call the main part of the model
- run_init to do initialization
- Atmos_Physics1 interface to atmospheric physics parameterizations before semi-Lagrangian advection
- NI_RAD_CTL interface between Atmos_physics1 and radiation code
- glue_rad interface to atmospheric physics radiation code
- R2_SWRAD3C & R2_LWRAD3C, respective SW and LW interface to the Edwards-Slingo radiation scheme
- FLUX_CALC calculates the radiative fluxes



(a)



(b)

Figure 5: The mean (a) incoming and (b) outgoing SW radiation at TOA for 01 April 2013.

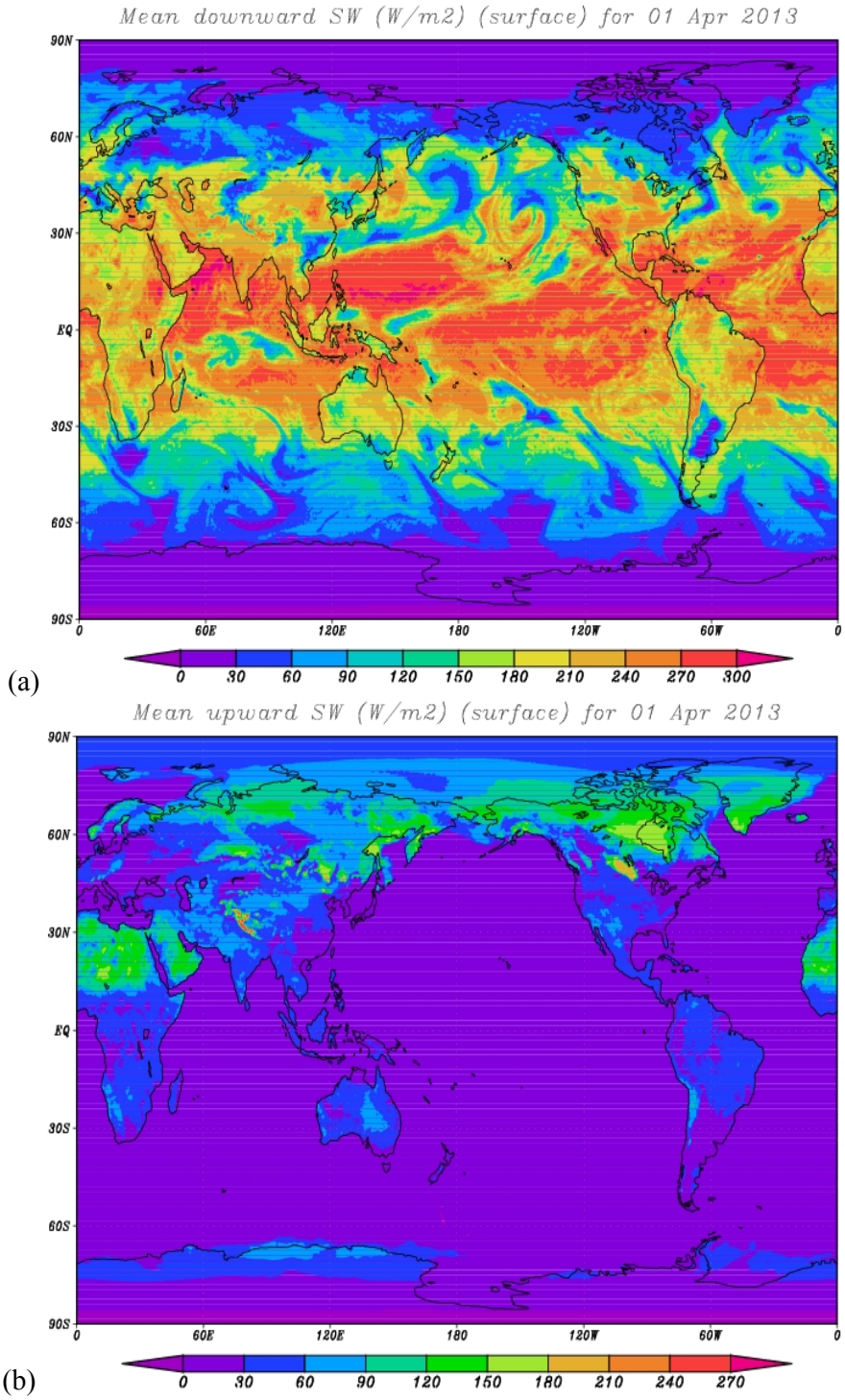
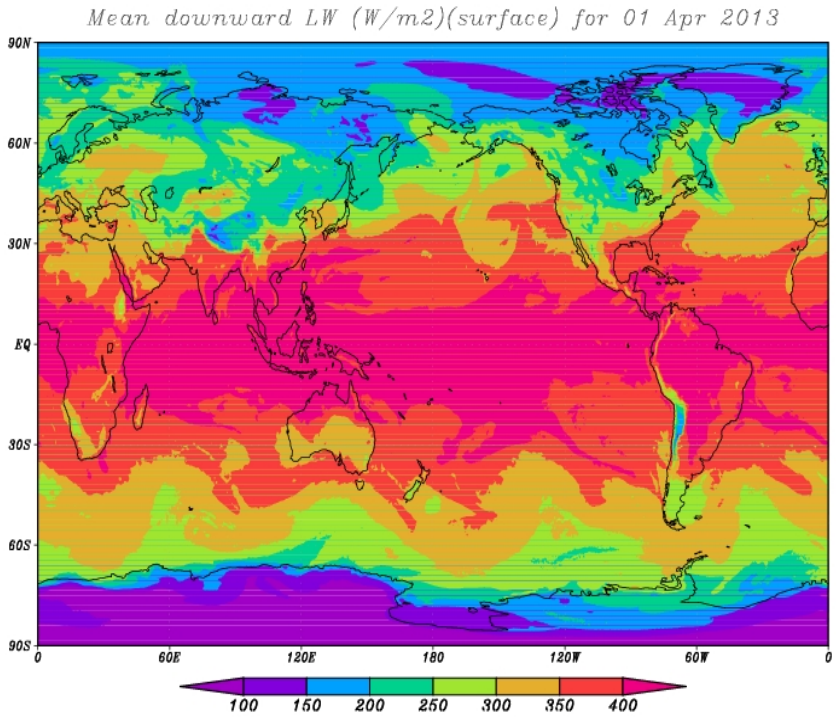
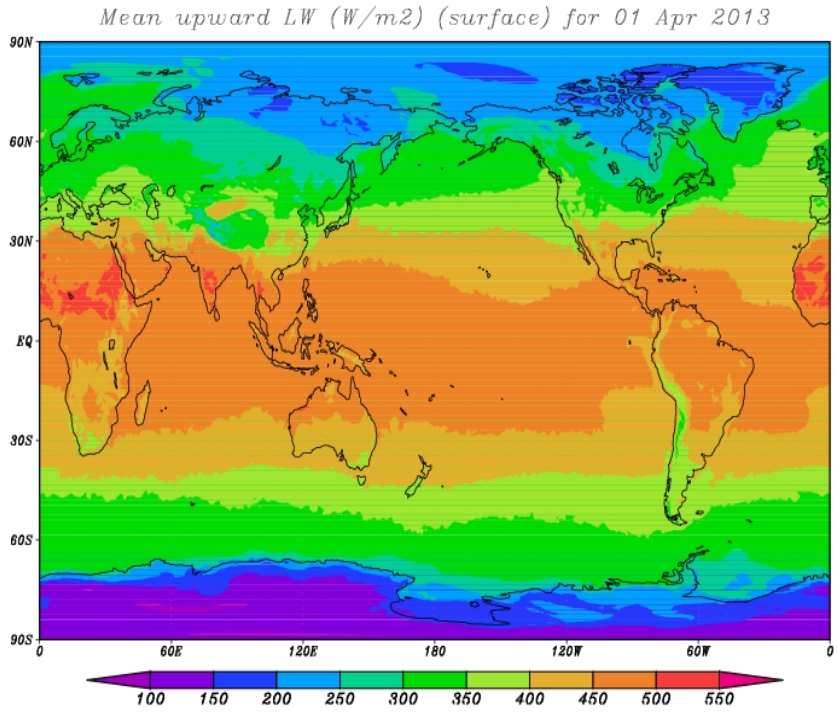


Figure 6: The mean (a) downward and (b) upward SW radiation at surface for 01 April 2013.


Mean downward LW (W/m2)(surface) for 01 Apr 2013
90N
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
0
100
150
200
250
300
350
400

(a)


Mean upward LW (W/m2) (surface) for 01 Apr 2013
90N
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
0
100
150
200
250
300
350
400
450
500
550

(b)

(c)

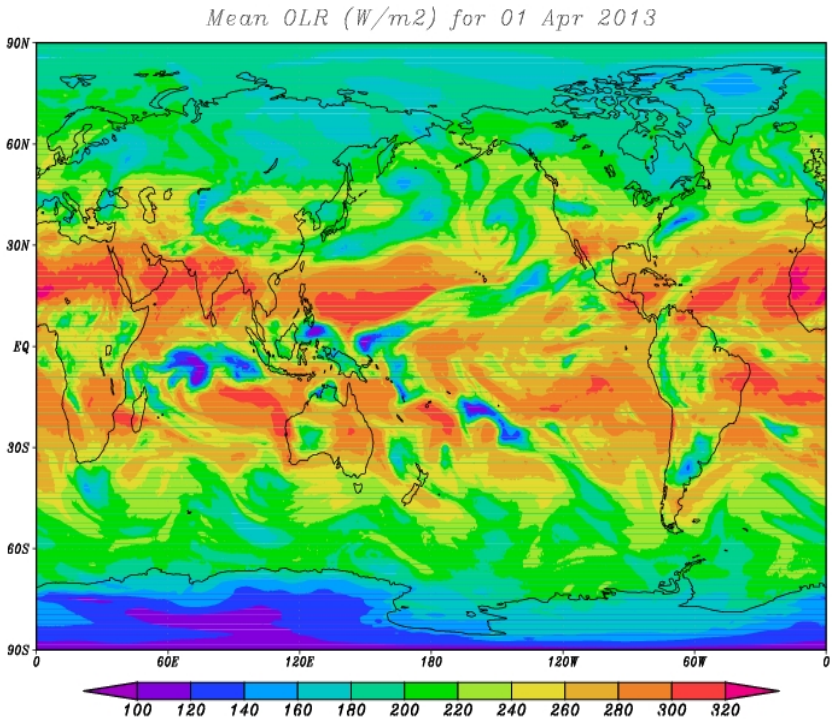


Figure 7: The mean (a) downward (surface) (b) upward (surface) and (c) outgoing LW radiation (TOA) for 01 April 2013.

Appendix-I

Description of the spectral files

1. Introduction

The discretization in wavelength or frequency is considered to cover a broad range of wavelength in atmospheric radiation for use in general circulation models. The region of solar and infrared is divided into a number of bands, across which all radiative quantities (except the absorption coefficients of gases) is considered uniform. The discretization in frequency within the radiation code is not fixed but is set in an external file, which is known as the spectral file, by the user. The generation of such files requires a detailed knowledge of the radiative transfer. The standard files for use in the Unified Model (UM) are provided in a central directory, /gpfs1/home/moum/UM/vn7.9/ctldata/spectral. These files are mentioned in the radiation window in the Unified Model user interface. The following general points need to be noted:

a) A spectral file is not an ancillary file, there is no geographical information, but refers to discretization in frequency.
b) A spectral file released with a certain version of UM is compatible with higher versions, but the vice-versa is not true.
c) The name of shortwave spectral files begins with the string spec3a_sw and those of longwave spectral files with spec3a_lw. When a new release of the model is prepared, all the spectral files are copied from the old release to the new one without change.
d) The alteration of spectral files requires expertise in radiative transfer.

2. Structure of spectral files

The spectral file consists of a number of blocks of data, each referring to a different physical process. If a particular block, say i, is present, then the flag L_PRESENT(i) is set to .TRUE. For the calculations all the blocks are not required. Each of the blocks along with the elements of a spectral file is given in Table 1.

Table 1: The indexing numbers of gaseous absorbing species for two-stream radiation code.

BLOCK 0	
N_BAND	Number of spectral bands
N_ABSORB	Number of absorbers
N_AEROSOL	Number of aerosol species
TYPE_ABSORB (NPD_SPECIES)	Type of absorber
TYPE_AEROSOL (NPD_SPECIES)	Type of aerosol species
BLOCK 1	
WAVE_LENGTH_SHORT	Shorter wavelength limits
WAVE_LENGTH_LONG	Longer wavelength limits
BLOCK 2	
SOLAR_FLUX_BAND (NPD_BAND)	Fraction of the incident solar flux in each band
BLOCK 3	
RAYLEIGH_COEFFICIENT (NPD_BAND)	Rayleigh coefficients
BLOCK 4	
N_BAND_ABSORB (NPD_BAND)	number of absorbers in each band
INDEX_ABSORB (NPD_SPECIES, NPD_BAND)	List of absorbers in each band
BLOCK 5	
I_BAND_ESFT (NPD_BAND, NPD_SPECIES)	number of esft terms in each band for each gas
I_SCALE_ESFT (NPD_BAND, NPD_SPECIES)	type of esft scaling
I_SCALE_FNC (NPD_BAND, NPD_SPECIES)	type of scaling function
P_REFERENCE (NPD_SPECIES, NPD_BAND)	reference pressure for scaling function
T_REFERENCE (NPD_SPECIES, NPD_BAND)	reference temperature for scaling function
K_ESFT (NPD_ESFT_TERM, NPD_BAND, NPD_SPECIES)	esft exponents
W_ESFT (NPD_ESFT_TERM, NPD_BAND, NPD_SPECIES)	esft weights
SCALE_VECTOR (NPD_SCALE_VARIABLE, NPD_ESFT_TERM, NPD_BAND, NPD_SPECIES)	scaling parameters for each absorber and term

BLOCK 6	
N_DEG_FIT	degree of thermal polynomial
T_REF_PLANCK	Planck reference temperature
THERMAL_COEFFICIENT (0:NPD_THERMAL_COEFF-1, NPD_BAND)	coefficients in polynomial fit to source function
BLOCK 7	
I_SPEC_SURFACE (NPD_SURFACE)	method of specifying properties of surface
N_DIR_ALBEDO_FIT (NPD_SURFACE)	number of parameters fitting the direct albedo
L_SURFACE (NPD_SURFACE)	surface types included
SURFACE_ALBEDO (NPD_BAND, NPD_SURFACE)	surface albedos
DIRECT_ALBEDO_PARM (0:NPD_ALBEDO_PARM, NPD_BAND,NPD_SURFACE)	coefficients for fitting direct albedo
EMISSIVITY_GROUND (NPD_BAND, NPD_SURFACE)	surface emissivity
BLOCK 8	
N_BAND_CONTINUUM (NPD_BAND)	number of continua in each band
INDEX_CONTINUUM (NPD_BAND, NPD_CONTINUUM)	list of continua in each band
INDEX_WATER	index of water vapour
BLOCK 9	
I_SCALE_FNC_CONT (NPD_BAND, NPD_CONTINUUM)	type of scaling function for continuum
P_REF_CONTINUUM (NPD_CONTINUUM, NPD_BAND)	reference pressure for scaling of continuum
T_REF_CONTINUUM (NPD_CONTINUUM, NPD_BAND)	reference temperature for scaling of continuum
K_CONTINUUM (NPD_BAND, NPD_CONTINUUM)	grey extinction coefficients for continuum
SCALE_CONTINUUM (NPD_SCALE_VARIABLE, NPD_BAND,NPD_CONTINUUM)	scaling parameters for continuum
BLOCK 10	
L_DROP_TYPE (NPD_DROP_TYPE)	types of droplet present
I_DROP_PARAMETRIZATION (NPD_DROP_TYPE)	parameterization type of droplets
DROP_PARM_MIN_DIM (NPD_DROP_TYPE)	minimum dimension permissible in the parameterization
DROP_PARM_MAX_DIM (NPD_DROP_TYPE)	maximum dimension permissible in the parameterization

DROP_PARAMETER_LIST (NPD_CLOUD_PARAMETER, NPD_BAND, NPD_DROP_TYPE)	Parameters used to fit optical properties of clouds
BLOCK 11	
N_AEROSOL	Number of species of aerosol
TYPE_AEROSOL (NPD_AEROSOL_SPECIES)	Types of aerosol
I_AEROSOL_PARAMETRIZATION (NPD_AEROSOL_SPECIES)	Parameterization of aerosols
NHUMIDITY (NPD_AEROSOL_SPECIES)	Number of humidities
L_AEROSOL_SPECIES (NPD_AEROSOL_SPECIES)	Aerosol species included
AEROSOL_ABSORPTION (NPD_HUMIDITIES, NPD_AEROSOL_SPECIES, NPD_BAND)	Absorption by aerosols
AEROSOL_SCATTERING (NPD_HUMIDITIES, NPD_AEROSOL_SPECIES, NPD_BAND)	Scattering by aerosols
AEROSOL_ASYMMETRY (NPD_HUMIDITIES, NPD_AEROSOL_SPECIES, NPD_BAND)	Asymmetry of aerosols
BLOCK 12	
L_ICE_TYPE (NPD_DROP_TYPE)	types of ice crystal present
I_ICE_PARAMETRIZATION (NPD_DROP_TYPE)	Type of parameterization of ice crystals
ICE_PARM_MIN_DIM (NPD_DROP_TYPE)	minimum dimension permissible in the parameterization
ICE_PARM_MAX_DIM (NPD_DROP_TYPE)	maximum dimension permissible in the parameterization
ICE_PARAMETER_LIST (NPD_CLOUD_PARAMETER, NPD_BAND, NPD_DROP_TYPE)	Parameters used to fit single scattering of ice crystals
BLOCK 13	
L_DOPPLER_PRESENT(NPD_SPECIES)	Flag for Doppler broadening for each species
DOPPLER_CORRECTION(NPD_SPECIES)	Offset to pressure to represent Doppler broadening
BLOCK 14	
N_BAND_EXCLUDE(NPD_BAND)	number of excluded bands within each spectral band
INDEX_EXCLUDE(NPD_EXCLUDE,NPD_BAND)	indices of excluded bands
BLOCK 15	
N_AOD_WAVEL	Number of wavelengths
AOD_ABSORPTION	Monochromatic specific coefficient of absorption

AOD_SCATTERING	Monochromatic specific coefficient of scattering
I_AOD_TYPE	Relationship between aerosol component and type integer

The explanation to each of the above mentioned blocks (block 0 to 15) is given below:

Block 0

It contains the number and physical nature of gases and aerosols. The atmosphere consists of a number of gases and aerosols, all of which are not relevant in all the applications. In each of the spectral files, the gases (referred to as species) are selected and indexed 1,...,n. This number is referred to as the indexing number and used by the radiation code. The physical nature of gaseous absorbers (each species) is recorded by the type number and stored in the array TYPE_ABSORB. The number of indexed gases is 20. Table 2 lists the meaning of the numbers, which is set in the header file gasid3a.h. Similarly, aerosols are also indexed and stored in TYPE_AEROSOL (shown in Table 3), and recorded in aercmp3a.h. The number of aerosol components is 32.

Table 2: The indexing numbers of gaseous absorbing species for two-stream radiation code.

GASES	INDEX	GASES	INDEX
H_2O	1	NH_3	11
CO_2	2	HNO_3	12
O_3	3	N_2	13
N_2O	4	CFC11	14
CO	5	CFC12	15
CH_4	6	CFC113	16
O_2	7	HCFC22	17
NO	8	HFC125	18
SO_2	9	HFC134A	19
NO_2	10	CFC114	20

Block 1

It contains the limits of the spectral bands used as wavelengths (in m). It may be noted, in number of UM shortwave (SW) files that some bands have the same limits, which indicates that they are not true spectral bands. The fluxes in individual bands cannot be considered alone but the sum of the fluxes in the bands represents the true flux across the specified region. For example, if band 1 is taken as 0.2-0.32 μm, band 2 and 3 as 0.32-0.69 μm; the

flux in band 1 represents the true flux between 0.2 μm and 0.32 μm, but the flux in band 2 or band 3 is given as the sum of the fluxes in bands 2 and 3 taken in the region 0.32-0.69 μm.

Table 3: The indices of the aerosol components.

AEROSOL COMPONENTS	INDEX	AEROSOL COMPONENTS	INDEX
Water soluble	1	Dust 3	19
Dust like	2	Dust 4	20
Oceanic	3	Dust 5	21
Soot	4	Dust 6	22
Ash	5	Biomass 1	23
Sulphuric	6	Biomass 2	24
Accumulated sulphate	10	Biogenic	25
Aitken sulphate	11	Ocff fresh	26
Fresh soot	12	Ocff aged	27
Aged soot	13	Delta	28
Sea salt film	15	Nitrate	30
Sea salt jet	16	Two bin dust 1	31
Dust 1	17	Two bin dust 2	32
Dust 2	18	-	-

Block 2

It is required for the SW file and contains the fraction of the solar spectrum in each band.

Block 3

It is required only in SW files and contains the Rayleigh scattering coefficients.

Block 4

It contains the list of gaseous absorbers active in each band, which are listed by their indexing numbers. The first gas listed is the primary absorber in the band i.e. it makes the greatest contribution to the atmospheric absorption when considered alone.

Block 5

It contains the k-fits to the gaseous transmissions.

Block 6

It is required only for the infrared calculations and contains the coefficients of a polynomial fit to the Planck function in each band.

Block 7

It is obsolete and is not present in any file used in the UM.

Block 8

It contains the list of continuum absorbers in each band. In principle, there are several species of continuum absorbers, but the main continua are the self and foreign-broadened continua of water vapour, which is considered.

Block 9

It contains the continuum absorption coefficients in each band.

Block 10

It contains the parameterization for the single scattering properties of droplets. It contains data for different types of droplet. The different type indicates parameterization appropriate to a different collection of droplets, such as droplets in convective clouds and stratiform clouds, a different parameterization of the same data or different spectral averaging. The type numbers are in the UM user interface, which has to be selected for the appropriate spectral file. The parameterization is generated for a range of particle sizes; therefore, the minimum and maximum dimensions are also recorded.

Block 11

It contains data on aerosols.

Block 12

It contains the parameterization for the single scattering properties of ice crystals. It contains data for different types of droplet. The different type indicate parameterisation appropriate to a different collection of ice crystals, such as crystals in convective clouds and stratiform clouds, a different parameterization of the same data, a different crystal shape or different spectral averaging. The type numbers are in the UM user interface, which has to be selected for the appropriate spectral file. The parameterization is generated for a range of particle sizes; therefore, the minimum and maximum dimensions are also recorded.

Block 13

It is relevant in the longwave (LW) region and contains adjustments for the Doppler broadening.

Block 14

It specifies the exclusions. In the original version of the radiation code a band had to be a contiguous range of frequencies, but in UM bands need to be split. For example, let us take band 5 that extends from 8 μm to 12 μm and band 6 from 10-11 μm, and exclude band 6

from band 5. Now, band 5 consists of the regions 8-10 μm and 11-12 μm. The limit for band 6 is 10 μm and 11 μm and band 5 has the limits as 8 μm and 12 μm. These exclusions are important in the generation of the spectral file but are not relevant during UM runs. If diagnostics is covering only a portion of the spectrum, then it is necessary to know the exclusions in order to weight the contributions from individual bands appropriately.

Block 15

It contains the specific absorption and scattering coefficients of each aerosol mode (in the same order as given in block 11). The contents in block 11 are averaged across spectral bands, but the coefficients in block 15 are monochromatic. There are six wavelengths: 0.38 μm, 0.44 μm, 0.55 μm, 0.67 μm, 0.87 μm, and 1.02 μm. The aerosols which are hygroscopic have relative humidity dependent coefficients.

3. Standard spectral files

The spectral files used for the atmospheric parameters, the SW and LW radiations, are listed below:

- spec_sw_cloud3_0
- spec_lw_cloud3_0
- spec_sw_ga3_0
- spec_lw_ga3_1

The dimensions and elements used in the spectral file are given below.

The dimensions for the spectrum.

NPD_BAND	number of spectral bands
NPD_EXCLUDE	number of excluded bands
NPD_SPECIES	number of gaseous species
NPD_ESFT_TERM	number of esft terms
NPD_SCALE_FNC	number of scaling functions
NPD_SCALE_VARIABLE	number of scaling variables
NPD_SURFACE	number of surface types
NPD_ALBEDO_PARM	number of albedo parameters
NPD_CONTINUUM	number of continua
NPD_DROP_TYPE	number of drop types
NPD_ICE_TYPE	number of ice types
NPD_AEROSOL_SPECIES	number of aerosol species
NPD_CLOUD_PARAMETER	maximum number of cloud parameters
NPD_HUMIDITIES	maximum number of humidities
NPD_THERMAL_COEFF	number of thermal coefficients

3.1. spec_sw_cloud3_0 and spec_lw_cloud3_0

These are simple spectral file used specifically with the incremental radiative time-stepping scheme for improved sampling of cloud. They represent regions of high transmissivity in the SW and LW in order to capture the radiative effects of changes in low cloud. More details are given in Manners et al. (2009). The parameterization values (for water droplets and ice crystals) can be obtained from the spec_sw_cloud3_0 and spec_lw_cloud3_0 spectral files.

3.2. spec_sw_ga3_0 and spec_lw_ga3_1

Spectral file: spec_sw_ga3_0

The spectrum is divided into six bands, the second and third of which are not true bands, as discussed in block 1 in section 1.1.

Solar spectrum

The Lean (Lean, 2000) and Kurucz spectrum based on satellite observations for wavelengths shorter than 735 nm and longer wavelengths, respectively are used. The satellite observations provide the monthly data, which has been averaged for the two solar cycles (1983-2004).

Gaseous absorption

The O_3 heating rate calculations are improved and solar variability is included. The first ultraviolet (UV) band is divided into six relatively narrow sub-bands, each of which has only one O_3 absorption coefficient. Each new sub-band has realistic band limits and the O_3 absorption coefficients are obtained from mean transmission functions calculated with high resolution (1 cm^{-1}) and fitting procedure is as described by Chou and Lee (1996). O_3 cross-sections are a combination of HITRAN2004 (High Resolution Transmission) (0.24-0.34 μm), Molina and Molina (1986) (0.24-0.34 μm) and Voigt et al. (2001) (above 0.34 μm). This has a greater accuracy due to the higher number of bands within the UV. More details are given in Zhong et al. (2008).

Aerosols

Aerosols included comprises the five aerosols of the standard climatology given by Cusack et al. (1998) and two modes each for sulphate, black carbon, sea-salt, and biomass aerosols and six divisions of mineral dust. The optical properties of mineral dust have been revised using the refractive index from Balkanski et al. (1997), which makes mineral dust less absorbing in the SW and more absorbing in the LW. The properties of aerosols depend on their nature and the size distribution, which are mentioned in the standard WMO report

(Cusack et al., 1998). The single scattering parameters for aerosols are generated by running the Mie scattering code and averaging over the size distribution. The aerosol optical depth climatology is mentioned. The sulphate aerosols being hygroscopic, their optical properties depend on the relative humidity. Two distinct modes of aerosols are included in this, the aitken and accumulation modes and a log normal size distribution is assumed. Black carbon aerosols are not hygroscopic and they are represented as fresh and aged aerosols, which follow a log normal distribution. Film and jet modes of sea salt aerosols are included. The prognostic dust aerosols are modelled using six classes with limits and two modes of biomass smoke are also included. In addition, fresh and aged OCFF (organic carbon fossil fuel), delta, and nitrate aerosols are included.

Cloud droplets

The data for water droplets is generated using a Mie scattering code. The size distributions for droplets vary widely, depending on the location and moisture content of the atmosphere. For radiation, the droplet size is measured in terms of the effective radius (r_e). The numbers in the spectral file represent coefficients in a parameterization, which is generated by running a Mie scattering code for different size distributions at a range of wavelengths, averaging the single scattering properties across the spectral bands, weighting with an appropriate function of frequency and then fitting using some appropriate function of the effective radius. This can be done in a number of ways and hence, the type of droplet is used. Four types of droplets are available, namely, 2, 3, 4, and 5. In all the cases, the size distributions specified by Rockel et al. (1991) is with r_e in the range 1.5-50 microns. This is weighed using the solar spectrum of Labs and Neckel (1970). For types 2 and 4, the method of thin averaging (Edwards and Slingo, 1996) is used, whereas for types 3 and 5, the method of thick averaging is used. The Slingo and Schrecker (1982) functional form fitting is used for types 2 and 3. The type 4 and 5 are generated using thin and thick averaging, respectively. The type 5 is preferred for both convective and large-scale clouds.

Ice crystals

The generation of single scattering data for ice crystals is much more complicated compared to cloud droplets because the crystal shape need to be considered. The data for type 1 are obtained using the size distributions specified by Rockel et al. (1991) with r_e in the range 24-80 microns. This was weighed with the solar spectrum of Labs and Neckel (1970) and spectrally averaged using the method of thin averaging (Edwards and Slingo, 1996) for type 2 and thick averaging for type 3. The type 2 is used for large scale cloud and type 3 for convective cloud. The type 7 treats ice crystals as planar polycrystals based on the anomalous

diffraction approximation (given by Kristjánsson et al. (1999) and Kristjánsson et al. (2000)). In this case, the parameters represent a fit in terms of the mean maximum dimension of the crystals. The data is generated from a aggregate database using 83 representative size distributions measured during Central Equatorial Pacific Experiment (CEPEX) and fitted using the appropriate functional form and thin averaging was performed. It is to be noted that this fit is provided in terms of the effective dimension and is represented by the type 8 ice crystals. Thickly averaged data are not available for non-spherical ice crystals. A new parameterization for the optical properties of ice crystals is developed based on the latest observed particle size distributions (from Paul field) and an ensemble model of ice crystal type and orientation. The optical properties are linked directly to temperature and ice water content with no dependence on ice crystal size and this parameterization is added as type 9.

Spectral file: spec_lw_ga3_1

The spectral file spec_lw_ga3_1 is used for forecast configurations where speed of computation and accurate treatment of the troposphere is required. It is the standard LW file. The spectrums is divided into nine bands, the third and fifth are split as discussed under block 14 in section 1.1.

Planck function

The Planck function in each band is represented by a quartic fit in the temperature, which is generated by a least square fit over the range 180-330 K.

Gaseous absorption

The gaseous absorption by water vapour, O_3, CO_2, CH_4, N_2O, CFC11, CFC12, CFC113, HCFC22, HFC125 and HFC134a is included. The absorption coefficients for gases (except halocarbons and water vapour) are from HITRAN92, the detail of which is given in Cusack et al. (1999). Absorption cross-sections for the halocarbons are from Highwood and Shine (2000), water vapour from HITRAN2000. The water vapour continuum is represented explicitly using the Clough–Kneizys–Davies (CKD) model (version 2.4). The self-broadened continuum is represented explicitly. The foreign broadened continuum is combined with the line absorption and the combined absorption is fitted to give the line data.

Aerosols

Aerosols included comprise the five aerosols of the standard climatology (Cusack et al., 1998), two modes each for sulphate, black carbon, sea salt and biomass aerosols and six divisions of dust aerosol. Its properties depend on their nature and the size distribution, which are specified in the standard WMO report (Cusack et al., 1998). The properties of sulphate, black carbon, sea salt, dust and biomass smoke aerosols are same as mentioned under the

aerosol heading in the previous section. The Mie scattering calculations have provided the optical properties for seven more aerosols: six for mineral dust and one for biogenic aerosols. The biogenic aerosol size distribution is lognormal with a hygroscopic growth.

Cloud droplets

The data for type 1 are obtained using the size distributions specified by Rockel et al. (1991) with r_e in the range 1.5-50 microns. This was weighed using Planck function at a temperature of 250 K and spectrally averaged using the method of thin averaging (Edwards and Slingo, 1996) and fitting with the Slingo and Schrecker (1982) functional form. The type 4 and 5 are generated using thin and thick averaging, respectively but a different fitting method is used.

Ice crystals

The single scattering data generated is similar to that discussed for the spectral file spec_sw_ga3_0. The only difference being that the size distribution is weighed using Planck function at a temperature of 250K.

References

Ackerman, S. A., and G. L. Stephens (1987), The absorption of solar radiation by cloud droplets: an application of anomalous diffraction theory, *J. Atmos. Sci.*, *44*, 1574-1588.

Balkanski, Y., M. Schulz, T. Claquin, and S. Guibert (2007), Reevaluation of mineral aerosol radiativeforcings suggests a better agreement with satellite and aeronet data, *Atmos. Chem. Phys.*, *7,* 81-95.

Barker, H. W., J. N. S. Cole, J. J. Morcrette, R. Pincus, P. Räisänen, K. von Salzen, and P. A. Vaillancourt (2008), The Monte Carlo Independent Column Approximation: An assessment using several global atmospheric models, , *Q. J. R. Meteorol. Soc.*, *134*, 1463-1478.

Barker, H. W., and Z. Li (1995), Improved simulation of clear-sky shortwave radiative transfer in the CCC-GCM, *J. Climate*, *8*, 2213-2223.

Chou, M. D., and K. T. Lee (1996), Parameterizations for the absorption of solar radiation by water vapor and ozone, *J. Atmos. Sci.*, *53*, 1203-1208.

Cusack, S., J. M. Edwards, and J. M. Crowther (1999), Investigating k distribution methods for parameterizing gaseous absorption in the Hadley centre climate model, *J. Geophys. Res.*, *104,* 2051-2057.

Cusack, S., A. Slingo, J. M. Edwards, and M. Wild (1998), Theradiative impact of a simple aerosol climatology on the Hadley Centre atmospheric GCM, *Q. J. Roy. Meteorol. Soc.*, *124,* 2517-2526.

Ebert, E. and J. A. Curry (1993), An intermediate one-dimensional thermodynamic sea ice model for investigating ice-atmosphere interactions, *J. Geophys. Res.*, *98*, 10085-10109.

Edwards, J. M., J. Manners, J. C. Thelen, W. J. Ingram, and P. G. Hill (2012), The radiation code, *Unified Model Documentation Paper No. 23*, Met Office, UK.

Edwards, J. M., J. C. Thelen and W. J. Ingram (2004), The radiation code, *Unified Model Documentation Paper No. 23*, Met Office, UK.

Edwards, J. M. (1996), Studies with a flexible new radiation code I: choosing a configuration for a large scale model, *Q. J. Roy. Meteorol. Soc.*, *122*, 689-719.

Edwards, J. M., and A. Slingo (1996), Studies with a flexible new radiation code. I: Choosing a configuration for a large-scale model, *Q. J. Roy. Meteorol. Soc.*, *122,* 689-719.

Highwood, E. J., and K. P. Shine (2000), Radiative forcing and global warming potentials of 11 halogenated compounds, *J. Quant. Spectrosc. Radiat. Transfer*, *66*, 169-183.

Joseph, J. H., Wiscombe, W. J., and Weinman, J. A. (1976), The δ-Eddington approximation for radiative flux transfer, *J. Atmos. Sci.*, *33*, 2452-2459.

Kristjánsson, J. E., J. M. Edwards, and D. L. Mitchell (2000), The impact of a new scheme for the optical properties of ice crystals on the climates of two GCMs, *J. Geophys. Res.,* 105, 10,063-10,079.

Labs, D., and H. Neckel (1970), Transformation of the absolute solar radiation data into the international practical temperature scale of 1968, Solar Physics, *15*, 79–87.

Lean, J. (2000), Evolution of the sun's spectral irradiance since the maunder minimum, *Geophys. Res. Lett.*, *27*, 2425-2428.

Manners, J., J. M. Edwards, and J. C. Thelen (2012), Spectral files for the radiation scheme, *Unified Model Documentation Paper No. 23a*, Met Office, UK.

Manners, J., J. C. Thelen, J. Petch, P. Hill, and J. M. Edwards (2009), Two fast radiative transfer methods to improve the temporal sampling of clouds in numerical weather prediction and climate models, *Q. J. R. Meteorol. Soc.*, *135*, 457-468.

Molina, L. T., and M. J. Molina (1986), Absolute absorption cross section of ozone in the 185 to 350 nm wavelength range, *J. Geophys. Res.*, *91*, 14,501-14,508.

Rajagopal, E.N., G.R. Iyengar, John P. George, Munmun Das Gupta, Saji Mohandas, Renu Siddharth, Anjari Gupta, Manjusha Chourasia, V.S. Prasad, Aditi, Kuldeep Sharma and Amit Ashish (2012), Implementation of Unified Model based analysis-forecast system at NCMRWF, *Technical Report.*, NMRF/TR/2/2012, 46 p.

Räisänen, P., H. W. Barker, M. F. Khairoutdinov, J. Li, and D. A. Randall (2004), Stochastic generation of subgrid-scale cloudy columns for large scale models, *Q. J. Roy. Meteorol. Soc.*, *130,* 2047-2067.

Rockel, B., E. Raschke, and B. Weyres (1991), Aparametrization of broad band radiative transfer properties of water, ice and mixed clouds, *Beitrage Phys. Atmosph.*, *64*, 1-12.

Slingo, A., and H. M. Schrecker (1982), On the shortwave radiative properties of stratiform water clouds, *Q. J. R. Meteorol. Soc.*, *108*, 407-426.

Voigt, S., J. Orphal, K. Bogumil, and J. P. Burrows (2001), The temperature dependence (203-293 k) of the absorption cross-sections of O3 in the 230-850 nm region measured by fourier transform spectroscopy, *J. Photochem. Photobiol. A*, *143*, 1-9.

Walters, D. N. et al. (2011), The Met Office Unified Model Global Atmosphere 3.0/3.1 and JULES Global Land 3.0/3.1 configurations, *Geosci. Model Dev. Discuss.*, *4*, 1213-1271.

Zdunkowski, W. G., Welch, R. M., and Korb, G. (1980), An investigation of the structure of typical two-stream methods form the calculation of solar fluxes and heating rates in clouds, *Beitr. Phys. Atmosph.*, *53*, 147-166.

Zhong, W., S. M. Osprey, L. J. Gray, and J. D. Haigh(2008), Influence of the prescribed solar spectrum on calculations of atmospheric temperature, *Geophys. Res. Lett.*, *35*(L22813).