The introduction of a parameterization for multiple scattering in RTIASI, the ECMWF fast radiative transfer model for the Infrared Atmospheric Sounding Interferometer

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% A prerequisite for exploiting radiances from conventional and high-resolution sounders in NWP models is the availability of a fast radiative transfer model to predict a first guess radiance from the model fields.

% As part of the preparations being made at ECMWF to exploit the Infrared Atmospheric Sounding Interferometer (IASI) (Cayla 1993) datasets, EUMETSAT has funded the development of RTIASI (Matricardi and Saunders 1999, Matricardi 2003, Matricardi 2005), the ECMWF fast radiative transfer model for IASI.

% RTIASI is a regression based (on fixed pressure levels) fast radiative transfer model where the atmospheric optical depths, $\tau_{j,}$ are modelled as functions of profile dependent predictors $X_{k,j}$:

$$\tau_j = \sum_{k=1}^{M} a_{k,j} X_{k,j}$$

% The expansion coefficients $a_{k,j}$ are obtained by multiple linear regression of accurate line-by-line computed optical depths against the corresponding values of $X_{k,j,}$ for a diverse set of atmospheric profiles.

% Radiance calculations in RTIASI are performed assuming the atmosphere is divided into 89 layers of fixed pressure levels. The pressure grid extents from 1050 hPa to 0.005 hPa.

% In RTIASI, fixed amounts are used for N_2, O_2, OCS, CCl_4, CF_4, CCl_3F, CCl_2F_2 and HNO_3 whereas H_2O, CO_2, O_3, N_2O, CO, CH_4 are allowed to vary and are profile variables in the fast model.

% Radiance computations in RTIASI are performed assuming the atmospheric source function throughout an atmospheric layer varies linearly with the optical depth of the layer (linear in τ approximation).

% The RTIASI radiative transfer can optionally include solar radiation in region of the spectrum between 3.6 μm and 5 μm.

- → Over land, a Lambertian surface is assumed
- → Over a wind roughened water surface, the bidirectional reflectivity is computed explicitly considering the full geometry of the situation.

% A new feature included in the latest version of RTIASI, RTIASI-5, is the introduction in the radiative transfer of multiple scattering by aerosols and clouds.

% It should be mentioned that work is in progress to merge the science of RTIASI into RTTOV (Saunders et al. 2002), the NWP SAF fast radiative transfer model.

% This will enable the RTTOV wider community of users to make use of the advanced capabilities of RTIASI.

→ This is especially important for ECMWF where (among other NWP centres) RTTOV is used operationally. In fact the development and implementation at ECMWF of a global data assimilation/forecast system for atmospheric composition and dynamics (GEMS project) will require the availability of a fast radiative transfer model with the capability of including aerosols and trace gases in the forward calculations.

% The azimuthally independent radiative transfer equation for the problem of multiple scattering in plane parallel atmospheres can be written as

$$\mu\frac{dI(\tau,\mu)}{d\tau}=I(\tau,\mu)-\frac{\omega}{2}\int_{-1}^{1}I(\tau,\mu')\bar{P}(\mu,\mu')d\mu'-\frac{\omega}{4\pi}F\bar{P}(\mu,-\mu_o)\,e^{\frac{-\tau}{\mu_o}}+(1-\omega)B[T(\tau)]$$

where ω is the single scattering albedo, $\bar{P}$ is the azimuthally averaged phase function, τ is the extinction optical depth and F is the solar irradiance.

→ Since the source function includes the local radiation field, the solution is an integral equation.

% Numerical solutions (e.g. discrete-ordinates, doubling-adding) are available that present few difficulties.

→ It should be noted that within the framework of RTIASI we can only consider, in principle, an analytical solution given by approximate methods since numerical solutions are too computationally expensive.

%A useful and accurate approximation is the two-stream approximation sometimes used in climate models (Liou 2002).

→ However, since RTIASI uses the polychromatic form of the radiative transfer equation, we found the two-stream approximation not amenable to incorporation in RTIASI. In fact, we carried out trials that show that this would results in too large errors (several degrees Kelvin).

% In RTIASI-5, multiple scattering is parameterized by scaling the optical depth by a factor derived by including the effect of backward scattering in the emission of a layer and in the transmission between levels (Chou et al. (1999)).

→ This parameterization rests on the assumption that the diffuse radiance field is isotropic and can be approximated by the Planck function.

% Since the parameterization (referred to hereafter as scaling approximation) does not require explicit calculations of multiple scattering (the radiative transfer equation is identical to that in clear sky conditions) the computational efficiency of RTIASI can be retained.

% In the scaling approximation, multiple scattering is parameterized by replacing the absorption optical depth, τ_a, with an effective extinction optical depth, $\tilde{\tau}_e$, defined as

$$\tilde{\tau}_e = \tau_a + b\tau_s$$

where τ_s is the scattering optical depth and *b* is the integrated fraction of energy scattered backward for incident radiation from above or below.

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

%In presence of solar radiation, in addition to the direct component we include in the radiative transfer equation the diffuse component represented by the single scattering of the solar beam.

→In the present implementation of RTIASI the direct and diffuse solar components are evaluated using the effective extinction optical depth, $\tilde{\tau}_e$. However, a comparison with measured radiances (DeSouza-Machado, personal communication) shows that a better agreement can be obtained if for these components the extinction (i.e. $\tau_e = \tau_a + \tau_s$) is used instead.

% The RTIASI-5 radiative transfer can include by default eleven basic aerosol components, five types of water clouds and eight types of cirrus clouds correspondent to the eight size distributions given by Heymsfield and Platt (1984).

% A database of optical properties (i.e. absorption coefficient, scattering coefficient, backscatter parameter and phase function) for aerosols and water droplets has been generated using the Lorentz-Mie theory for spherical particles for every single IASI channel.

- Note that in RTIASI values of the phase function are available for a total of 208 scattering angles. Values are given for every 0.1º from 0º to 3º otherwise they are given for every 1º.

- The microphysical parameters (e.g. size distribution, refractive indices) used to generate the database of optical properties for aerosols and water clouds are those included in the Optical Properties of Aerosols and Clouds (OPAC) software package (Hess et al. 1998).

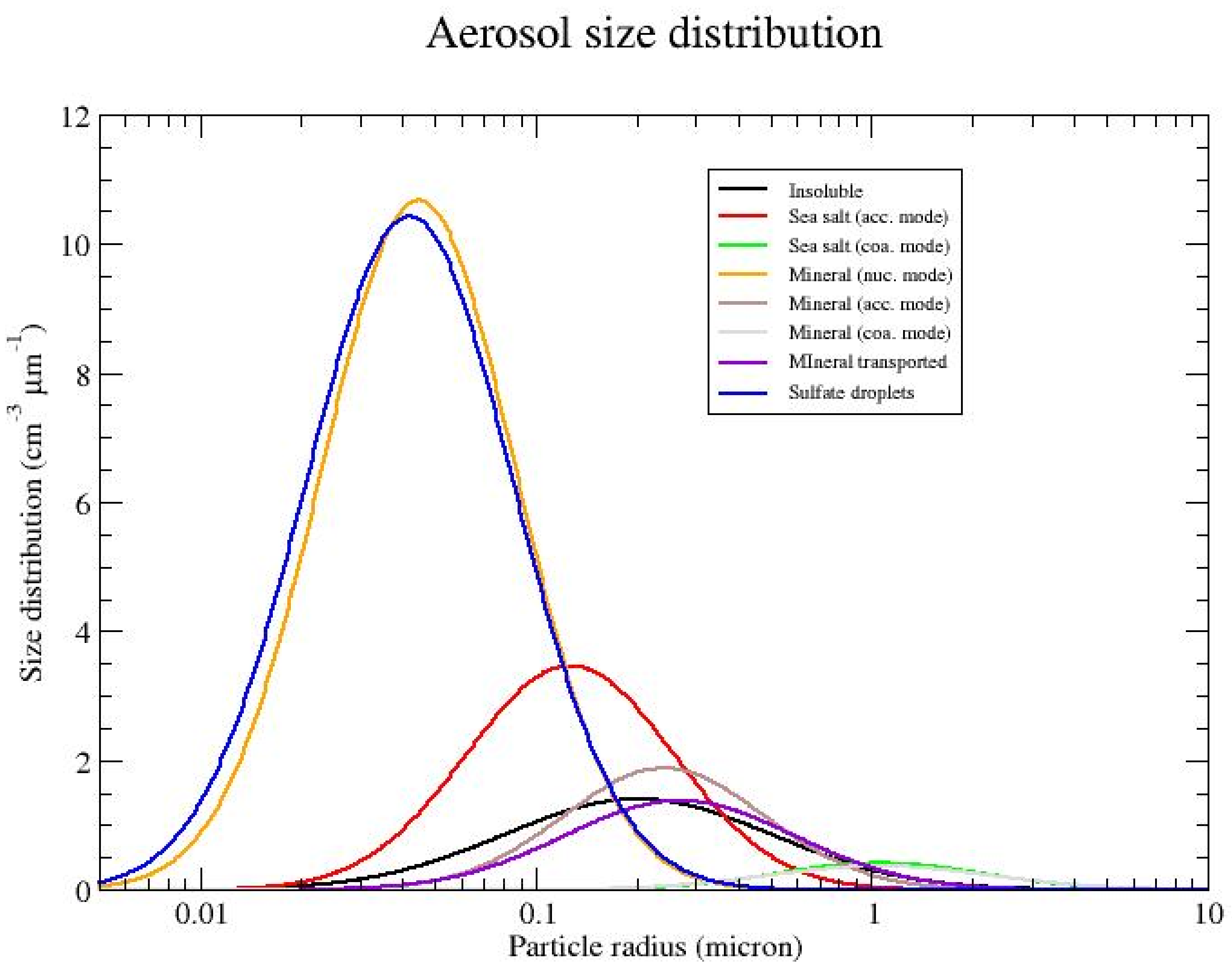
% The aerosols optical properties can be computed for any mixture of the default eleven components or, alternatively, for 10 aerosols types composed of pre-defined mixtures of basic components representative of average and extreme conditions for a range of climatological important aerosols.

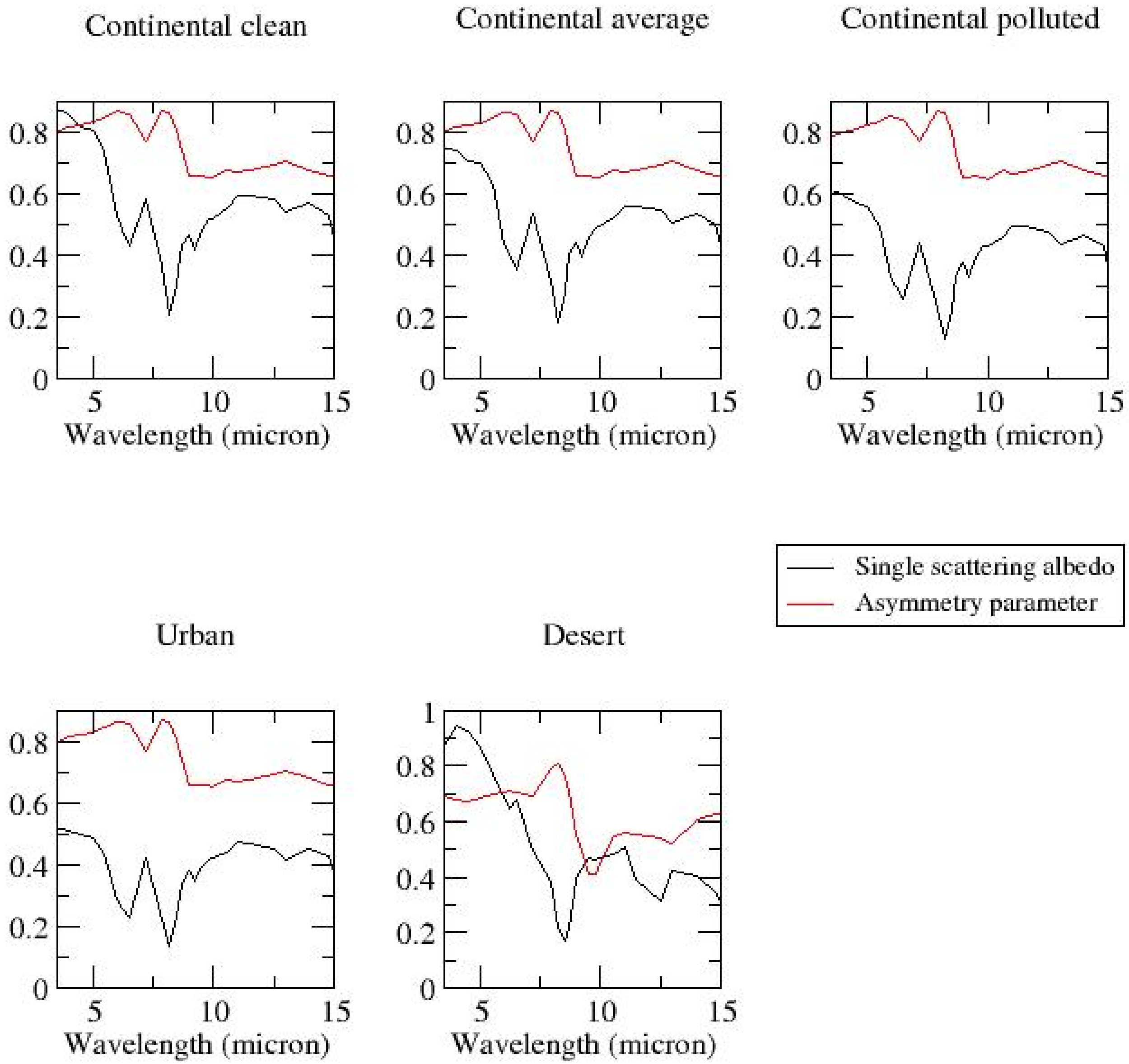
The aerosol components

- Insoluble
- Water-soluble
- Soot
- Sea salt (two modes)
- Mineral (three modes)
- Mineral-transported
- Sulfate droplets
- Volcanic ash

The aerosol types

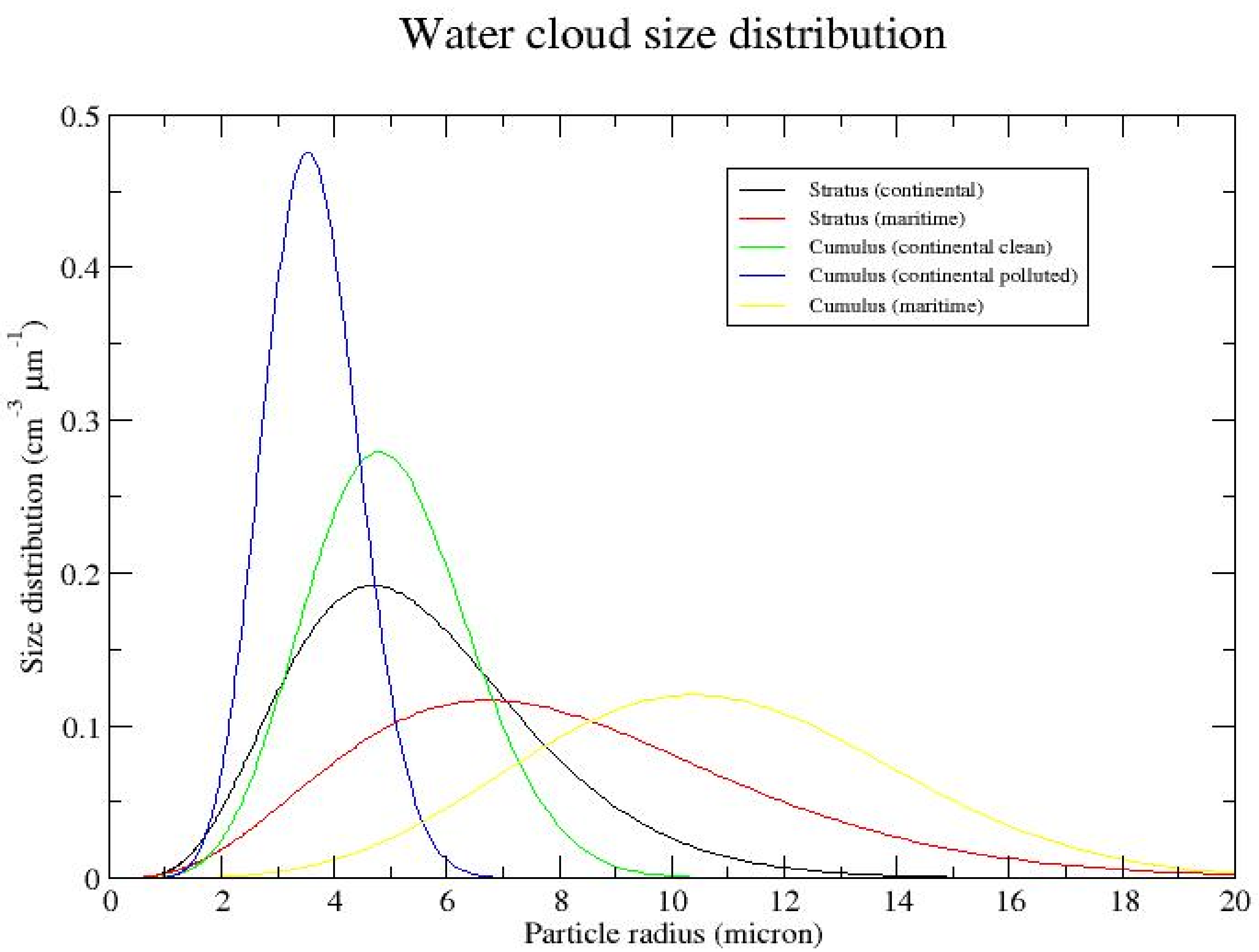
- Continental clean
- Continental average
- Continental polluted
- Urban
- Desert
- Maritime clean
- Maritime polluted
- Maritime tropical
- Arctic
- Antarctic

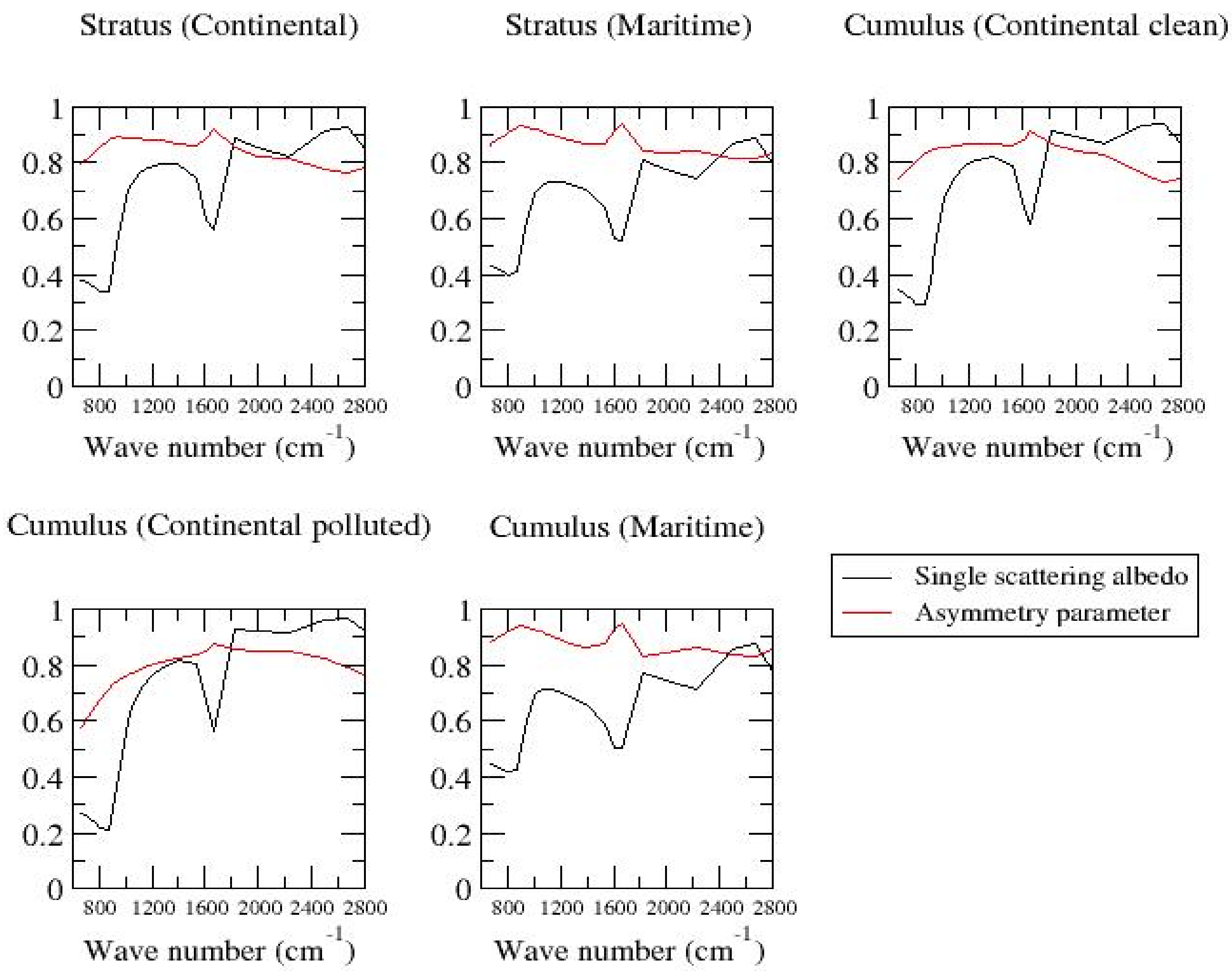

Aerosol size distribution
Size distribution (cm-3 µm-1)
Particle radius (micron)
0
2
4
6
8
10
12
0.01
0.1
1
10
Insoluble
Sea salt (acc. mode)
Sea salt (coa. mode)
Mineral (nuc. mode)
Mineral (acc. mode)
Mineral (coa. mode)
MIneral transported
Sulfate droplets


Continental clean
Continental average
Continental polluted
Urban
Desert
Wavelength (micron)
Single scattering albedo
Asymmetry parameter

% In RTIASI-5 optical properties for water clouds are available for any of the following cloud types:

	Effective radius (μm)	Liquid water content (g m^{-3})
→ Stratus (continental)	7.33	0.28
→ Stratus (maritime)	11.30	0.3
→ Cumulus (continental clean)	5.77	0.26
→ Cumulus (continental polluted)	4.00	0.3
→ Cumulus (maritime)	12.68	0.44


Water cloud size distribution
Stratus (continental)
Stratus (maritime)
Cumulus (continental clean)
Cumulus (continental polluted)
Cumulus (maritime)
Size distribution (cm^{-3} μm^{-1})
Particle radius (micron)
0
0.1
0.2
0.3
0.4
0.5
0
2
4
6
8
10
12
14
16
18
20



Stratus (Continental)
Stratus (Maritime)
Cumulus (Continental clean)
Cumulus (Continental polluted)
Cumulus (Maritime)
0
0.2
0.4
0.6
0.8
1
800 1200 1600 2000 2400 2800
Wave number (cm^{-1})
Single scattering albedo
Asymmetry parameter

% In RTIASI-5, cirrus clouds are considered to be made of hexagonal ice crystals randomly oriented in space. Optical properties are available for the eight Heymsfield and Platt size distributions.

Temperature range (K)	IWC (g m^{-3})	Effective size (µm)
-20 to -25	0.025	64.3
-25 to -30	0.026	59.3
-30 to -35	0.022	80.3
-35 to -40	0.028	59.6
-40 to -45	0.0051	29.7
-45 to -50	0.0026	30.0
-50 to -55	0.0027	22.1
-55 to -60	0.00071	39.0

% To better resolve the structure of the spectra we have discretized the size distribution into 24 bins. The midpoint crystal length varies from 4 µm to 3500 µm.

% 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 crystal length (µm)

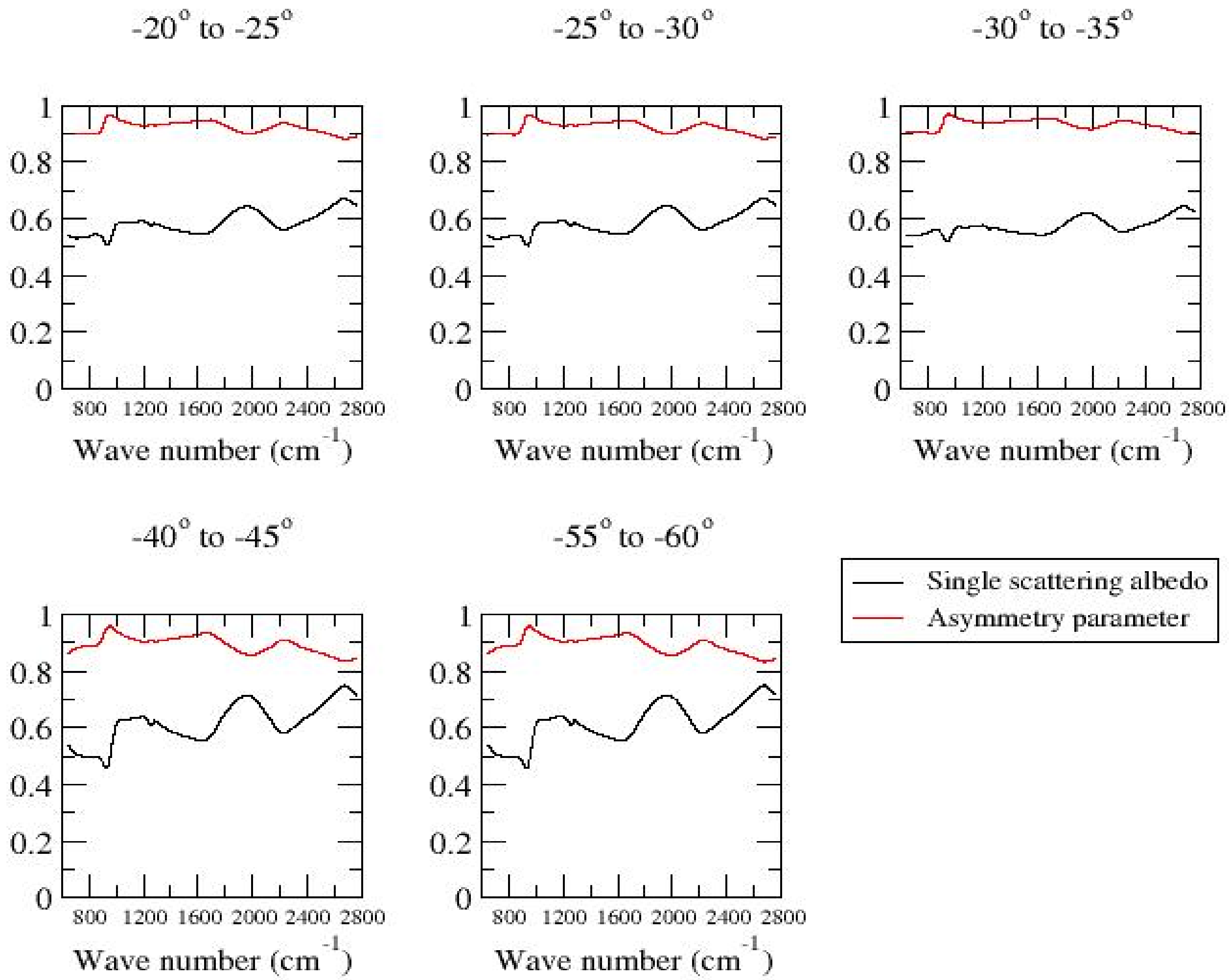
4	100	650
7.5	130	750
15	175	900
25	225	1150
35	275	1400
45	350	1750
60	450	2500
80	550	3500

The aspect ratio

$$\frac{D}{L} = \begin{cases} 1 & L \le 40\mu m \\ \exp(-0.017835(L-40)) & 40 < L \le 50\mu m \\ \frac{5.916}{\sqrt{L}} & L > 50\mu m \end{cases}$$

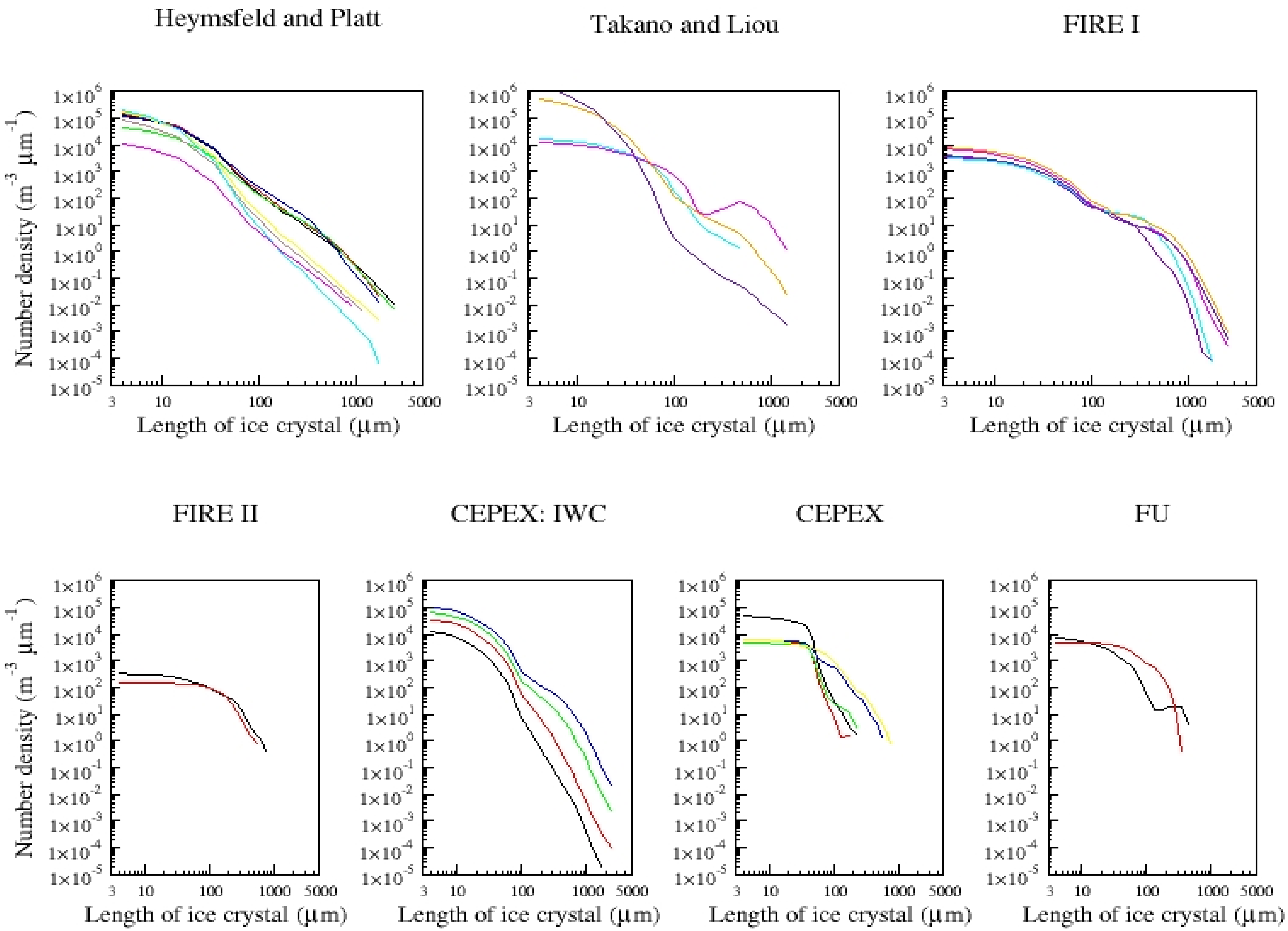
% A composite database of optical properties (i.e. absorption coefficient, scattering coefficient, backscatter parameter and phase function) for hexagonal ice crystals has been generated using the Geometric Optics (GO) method (Macke et al., 1996) for large crystals and the T-matrix method (Kahnert 2004) for small crystals.

Crystal length (μ)		
4	T-matrix	Whole spectrum
7.5	T-matrix	Whole spectrum
15	T-matrix	Whole spectrum
25	T-matrix	Whole spectrum
35	T-matrix	Whole spectrum
45	T-matrix	≥5μm
45	GO	<5μm
60	T-matrix	≥6μm
60	GO	<6μm
80	T-matrix	≥11μm
80	GO	<11μm
100	T-matrix	≥14μm
100	GO	<14μm
130	GO	Whole spectrum


-20° to -25°
-25° to -30°
-30° to -35°
-40° to -45°
-55° to -60°
Wave number (cm⁻¹)
800 1200 1600 2000 2400 2800
0 0.2 0.4 0.6 0.8 1
Single scattering albedo
Asymmetry parameter

% It is envisaged that when RTIASI is merged into RTTOV, optical properties will also be available for ice crystals made of randomly oriented ice aggregates (Baran 2003).

% In addition, the eight size distributions by Heymsfeild and Platt will be complemented by the size distributions prepared by Fu (1996).


Heymsfeld and Platt
Takano and Liou
FIRE I
FIRE II
CEPEX: IWC
CEPEX
FU
Number density (m^{-3} µm^{-1})
Length of ice crystal (µm)
1x10^{6}
1x10^{5}
1x10^{4}
1x10^{3}
1x10^{2}
1x10^{1}
1x10^{0}
1x10^{-1}
1x10^{-2}
1x10^{-3}
1x10^{-4}
1x10^{-5}
3
10
100
1000
5000

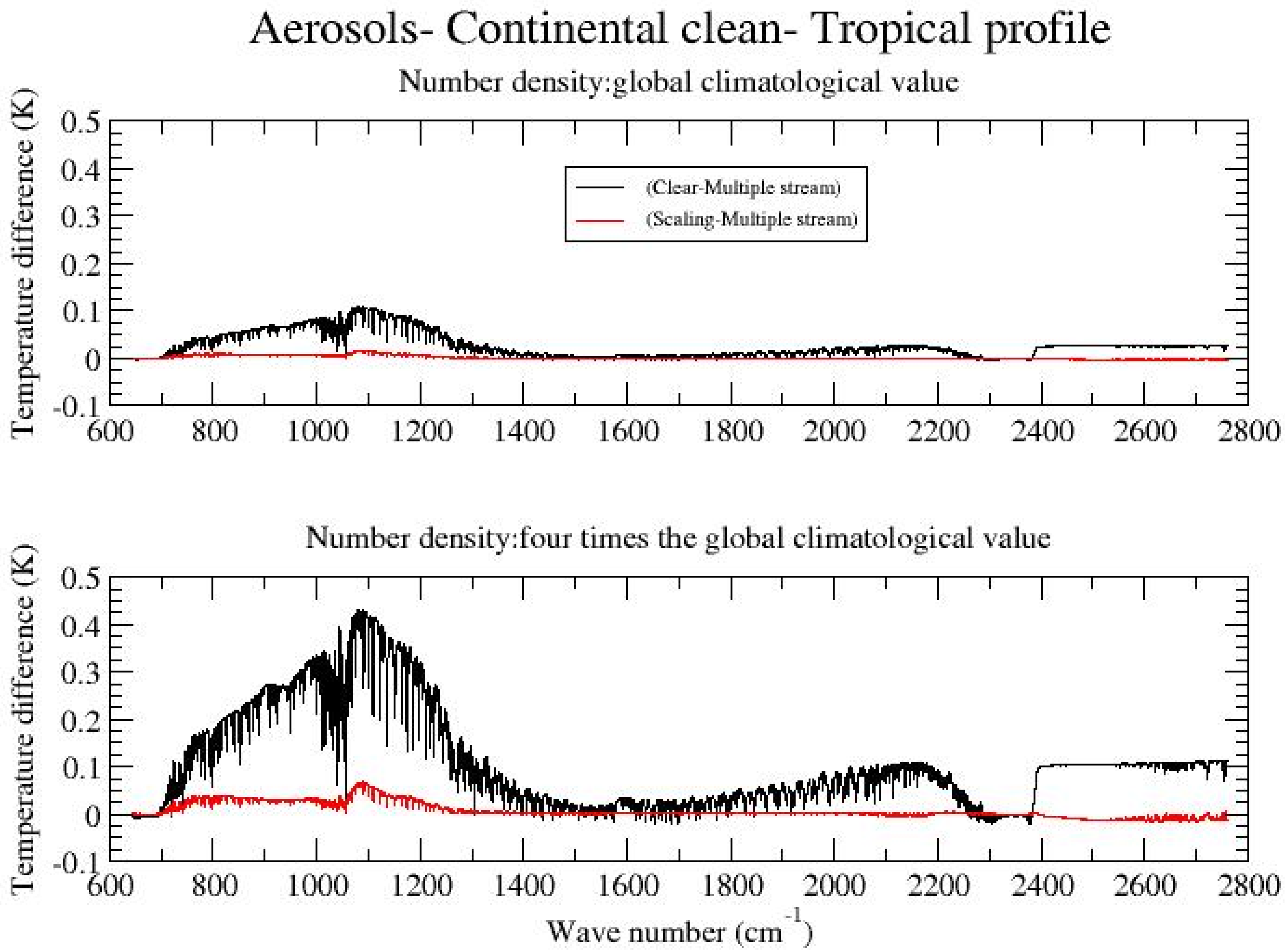
.

% The optical properties used by default in RTIASI-5 for aerosols, water clouds and cirrus clouds, have been obtained on the basis of microphysical properties that, given their highly variable nature, do not necessarily reflect an actual situation. For this reason, RTIASI-5 allows the user to externally specify the values of the optical properties used in the radiative transfer.

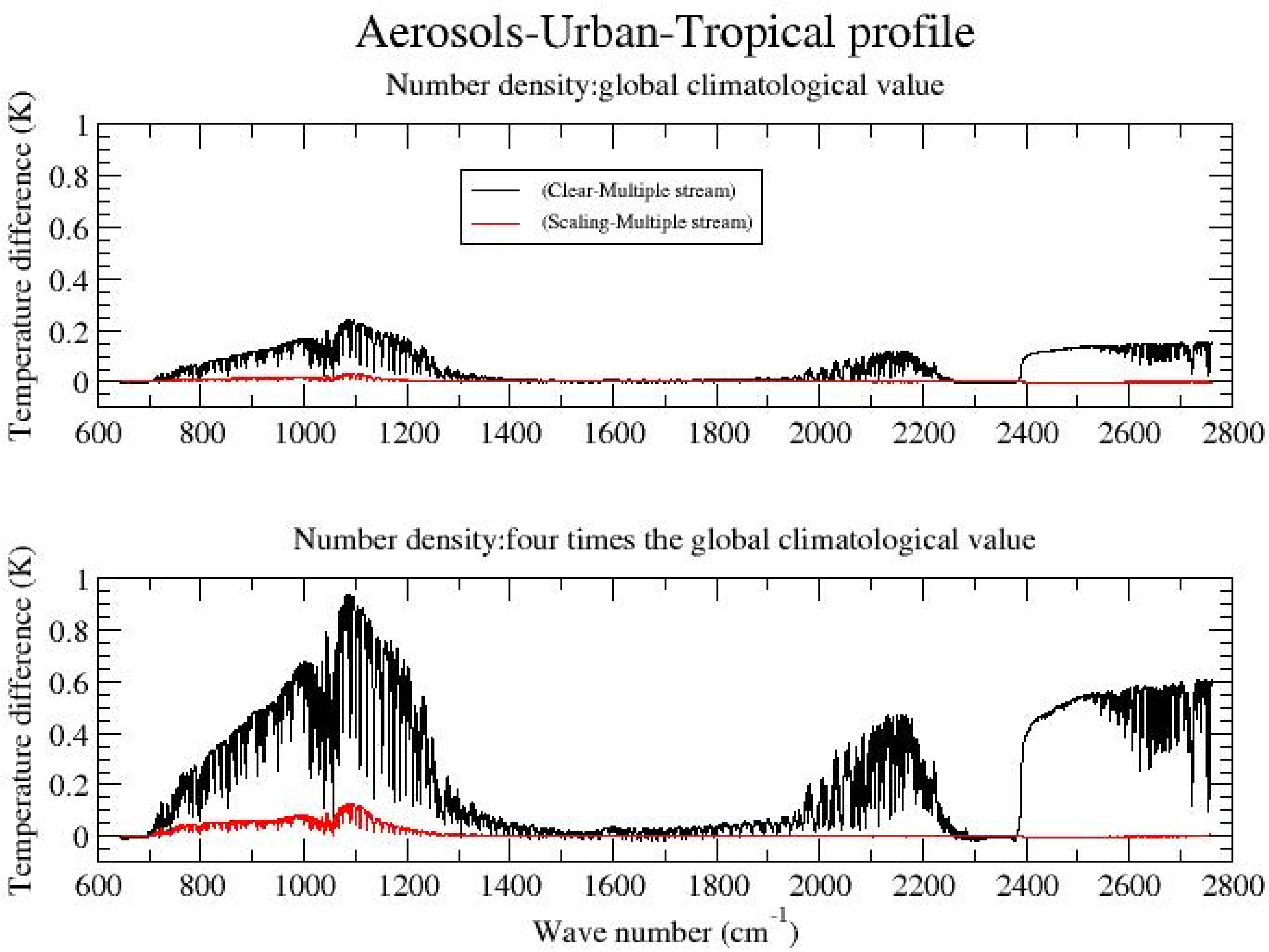
% To asses the accuracy of the scaling approximation we have compared approximate radiances with reference radiances computed by using a doubling-adding algorithm.

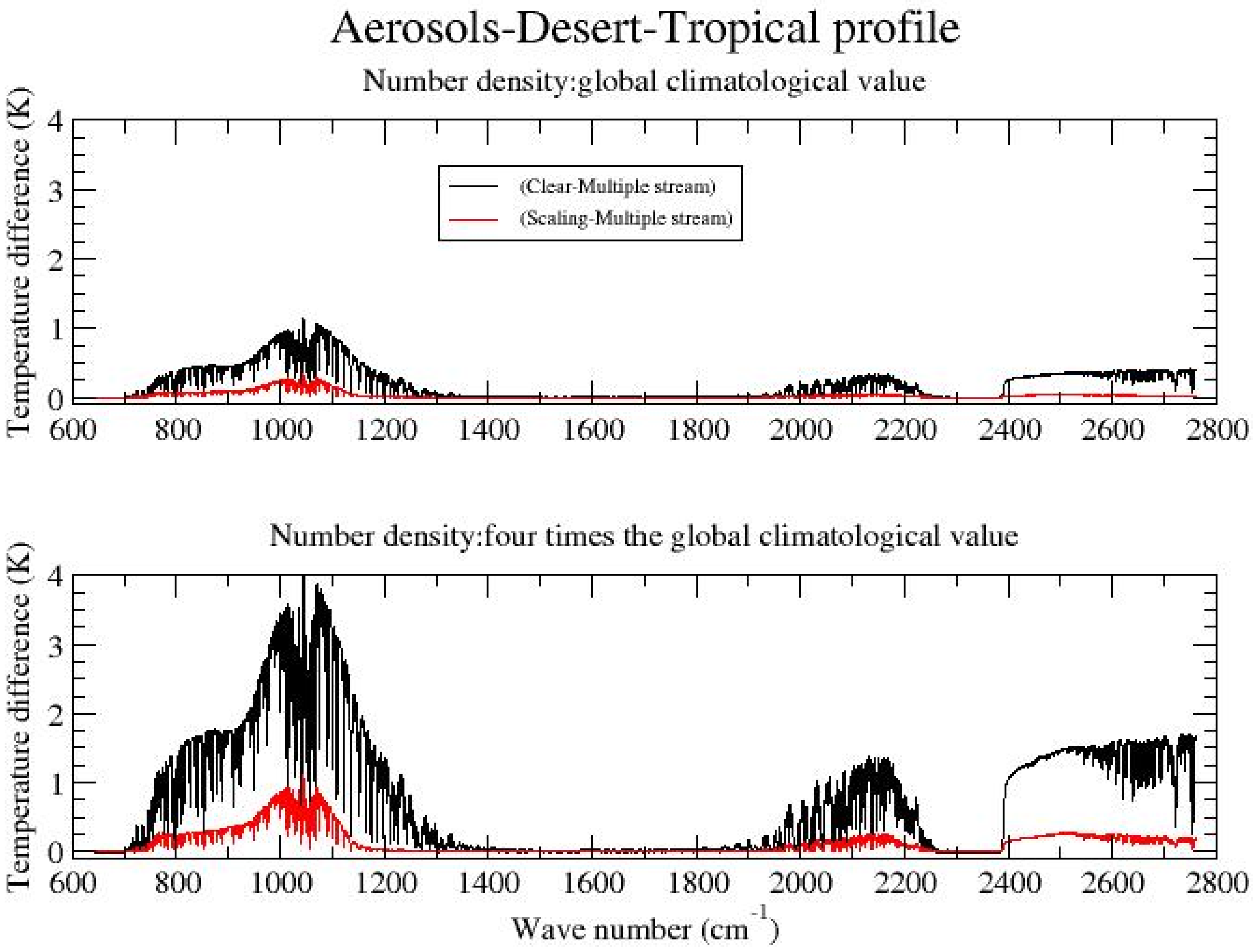
→ For water clouds, errors are typically less than 1K in the thermal infrared and less than 4K in the short wave (the inclusion of a water cloud can result in a reduction of the top of the atmosphere radiance by 30K in the thermal infrared and by 40K in the short wave).

→ 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 below 0.1K.

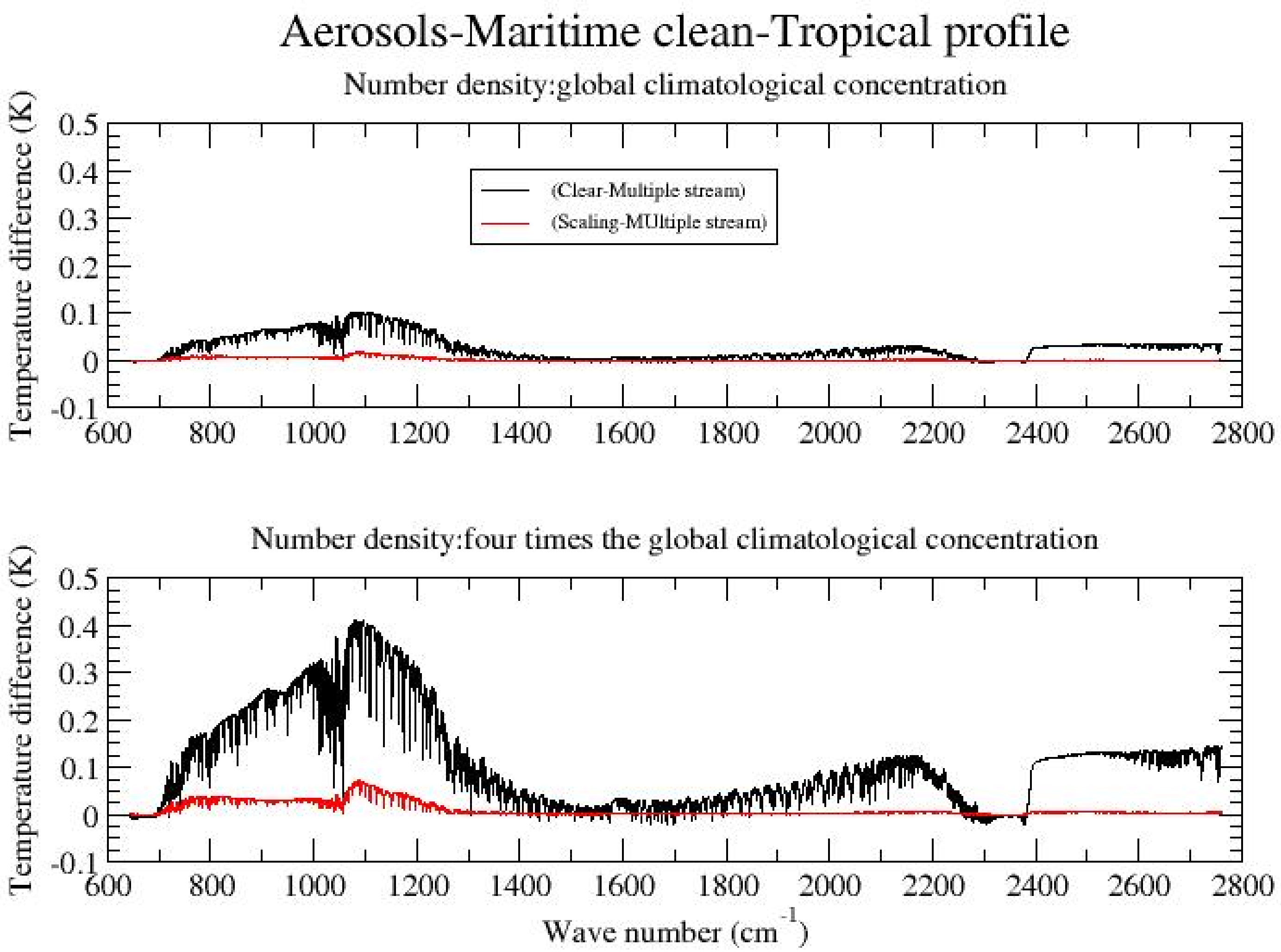


Aerosols- Continental clean- Tropical profile
Number density:global climatological value
Temperature difference (K)
(Clear-Multiple stream)
(Scaling-Multiple stream)
0.5
0.4
0.3
0.2
0.1
0
-0.1
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
Number density:four times the global climatological value
Temperature difference (K)
Wave number (cm-1)

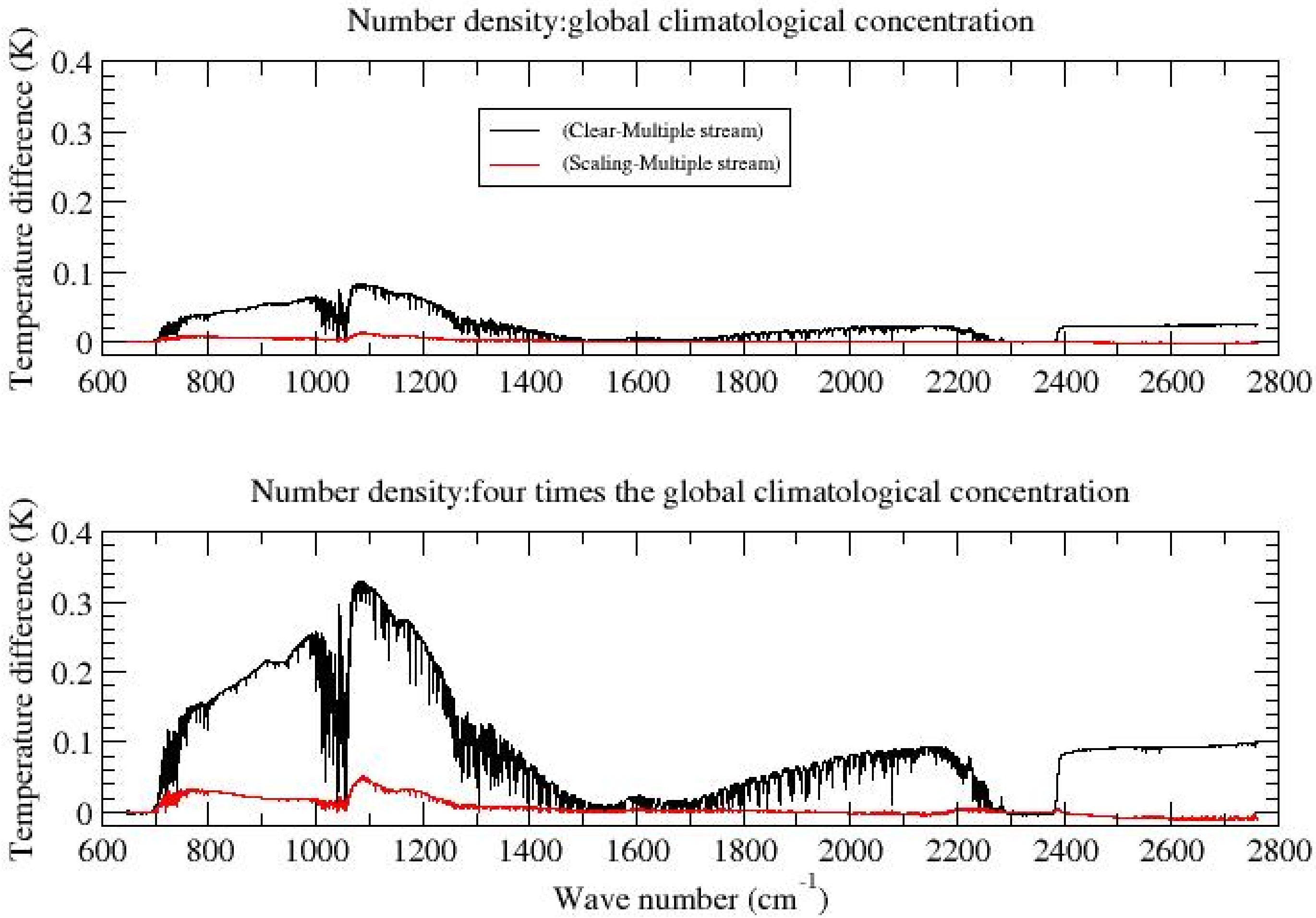

Aerosols-Urban-Tropical profile
Number density:global climatological value
Temperature difference (K)
1
0.8
0.6
0.4
0.2
0
(Clear-Multiple stream)
(Scaling-Multiple stream)
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
Number density:four times the global climatological value
Temperature difference (K)
Wave number (cm-1)



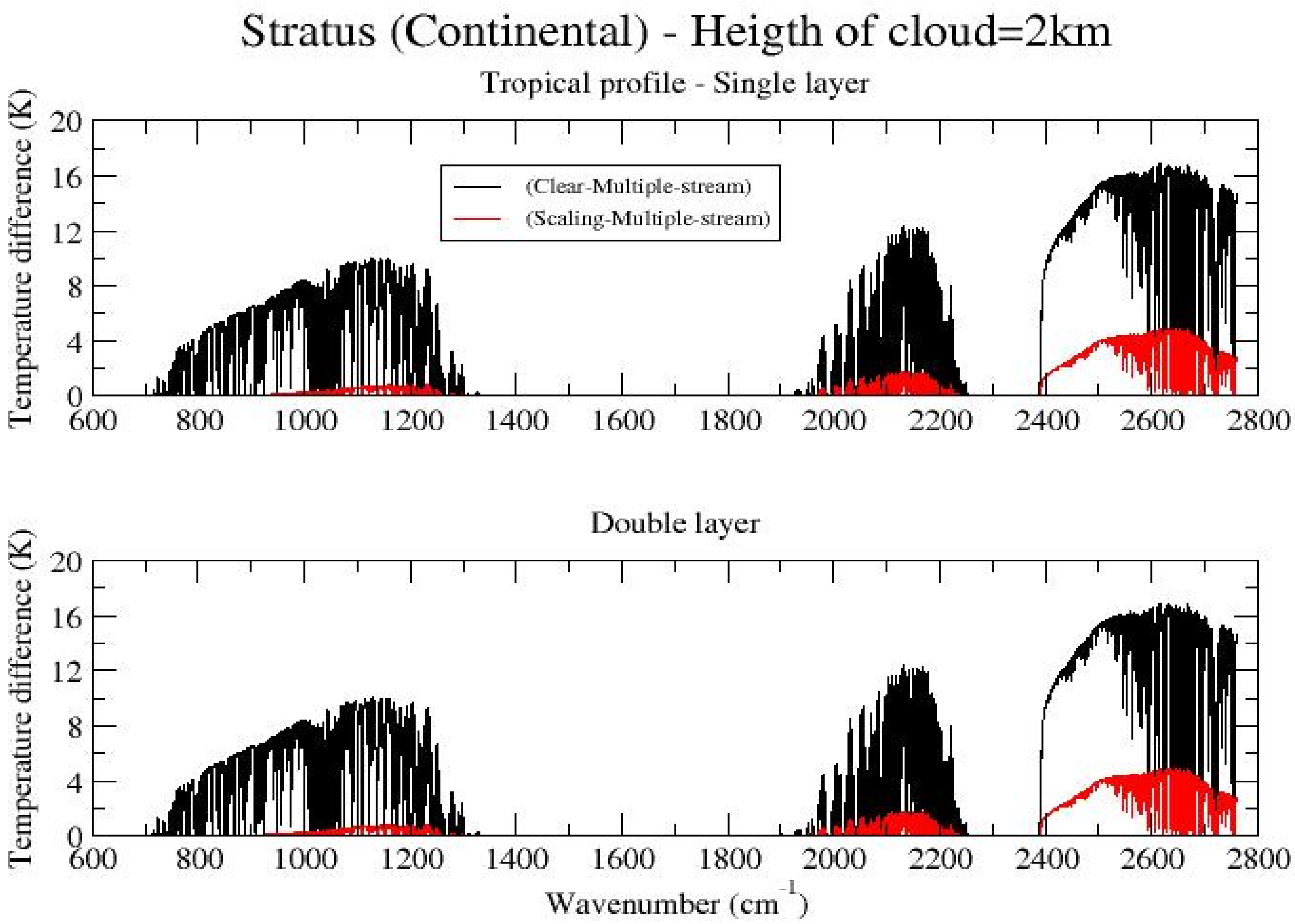
Aerosols-Desert-Tropical profile
Number density:global climatological value
(Clear-Multiple stream)
(Scaling-Multiple stream)
Temperature difference (K)
Number density:four times the global climatological value
Temperature difference (K)
Wave number (cm^{-1})

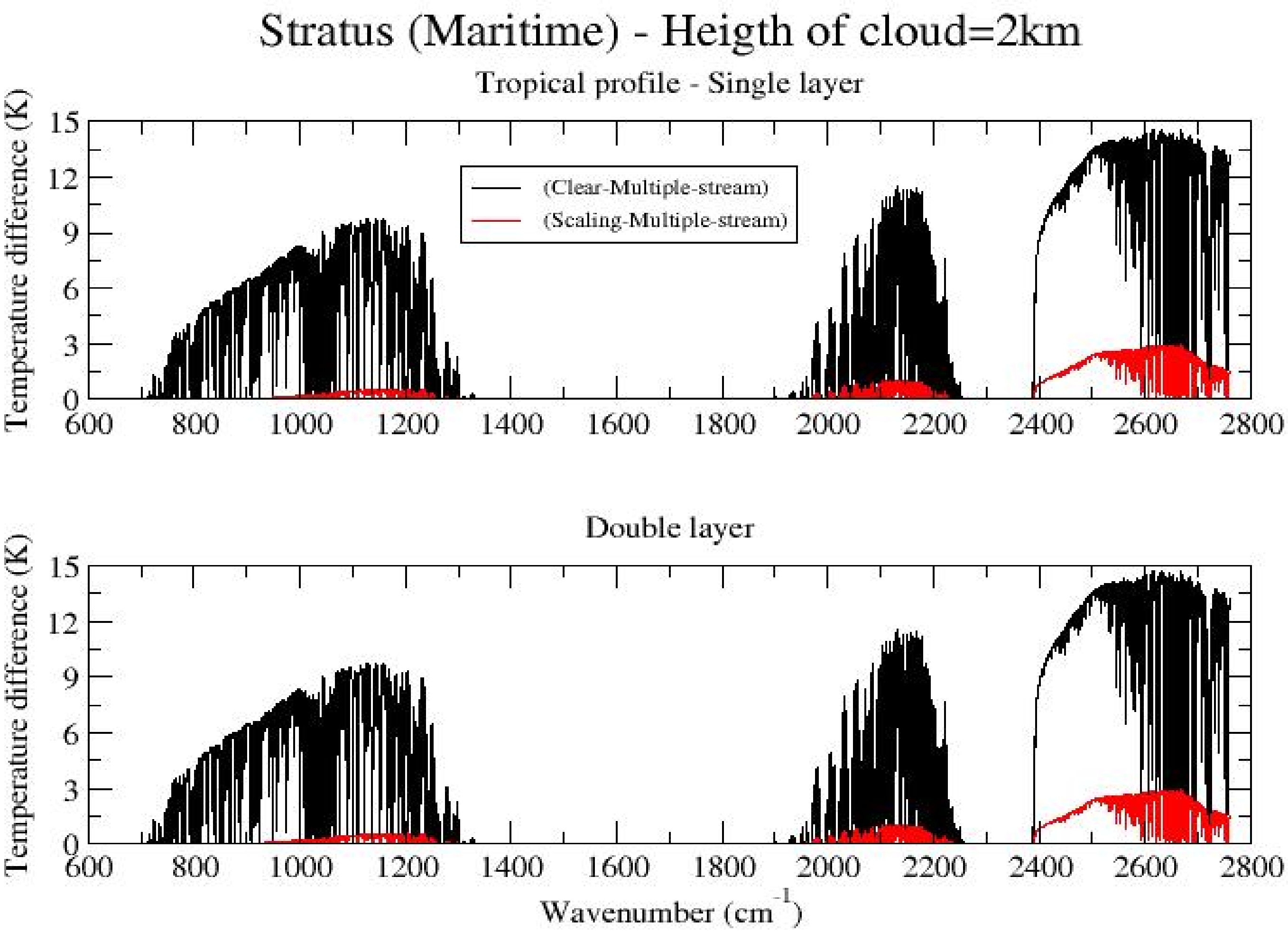

Aerosols-Maritime clean-Tropical profile
Number density:global climatological concentration
Temperature difference (K)
(Clear-Multiple stream)
(Scaling-MUltiple stream)
0.5
0.4
0.3
0.2
0.1
0
-0.1
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
Number density:four times the global climatological concentration
Temperature difference (K)
Wave number (cm^{-1})

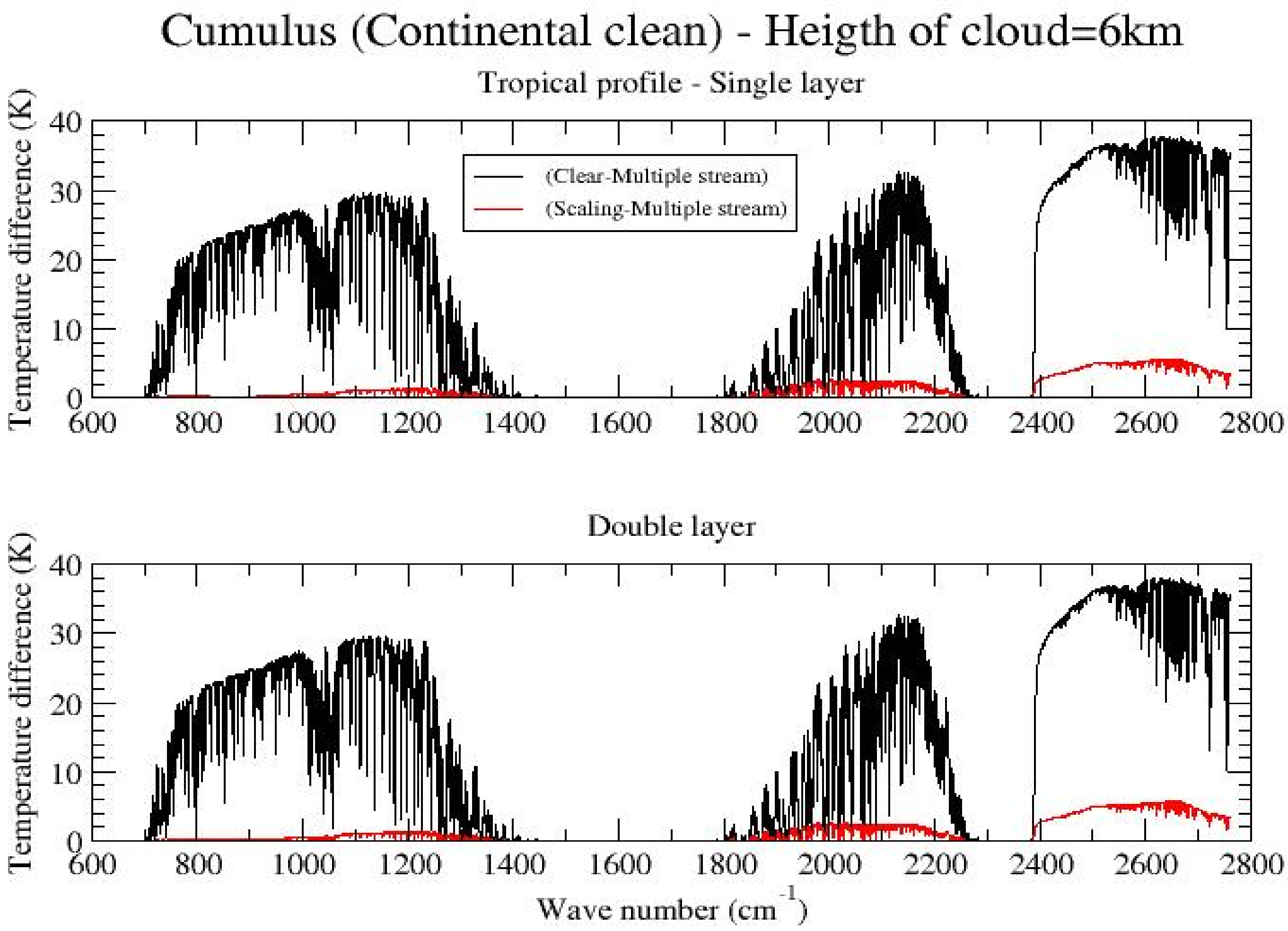
Aerosols-Artic-Arctic profile



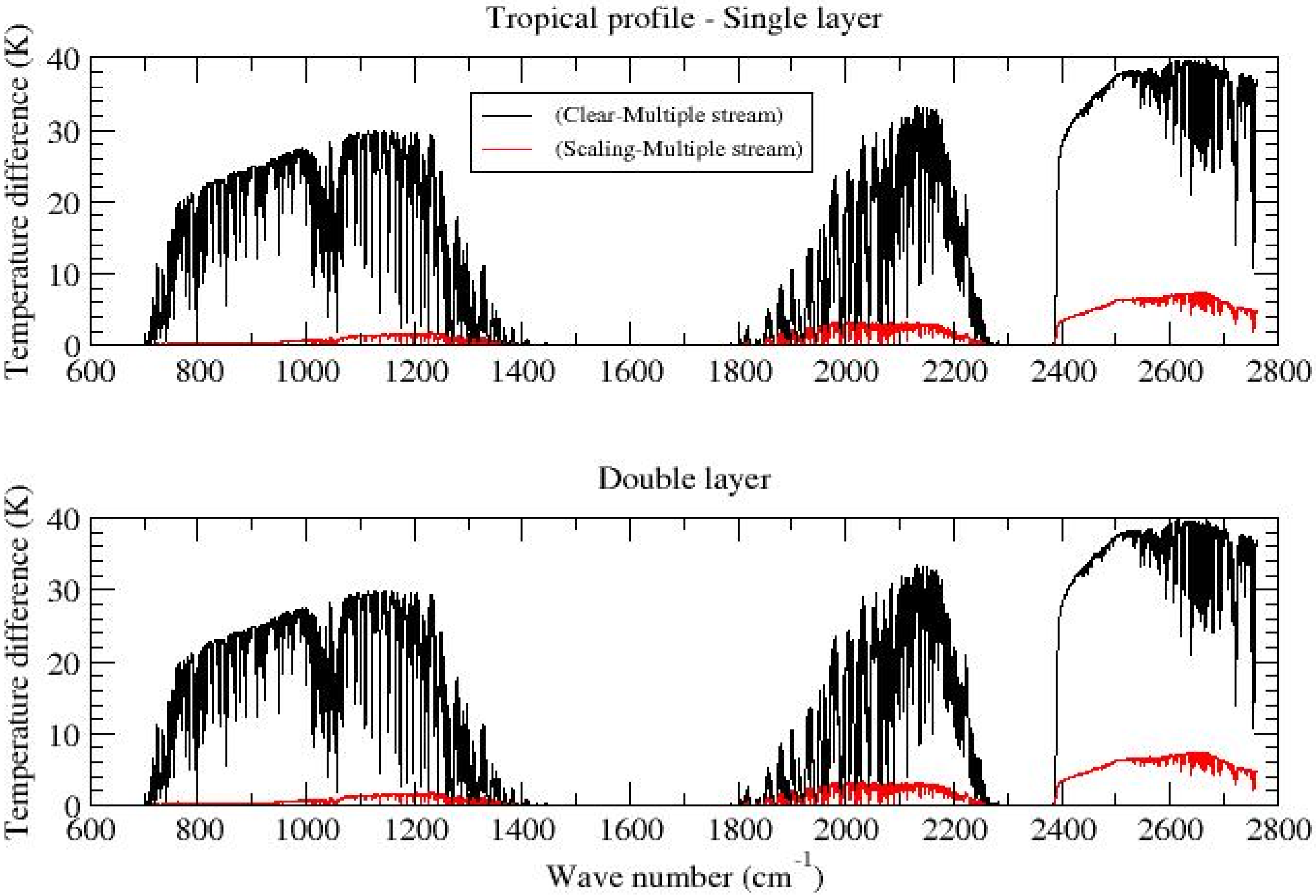
ECMWF

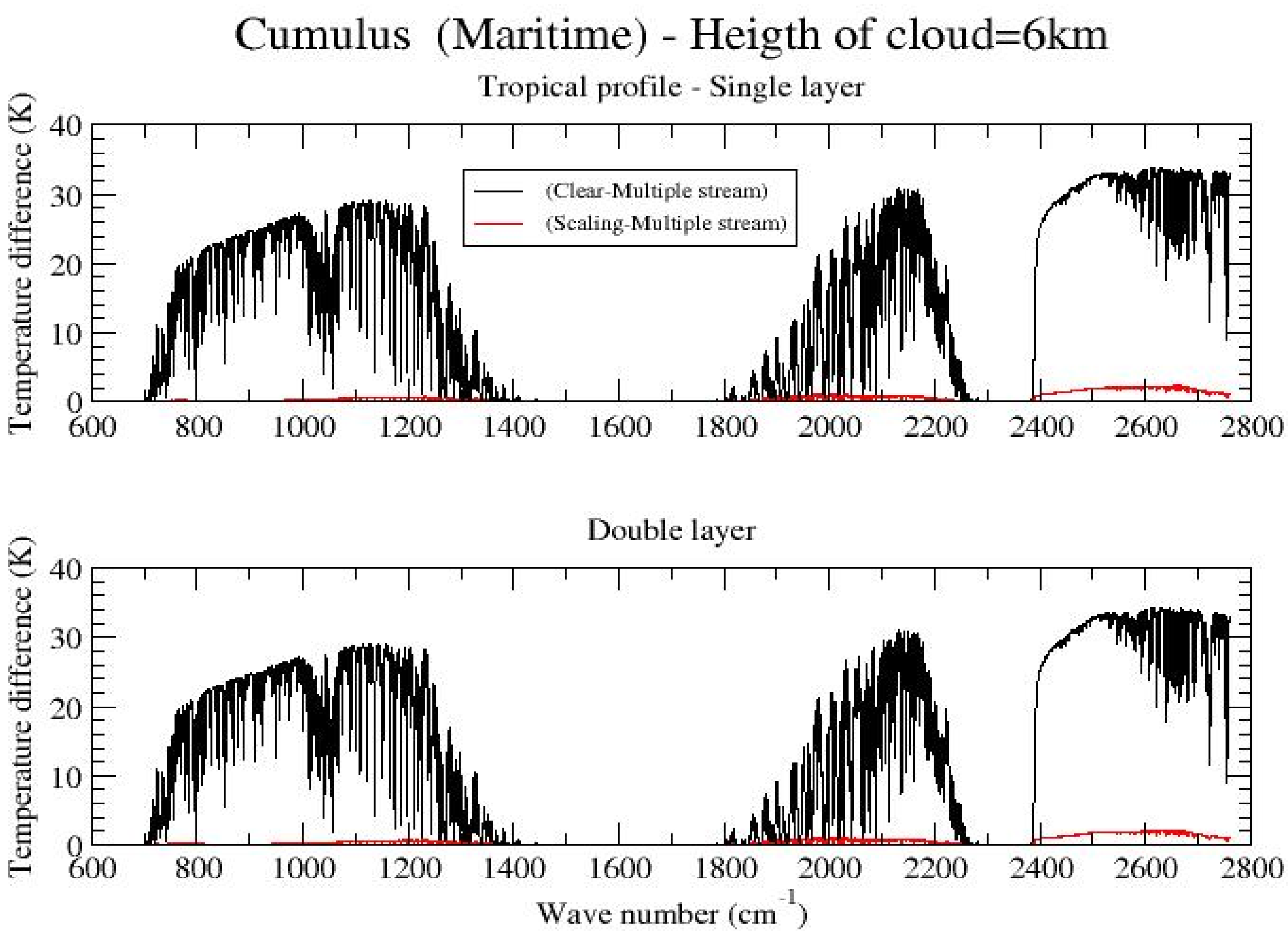

Stratus (Continental) - Heigth of cloud=2km
Tropical profile - Single layer
(Clear-Multiple-stream)
(Scaling-Multiple-stream)
Temperature difference (K)
Double layer
Wavenumber (cm-1)
0
4
8
12
16
20
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800


Stratus (Maritime) - Heigth of cloud=2km
Tropical profile - Single layer
Temperature difference (K)
(Clear-Multiple-stream)
(Scaling-Multiple-stream)
Double layer
Temperature difference (K)
Wavenumber (cm-1)
0
3
6
9
12
15
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800

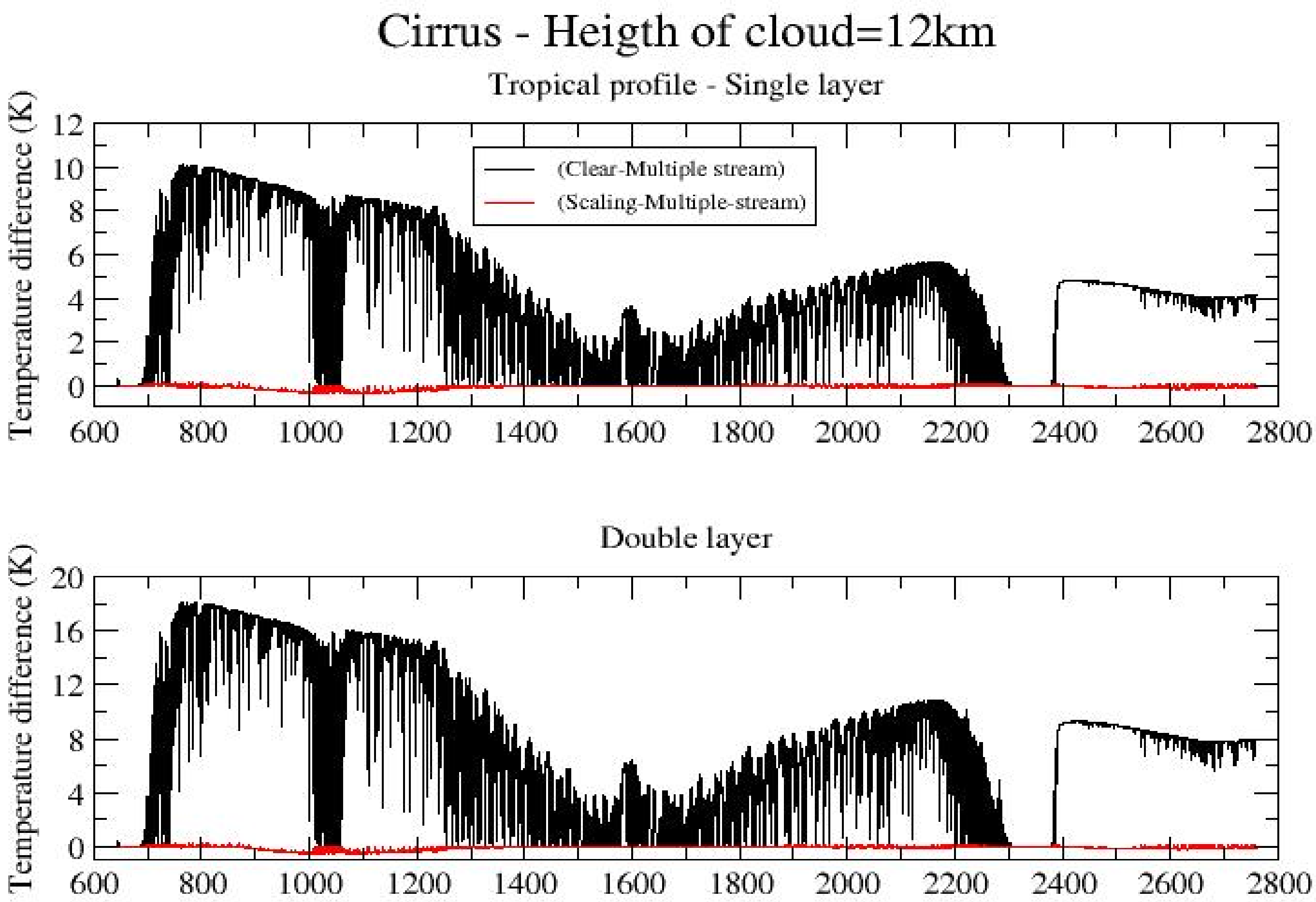

Cumulus (Continental clean) - Heigth of cloud=6km
Tropical profile - Single layer
(Clear-Multiple stream)
(Scaling-Multiple stream)
Temperature difference (K)
0
10
20
30
40
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
Double layer
Temperature difference (K)
Wave number (cm -1)

Cumulus (Continental polluted) - Heigth of cloud=6km

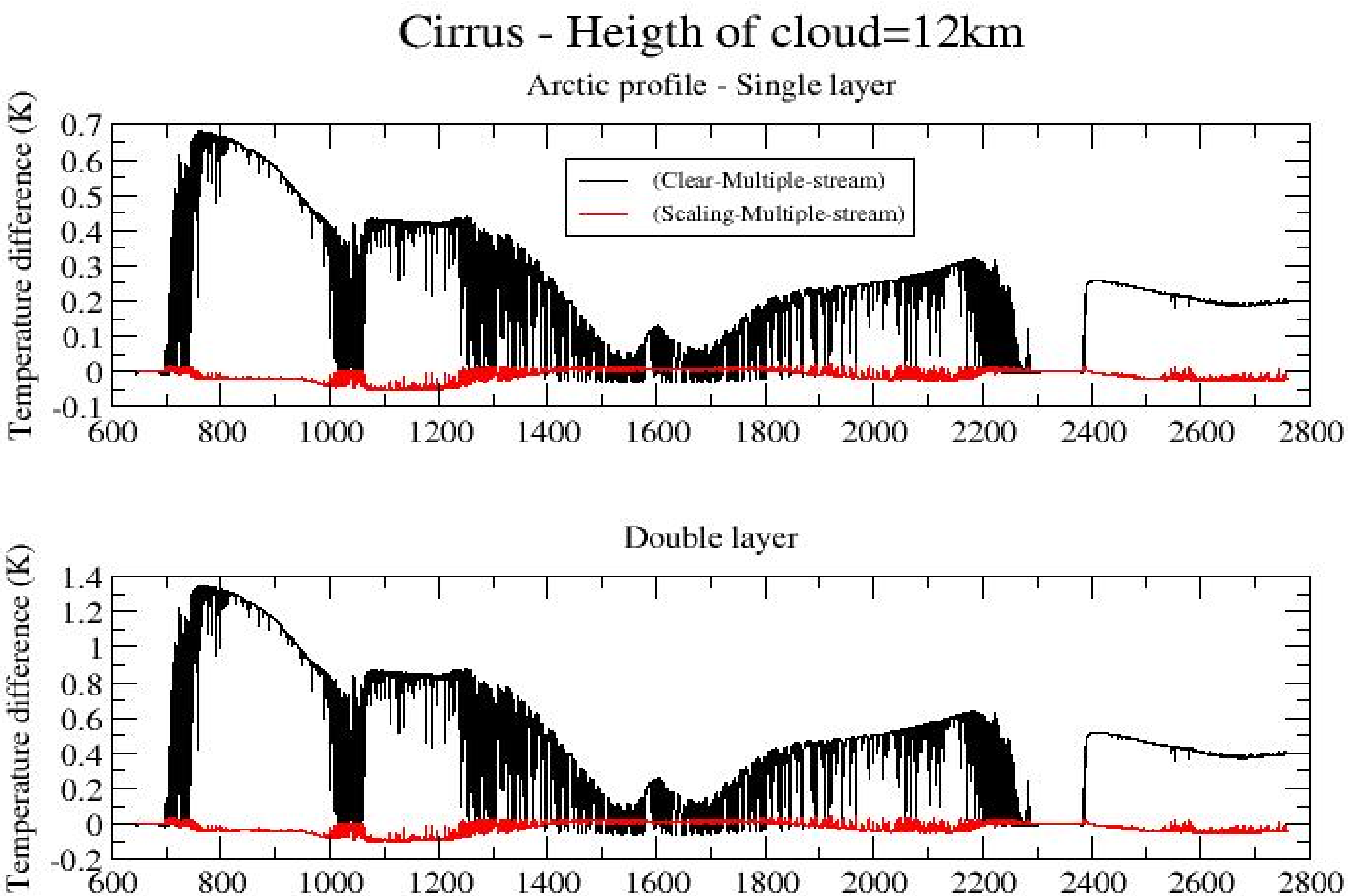


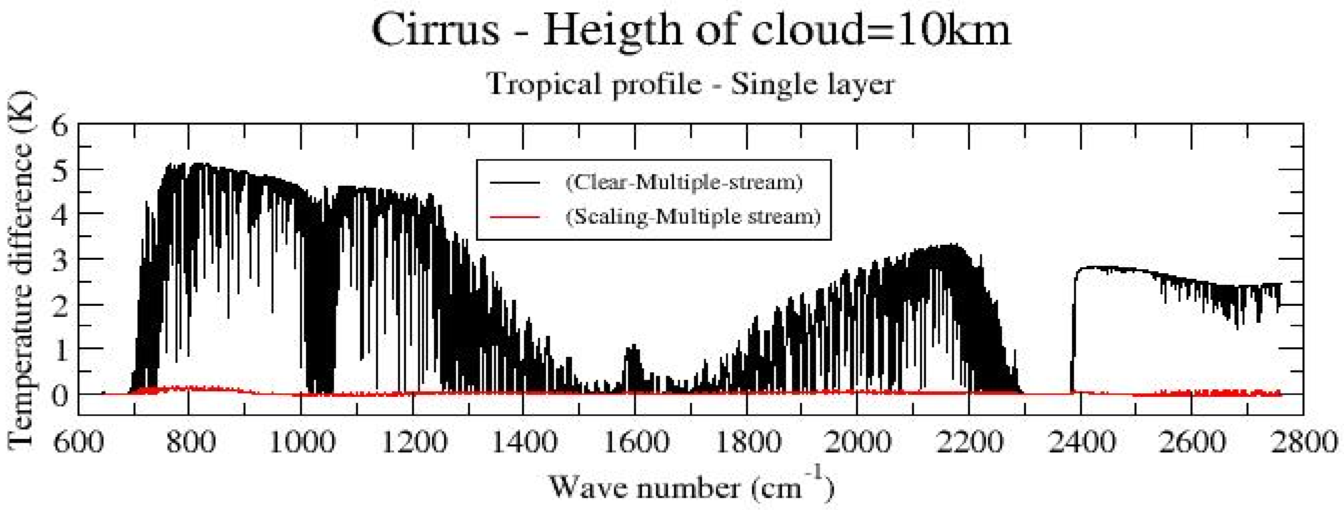

Cumulus (Maritime) - Heigth of cloud=6km
Tropical profile - Single layer
(Clear-Multiple stream)
(Scaling-Multiple stream)
Temperature difference (K)
Double layer
Wave number (cm -1)

ECMWF

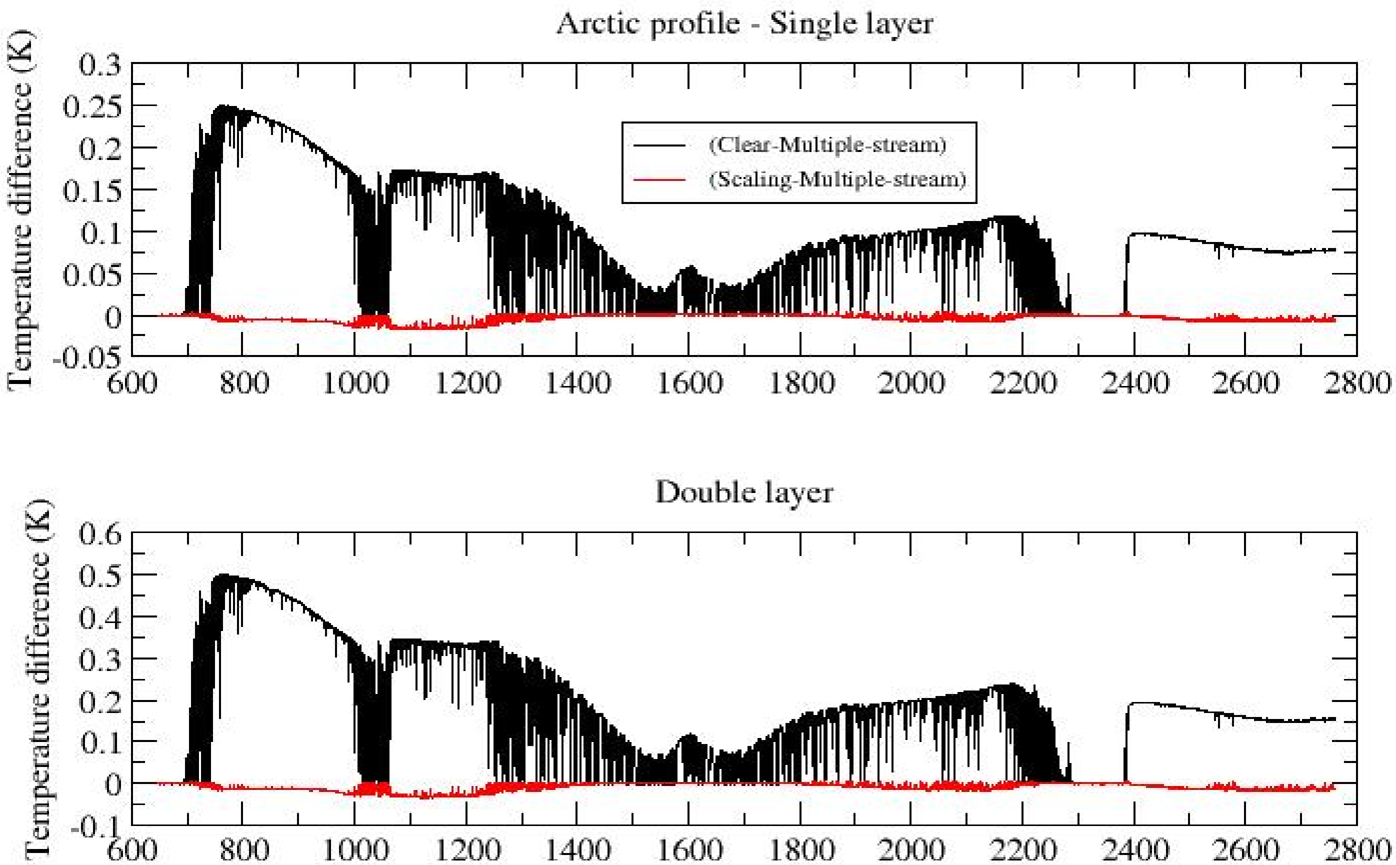


Cirrus - Heigth of cloud=12km
Tropical profile - Single layer
Temperature difference (K)
(Clear-Multiple stream)
(Scaling-Multiple-stream)
Double layer
Temperature difference (K)
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800


Cirrus - Heigth of cloud=12km
Arctic profile - Single layer
Temperature difference (K)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
(Clear-Multiple-stream)
(Scaling-Multiple-stream)
Double layer
Temperature difference (K)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800

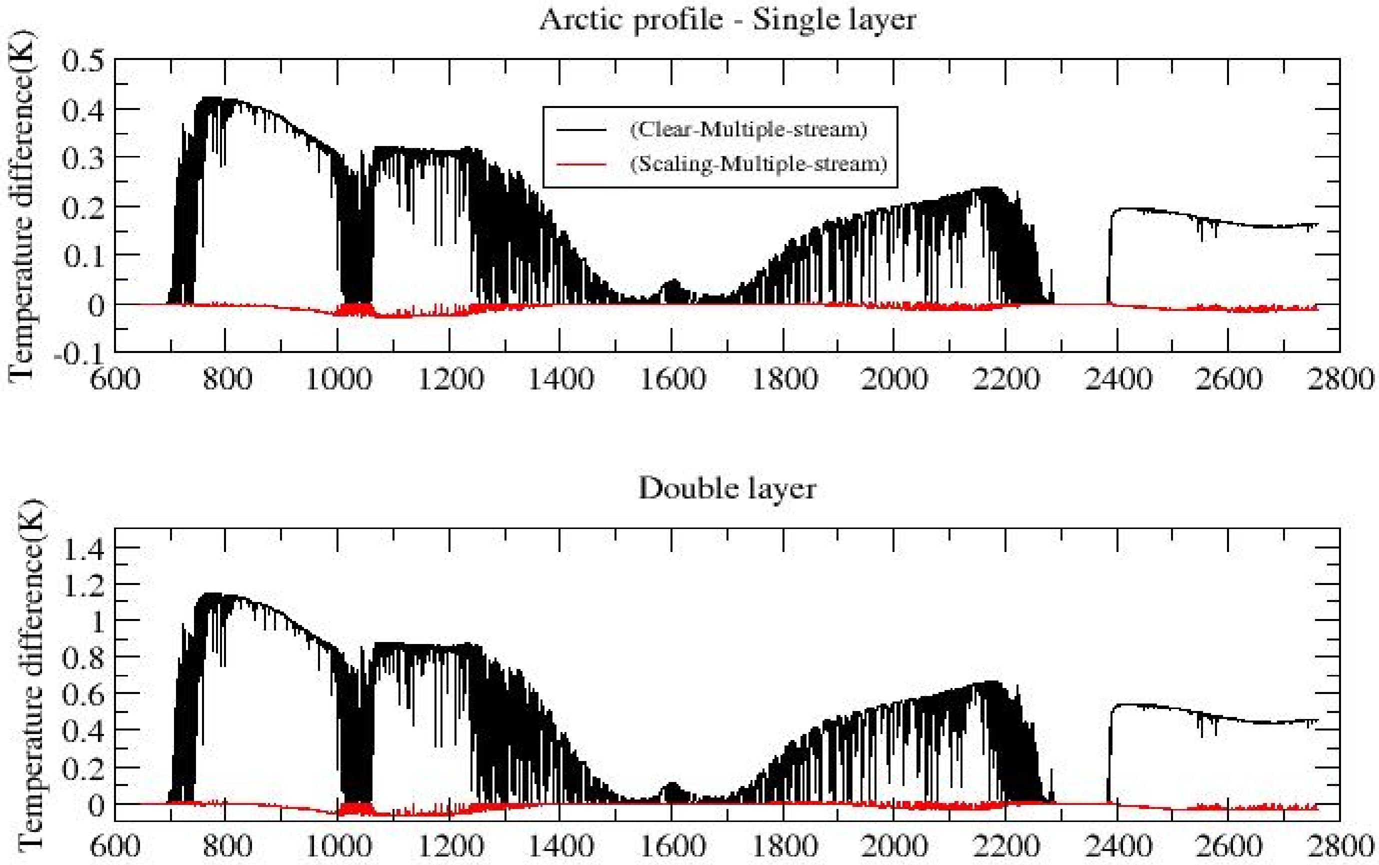

Cirrus - Heigth of cloud=10km
Tropical profile - Single layer
Temperature difference (K)
Wave number (cm-1)
(Clear-Multiple-stream)
(Scaling-Multiple stream)
0
1
2
3
4
5
6
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800

Cirrus - Heigth of cloud=10km



ECMWF

Cirrus- Heigth of cloud=7km



% To solve the radiative transfer for a partly cloudy atmosphere (i.e. horizontally non-homogeneous) RTIASI-5 features a scheme, stream method,) that divides the field of view (FOV) 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.

→ Alternative implementations of the stream method have been presented in Amorati and Rizzi (2002) and Räisänen et al.(2004).

% Despite being potentially more accurate than the widely used approach of reducing a partly cloudy layer to an equivalent homogeneous layer, the stream method has seldom been exploited since depending on the number of layers and the overlapping assumption, the number of column can become so large that is impractical to use when lower order approximations (e.g two stream method) are used for multiple scattering.

→ However, given the nature of the multiple scattering parameterization used in RTIASI-5, the computational burden of the stream method is only a fraction of the total and consequently we have implemented it in RTIASI.

The number of columns depends on the cloud overlapping assumption (maximum-random in RTIASI-5) and the total radiance is obtained as the sum of the radiances from the single columns weighted by the column fractional coverage:

$$L^{total} = \left\{ \sum_{s=1}^{n_c} L^{overcast} (X_{s+1} - X_s) \right\} + L^{clear} (1 - X_{n_c+1})$$