

# THE INTRODUCTION OF CLOUDS AND AEROSOLS IN THE ECMWF FAST RADIATIVE TRANSFER MODEL FOR THE INFRARED ATMOSPHERIC SOUNDING INTERFEROMETER

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## Abstract

A new version of RTIASI, the ECMWF fast radiative transfer model for the Infrared Atmospheric Sounding Interferometer (IASI) has been developed that features the introduction of multiple scattering by aerosols and clouds. In RTIASI, multiple scattering is parameterized by scaling the optical depth by a factor derived by including the backward scattering in the emission of a layer and in the transmission between levels. The RTIASI radiative transfer can include eleven aerosol components, five types of water clouds and eight types of cirrus clouds. The database of optical properties for aerosols and water droplets has been generated using the Lorentz-Mie theory for spherical particles. For cirrus clouds, a composite database of optical properties has been generated using the Geometric Optics method for large crystals and the T-matrix method for small crystals assuming the ice crystals are hexagonal prisms randomly oriented in space. To solve the radiative transfer for an atmosphere partially covered by clouds, RTIASI uses a scheme that divides the field of view into a number of homogeneous columns. Each column is characterized by a different number of cloudy layers, hence different radiative properties, and contributes to a fraction of the overcast radiance that depends on the cloud overlapping assumption. To assess the accuracy of the scattering parameterization we have compared approximate radiances with reference radiances computed by using a doubling-adding algorithm. For aerosols, the largest errors are observed for the desert dust type. For this case, errors are less than 1 K in the thermal infrared and less than 0.25 K in the short wave. For water clouds, errors are typically less than 1K in the thermal infrared and less than 4 K in the short wave. For the cirrus cloud type, we found a remarkable agreement between approximate and reference radiances. For a tropical profile, errors introduced by the scaling approximation never exceed 0.5K whereas for an arctic profile errors are typically less than 0.1 K.

## 1. Introduction

A potentially useful addition to the current satellite sounders is the Infrared Atmospheric Sounding Interferometer (IASI) (Cayla 1993). IASI is the core payload of the European Organisation for Exploitation of Meteorological Satellites (EUMETSAT) Meteorological Operational Satellite (METOP) (Klaes et al. 2000) and will contribute to the primary mission objective of METOP that is the measurement of meteorological parameters for NWP and climate models.

A prerequisite for exploiting radiances from conventional and high-resolution sounders in Numerical Weather Prediction (NWP), is the availability of a fast and accurate radiative transfer model to predict a first guess radiance from the model fields (temperature, water vapour, ozone, surface emissivity and perhaps clouds in the future). As part of the preparations being made at ECMWF to exploit the IASI datasets, RTIASI, the ECMWF fast radiative transfer model for IASI, has been developed (Matricardi and Saunders 1999, Matricardi 2003). This paper deals with the methods that were applied to develop the most recent versions of RTIASI, RTIASI-5. In Section 2 we describe the radiative transfer used in RTIASI-5 to parameterize multiple scattering. This has involved the generation of a database of optical properties for aerosols, water clouds and cirrus clouds discussed in Section 3, 4, and 5 respectively. In Section 6 we describe the method used to

solve the radiative transfer in presence of an atmosphere partially covered by clouds. Errors introduced by the parameterization for multiple scattering are discussed in Section 7. Conclusions are given in Section 8.

## 2. The radiative transfer for multiple scattering

The scheme we have introduced in RTIASI to parameterize multiple scattering is based on the approach followed by Chou et al. (1999). In this scheme (referred to hereafter as scaling approximation), the effect of scattering is parameterised by scaling the optical depth by a factor derived by including the backward scattering in the emission of a layer and in the transmission between levels. Since this parameterisation of multiple scattering rests on the hypothesis that the diffuse radiance field is isotropic and can be approximated by the Planck function, we can expect it to have an effect on the accuracy of the radiance calculations. However, the scaling approximation does not require explicit calculations of multiple scattering and since the radiative transfer equation can be written in the same form as in clear sky conditions, the computational efficiency of RTIASI can be retained. In the scaling approximation, the absorption optical depth,  $\tau_a$ , is replaced by an effective extinction optical depth,  $\tilde{\tau}_e$ , defined as:

$$\tilde{\tau}_e = \tau_a + b\tau_s \quad (1)$$

where  $\tau_s$  is the scattering optical depth and  $b$  is the integrated fraction of energy scattered backward for incident radiation from above or below. If  $\bar{P}(\mu, \mu')$  is the azimuthally averaged value of the phase function and  $\mu$  is the cosine of the scattering angle,  $b$  can be written in the form:

$$b = \frac{1}{2} \int_0^1 d\mu \int_{-1}^0 \bar{P}(\mu, \mu') d\mu' \quad (2)$$

The introduction of scattering in RTIASI required the introduction of an improved parameterization of the Planck function,  $B$ . In the previous version of RTIASI a layer average value of the Planck function was used that gives equal weight to the radiance emitted from all regions within the layer. In presence of optically thick clouds this would put too much weight on the radiance coming from the lower regions of the layer. To improve the accuracy of radiance calculations in RTIASI-5, we have introduced a new parameterisation of the Planck function based on the linear in  $\tau$  assumption that the atmospheric emission source function throughout the layer is linear with the optical depth of the layer:

$$B[T(\tau)] = B_u + (B_b - B_u) \frac{\tilde{\tau}}{\tilde{\tau}^*} \quad (3)$$

Here  $B_u$  is the Planck function for the top of the layer,  $B_b$  is the Planck function at the bottom of the layer and  $\tilde{\tau}^*$  is the optical depth of the layer. The parameterisation is exact at the top ( $\tilde{\tau} = 0$ ) and bottom ( $\tau = \tilde{\tau}^*$ ) of the layer. When the new formulation of the source function was applied to RTIASI-5, we found that the error introduced by the use of the mean layer source function could be as large as 2K for an optically thick water cloud.

## 3. The dataset of optical properties for aerosols

The optical properties for the aerosols included in RTIASI-5 were computed using the microphysical properties assembled in the Optical Properties of Aerosols and Clouds (OPAC) software package (Hess et al. 1998). This database provides the microphysical properties (i.e. size distribution and refractive indices) for ten aerosol components. To be able to simulate the radiative

properties of the atmosphere in presence of a volcanic eruption, we have supplemented the OPAC database with the microphysical properties of the volcanic ash component.

The database of optical properties used by RTIASI-5 was generated using the Lorentz-Mie theory (Van de Hulst 1981) for spherical particles. The values of the refractive indices were interpolated to the central wavelength of each of the 8461 IASI channels and then used to compute the absorption coefficient, scattering coefficient, extinction coefficient, phase function and the backscattering parameter  $b$  defined in Eq. (2) for every single aerosol component. A lognormal size distribution was used for all the aerosol components except for the volcanic ash component for which a modified Gamma distribution was used. Values of the phase function were computed for every  $0.1^\circ$  from  $0^\circ$  to  $3^\circ$  otherwise they are given for every  $1^\circ$ . For those aerosols that can take up water, we have computed the optical properties for eight different values of the relative humidity assuming the width of the distribution does not change. The optical properties for an arbitrary value of the relative humidity can then be obtained by linear interpolation. Aerosols can be classified in terms of their location (i.e. continental, maritime, polar, etc.) and type (i.e. clear, polluted, desert, urban, etc.) Aerosols are formed as a mixture of several aerosol components. RTIASI-5 can compute optical properties for any mixture of aerosol components or, alternatively, it can compute optical properties for ten pre-defined mixtures of aerosol components, each mixture forming a typical climatological aerosol.

### **3. The dataset of optical properties for water clouds**

The OPAC package gives the microphysical properties for 5 types of water clouds: two stratus clouds (Stratus Continental and Stratus maritime) and 3 cumulus clouds. Analogous to the database of optical properties for aerosols, we have interpolated the refractive indices of water to the central wavelength of each of the 8461 IASI channels and then generated a database of optical properties for every single water cloud type using the Lorentz-Mie theory assuming a modified Gamma size distribution.

### **4. The dataset of optical properties for cirrus clouds**

Cirrus clouds are made of ice crystals. Typical shapes for ice crystals include bullet rosettes, hollow and solid columns, plates and aggregates. A shape often used in the literature is the hexagonal prism either in the form of column or plate. An exact solution for the interaction of a plane wave with a hexagonal ice crystal cannot be sought using the Lorentz-Mie theory. The problem is complicated by the fact that there is no practical solution that can be used to cover for all the crystal sizes that occur in the Earth's atmosphere. For RTIASI-5 we have generated a composite database of optical properties for hexagonal ice crystals randomly oriented in space using the geometric optics (GO) method (Macke et al. 1996) for large crystals and the T-matrix method (Kahnert et al. 2001) for small crystals. The size distribution used in this paper is from Heymsfield and Platt (1984). It covers eight different temperature ranges from  $-20^\circ\text{C}$  to  $-60^\circ\text{C}$  and crystal sizes less than  $20\ \mu\text{m}$ . To account for the radiative effect due to the presence of small ice crystals, the Heymsfield and Platt distribution has been extrapolated to  $4\ \mu\text{m}$  using the method described in Mitchell et al. (1996). To better resolve the structure of the spectra we have discretized the size distribution into 24 bins with the midpoint crystal length,  $L$ , varying from  $4\ \mu\text{m}$  to  $3500\ \mu\text{m}$ . The width,  $D$ , of the crystal has been derived from the length,  $L$ , of the crystal using the aspect ratio given in Yang et al. (2003)

The refractive indices for ice used in this paper are tabulated at 89 different frequencies. Given the computational time required to perform the GO and T-matrix computations, the procedure of interpolating the refractive indices to the IASI central frequencies and then perform the GO and T-matrix computations for each IASI channel is impractical. We have instead performed computations for each of the 89 tabulated refractive indices and then interpolated the results to each IASI channel.

## 5. The stream method

To solve the radiative transfer for a horizontally non-homogeneous atmosphere (i.e. an atmosphere partially covered by clouds) we follow the approach (referred to hereafter as stream method) of dividing the atmosphere into a number of homogeneous columns (Amorati and Rizzi 2002). Each column is characterized by a different number of cloudy layers, hence different radiative properties, and contributes to a fraction of the overcast radiance that depends on the cloud overlapping assumption. To describe the stream method we give here an example where seven atmospheric layers are considered. Once the cloud fractional cover in each layer is known ( $CFR$  in Figure 1), we compute the cumulative cloud coverage,  $N_{tot}(j)$ , from layer 1 to layer  $j$  using the maximum-random overlap assumption. For a slab extending from layer 1 to layer  $j$ , the total cloud cover is written as

$$N_{tot} = 1 - (1 - N_1) \prod_{i=2}^j \frac{1 - \max(N_{i-1}, N_i)}{1 - N_{i-1}} \quad (4)$$

A cloud (blue shaded region in Figure 1) is then placed in layer  $j$  that covers the range from  $N_{tot}(j) - CFR(j)$  to  $N_{tot}(j)$ . To determine the number of columns, we consider all the cloud configurations that result in a totally overcast column. In our example we obtain five,  $n_c$ , columns and one clear column.

Layer	CFR (%)	Cloud displacement in each stream											
1	0												
2	50												
3	0												
4	30												
5	80												
6	0												
7	0												
Areal coverage		0	0.1	0.35	0.5	0.65	0.9	1					
		$X_1$	$X_2$	$X_3$	$X_4$	$X_5$	$X_6$	$X_7$					
Stream number		1		2		3		4		5		6	

Figure 1 The cloud distribution for each stream

Once the top of the atmosphere radiance has been computed for each homogeneous column, the cloudy radiance is written as the sum of all the single column radiances weighted by the column fractional coverage

$$L^{cloudy} = \sum_{s=1}^{n_c} (X_{s+1} - X_s) L_s^{overcast} + L^{clear} (1 - X_{n_c+1}) \quad (5)$$

Note that if a clear column is present, this will be given a weight equal to  $(1 - X_{n_c+1})$ .

## 6. Results

The accuracy of the scaling approximation has been studied by comparing approximate radiances with reference radiances obtained using a doubling-adding algorithm. Results shown in this paper have been obtained by adapting to the infrared the code originally developed by Bauer (2002) for the microwave. Approximate and reference radiances have been computed using line-by-line optical depths for the molecular species whereas for aerosol and clouds we have used optical

depths from the respective databases assuming the optical depth is constant within the width of a channel. The accuracy of the scaling approximation is expressed in terms of the difference between approximated and reference radiances in presence of a scattering medium. To assess the impact of each aerosol/cloud on the top of the atmosphere radiance we have also computed the difference between clear-sky and reference spectra.

### 6.1 The results for aerosols

For each climatological aerosol we have computed spectra for a tropical and arctic profile. To obtain the aerosol vertical profile we have applied the methods described in Hess et al. (1998). Since these profiles are representative of global average conditions we have computed additional spectra assuming a value of the number density four times the global average value.

The desert aerosol type has by far the largest impact on the radiance. Figure 2 shows that for the extreme condition case (bottom panel) the presence of desert dust in a tropical profile can result in a reduction of the top of the atmosphere radiance (black curve) by 4K in the thermal infrared and by 1.8K in the short wave. Smaller differences are observed for the average condition case. Errors introduced by the scaling approximation (red curve) are less than 1K in the thermal infrared and less than 0.25 K in the short wave. For the Urban aerosol, the radiance attenuation for the extreme condition case can be as large as 1 K in the thermal infrared and 0.6 K in the short wave whereas for the average concentration case the radiance attenuation is typically less than 0.2 K for the whole spectrum. For the other aerosols the radiance attenuation seldom exceeds 0.1 K for the average condition case and 0.5 K for the extreme condition case. Errors introduced by the scaling approximation never exceed 0.1 K for the Urban aerosol whereas for the other aerosol they are typically below 0.05 K.

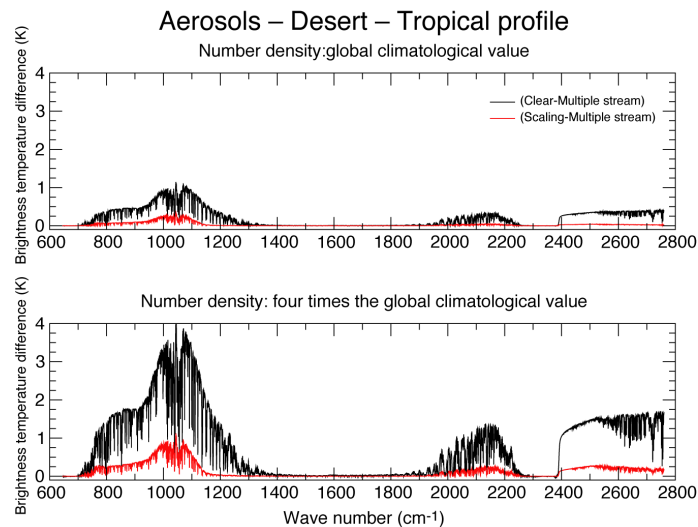


Figure 2 The radiative impact of the Desert aerosol type (black curve) and the error introduced by the scaling approximation (red curve) for the tropical profile for two different aerosol number densities.

### 6.2 The results for water clouds

Results for the Stratus Continental type are shown in Figure 3 for a tropical profile. The radiance attenuation resulting from the introduction of the cloud is larger in the shortwave and can reach 16 K for the tropical profile and 11 K for the arctic profile. No appreciable difference can be observed

when the cloud thickness is doubled, thus suggesting that the cloud is rendered opaque by extinction. The error introduced by the scaling approximation for the tropical profile is less than 1 K in the thermal infrared and can be as large as 5 K in the short wave. Smaller values are observed for the arctic profile.

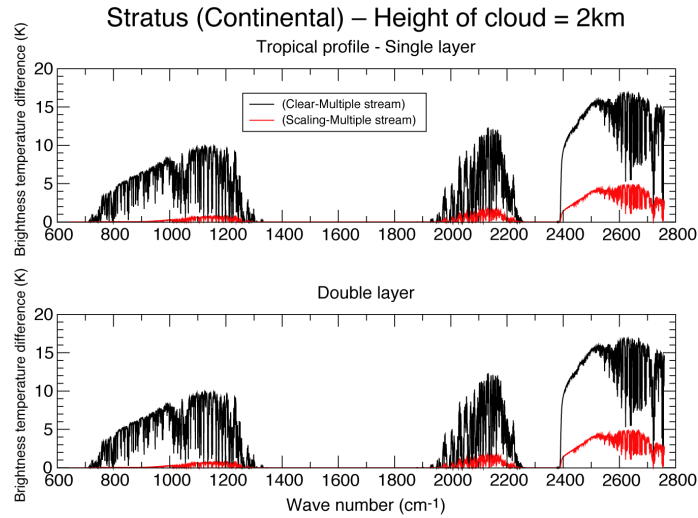


Figure 3 The radiative impact of the Stratus Continental cloud type (black curve) and the error introduced by the scaling approximation (red curve) for the tropical profile for two different values of the cloud thickness.

For the Stratus Maritime cloud a smaller radiance attenuation is observed. The error introduced by the scaling approximation is still less than 1 K in the thermal infrared but it is now significantly smaller in the short wave where it does not exceed 3 K. This can be partly explained by the fact that in the short wave the scaling factor  $b$  for the Stratus Maritime cloud is smaller than that for the Stratus Continental type.

Results for the Cumulus Continental Clean and the Cumulus Continental Polluted show that the radiance attenuation can be as large as 40 K in the short wave and 30 K in the thermal infrared. The error introduced by the scaling approximation does not exceed 2 K in the thermal infrared and is less than 7 K in the short wave. A smaller radiance attenuation is observed for the Cumulus Maritime cloud mainly in the shortwave. For this cloud type the error introduced by the scaling approximation is significantly lower. It is smaller than 0.8 K in the thermal infrared and does not exceed 1.2 K in the short wave. In fact, among the middle level cloud types, the Cumulus Maritime cloud is characterized by a smaller value of the scaling parameter  $b$  across the whole spectral range.

### 6.3 The results for cirrus clouds

The spectra for the cirrus cloud types have been computed by placing the top height of the cloud at 12 km, 10 km and 7 km. Results plotted in Figure 4 show that for the 12 km case the radiance attenuation can reach 10 K in the thermal infrared and 5 K in the short wave. Because of the moderate optical thickness of the cirrus cloud, doubling the thickness of the cloud results in a considerably larger attenuation. A remarkable feature is the accuracy achieved by the scaling approximation. The error never exceeds 0.5 K. This can be justified by the very small values of the

$b$  parameter. Note how for the cirrus cloud case the scaling approximation tends to underestimate the radiance in contrast to what happens for the aerosols and water clouds where the scaling approximation always overestimate the radiance. For the arctic profile case the error introduced by the scaling approximation is below 0.1 K. For the lower cloud height of 10 km we observe a reduction of the radiance departure; less than 5 K for the tropical profile and less than 0.3 K for the arctic profile. The scaling approximation now introduces an error that is typically less than 0.2 K.

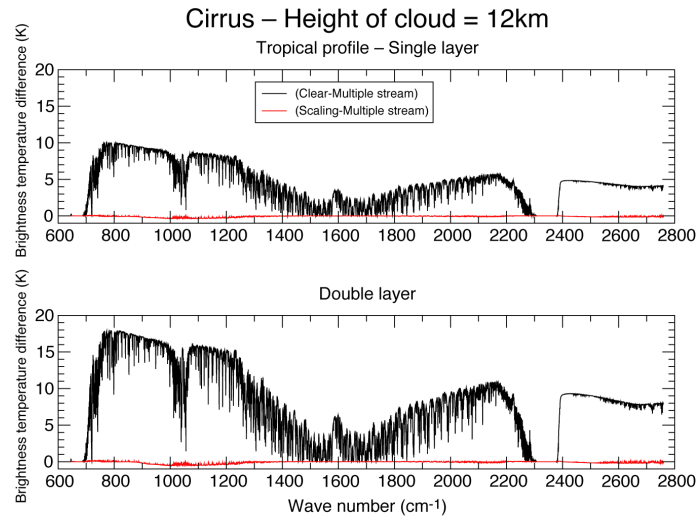


Figure 4 The radiative impact of the Cirrus cloud type (black curve) and the error introduced by the scaling approximation (red curve) for the tropical profile for two different values of the cloud thickness.

## 7. Conclusions

A new version of RTIASI, RTIASI-5, has been developed where multiple scattering is parameterized by scaling the optical depth by a factor derived by including the backward scattering in the emission of a layer and in the transmission between levels.

RTIASI-5 can include by default eleven aerosol components, five water cloud types and eight cirrus cloud types. The database of optical properties for aerosols and water droplets has been generated using the Lorentz-Mie theory for spherical particles using the microphysical parameters assembled in the OPAC software package. Cirrus clouds are assumed to be composed of hexagonal ice crystals randomly oriented in space. For these particles, a database of optical properties has been generated using the geometric optics (GO) method for large crystals and the T-matrix method for small crystals.

To improve the accuracy of the radiance computation in presence of optically thick layers, RTIASI-5 features a new parameterisation of the Planck function based on the 'linear in  $\tau$ ' assumption that the source function throughout the layer is linear with the optical depth of the layer. When compared to the parameterization used in the previous version of the code, the application of the new source function results in top of the atmosphere radiance differences up to 2 K in cloudy conditions.

To solve the radiative transfer for a partly cloudy atmosphere, a scheme (the stream method) has been implemented that divides the atmosphere into a number of homogeneous columns. Each column is characterized by different radiative properties and contributes to a fraction of the overcast radiance that depends on the cloud overlapping assumption.

To assess the accuracy of the scaling approximation we have compared approximate radiances with reference radiances computed by using a doubling-adding algorithm. Results have been obtained for each aerosol and cloud type for a tropical and arctic profile. For the desert aerosol,

errors introduced by the scaling approximation are less than 1K in the thermal infrared and less than 0.25 K in the short wave when a concentration four times the climatological value is assumed. For the Urban aerosol errors never exceed 0.1 K whereas for the other aerosols errors are typically below 0.05 K.

For the low level clouds the error introduced by the scaling approximation for the tropical profile is less than 1 K in the thermal infrared and can be as large as 5 K in the short wave for the Stratus Continental cloud. For the Stratus Maritime cloud the error introduced by the scaling approximation is still less than 1 K in the thermal infrared and does not exceed 3 K in the short wave.

Results for the middle level clouds show that the error introduced by the scaling approximation does not exceed 2 K in the thermal infrared and is less than 7 K in the short wave for the Cumulus Continental Clean and Cumulus Continental Polluted clouds. For the Cumulus Maritime cloud the error introduced by the scaling approximation is significantly lower. It is smaller than 0.8 K in the thermal infrared and does not exceed 1.2 K in the short wave.

Finally, for the cirrus cloud types we found a remarkable agreement between approximate and reference radiances. For the tropical profile the error introduced by the scaling approximation never exceeds 0.5 K whereas for the arctic profile is typically below 0.1 K.

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