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A new version of RTIASI (Matricardi 2003), 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 effect of backward scattering in the emission of a layer and in the transmission between levels (scaling approximation, Chou *et al.* (1999)).

Since the scaling approximation does not require explicit calculations of multiple scattering, the computational efficiency of RTIASI can be retained. In fact, the radiative transfer equation for multiple scattering is identical to that in clear sky conditions: the absorption optical depth, τ_a , is replaced by the effective extinction optical depth, $\tilde{\tau}_e$, defined as

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

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. If $\bar{P}(\mu, \mu')$ is the azimuthally averaged phase function, the scaling factor b can be written in the form

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

It should be noted that the scaling approximation rests on the hypothesis that the diffuse radiance field is isotropic and can be approximated by the Planck function.

The RTIASI radiative transfer can include by default eleven basic 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 taking the microphysical properties assembled 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 ten aerosol types composed of pre-defined mixtures of basic components representative of average and extreme conditions for a range of climatological important aerosols. For cirrus clouds, a composite database has been generated using the Geometric Optics method for large crystals and the T-matrix method for small crystals. The publicly available codes developed by Macke *et al.* (1996) and Kahnert (2004) have been used respectively. In either case, ice crystals have been assumed to have the shape of a hexagonal prism randomly oriented in space. For cirrus clouds we have used the Heymsfield and Platt (1984) size distribution. To account for the radiative effects due to the presence of small crystals, the Heymsfield and Platt distribution has been extrapolated to 4 μm using the method described in Mitchell *et al.* (1996). For all the aerosol components and cloud types included by default in RTIASI, the optical properties have been obtained based on microphysical properties that, given their highly variable nature, do not necessarily reflect an actual situation. For this reason, RTIASI allows the user to externally specify the values of the optical properties used in the radiative transfer. In figure 1 we have plotted the absorption, scattering and extinction coefficient for the five most significant (in radiative terms) aerosol types. The same optical properties for the five water clouds included in RTIASI are illustrated in figure 2 whereas for cirrus clouds they are plotted in figure 3 where a selection of different temperature ranges has been chosen.

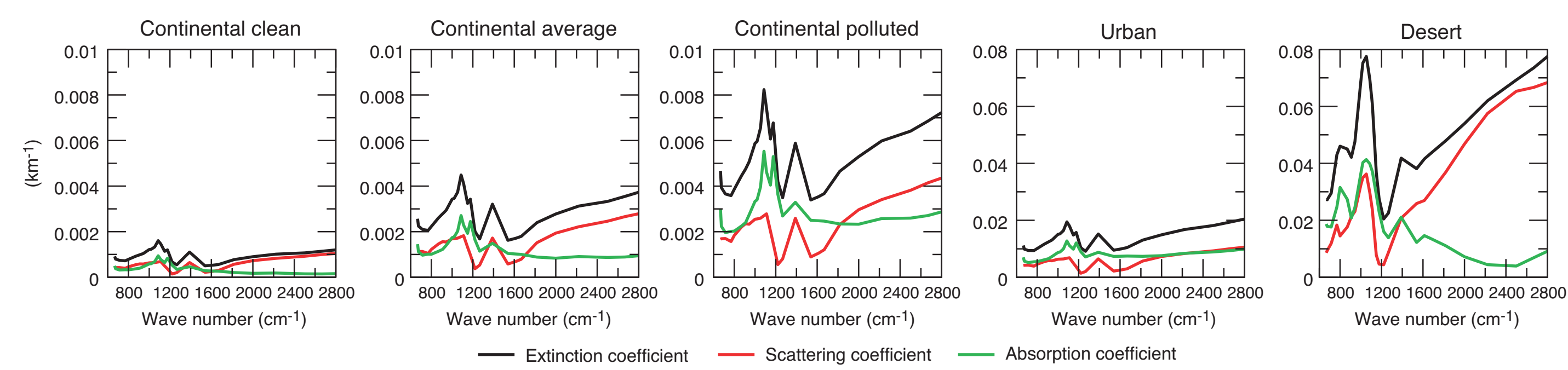


Figure 1 The absorption, scattering and extinction coefficient for five of the aerosol types included in RTIASI-5.

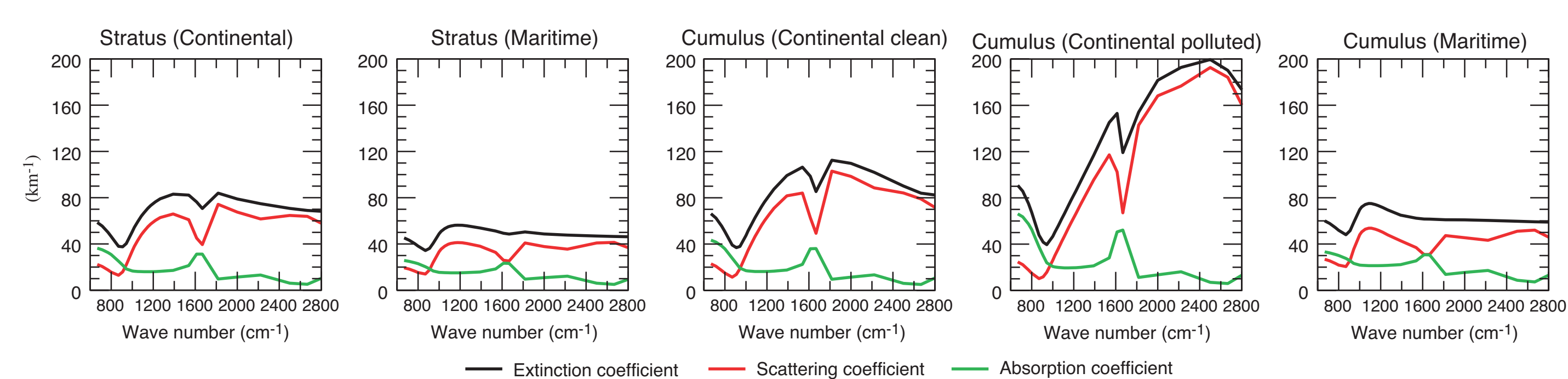


Figure 2 The absorption, scattering and extinction coefficient for the five water cloud types included in RTIASI-5.

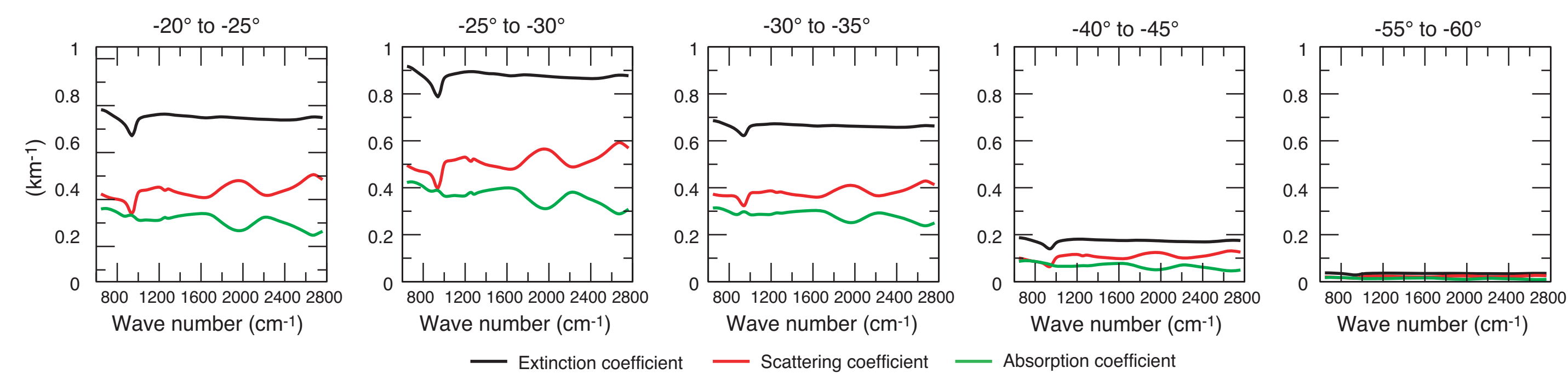


Figure 3 The absorption, scattering and extinction coefficient for a selected number of cirrus cloud types included in RTIASI-5.

References

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To solve the radiative transfer for a partly cloudy atmosphere (i.e. horizontally non-homogeneous), RTIASI uses a scheme (stream method, Amorati and Rizzi 2002) that divides the atmosphere 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 illustrate the stream method, we give here an example where a seven layer atmosphere is considered. Once the cloud fractional coverage in each layer is known (CFR in figure 4), we compute the cumulative cloud coverage, $N_{not}(j)$, from layer 1 to layer j using the maximum-random overlap assumption. A cloud (blue shaded region in figure 4) is then placed in layer j that covers the range from $N_{not}(j) - CFR(j)$ to $N_{not}(j)$. 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 , overcast columns and one clear column. Once the top of the atmosphere radiance has been computed for each homogeneous column, the total radiance, L^{total} , is written as the sum of all the single column radiances weighted by the column fractional coverage.

$$L^{total} = \sum_{s=1}^{n_c} L^{overcast}(X_{s+1} - X_s) + L^{clear}(1 - X_{n_c+1}) \quad (3)$$

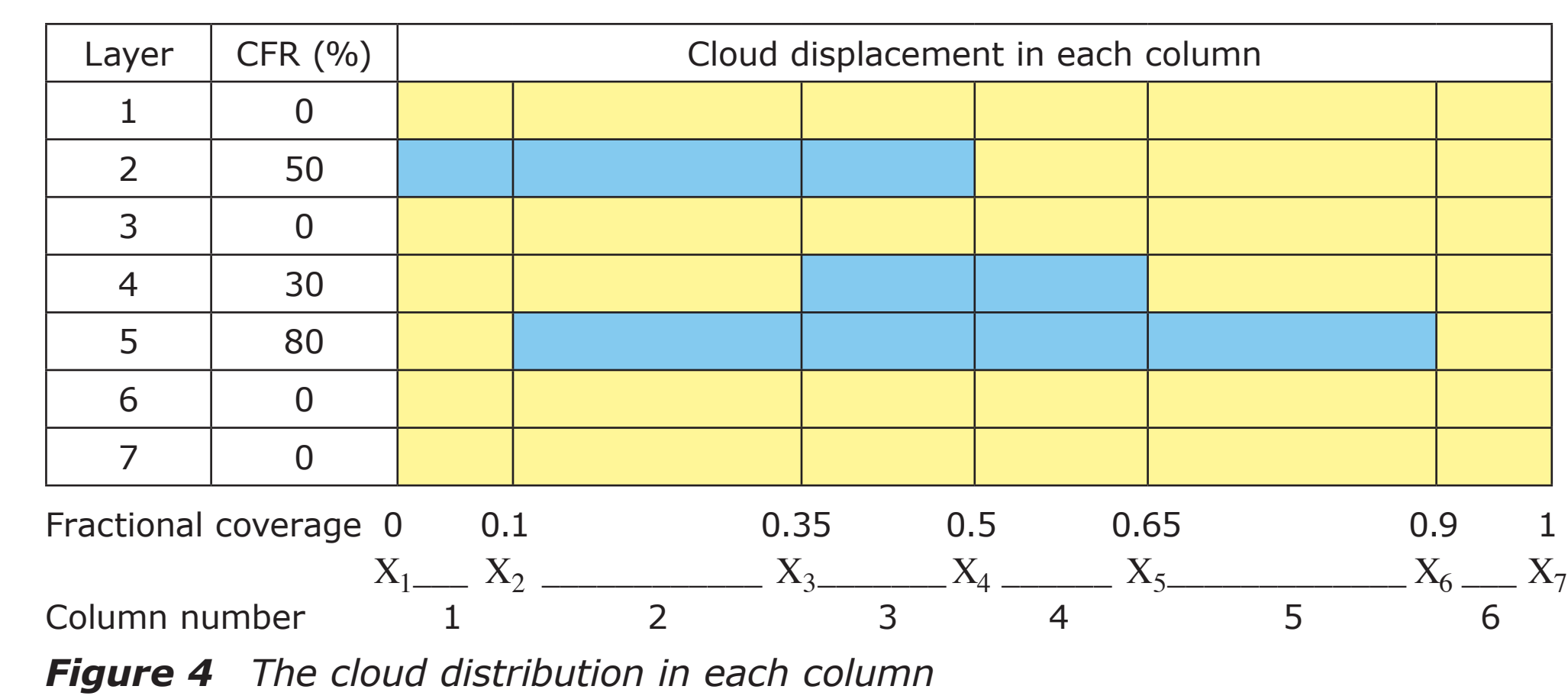


Figure 4 The cloud distribution in each column

The accuracy of the scaling approximation has been assessed by comparing approximate radiances (i.e. scaling approximation) with reference radiances computed using a 42-stream doubling-adding algorithm (Bauer 2002). Spectra have been computed for a tropical and arctic air mass. For each of the ten aerosol types included in RTIASI, we have considered vertical profiles representative of average and extreme conditions. The desert dust aerosol type has by far the largest impact on the radiance. Figure 5 shows that for the extreme condition case the presence of desert dust in a tropical air mass can result in a reduction of the top of the atmosphere clear-sky radiance by 4 K in the thermal infrared and by 1.8 K in the short wave. The same figure shows that errors introduced by the scaling approximation are less than 1 K in the thermal infrared and less than 0.25K in the short wave. For the other aerosol types, errors introduced by the scaling approximation never exceed 0.1 K. For all the water cloud types considered in RTIASI, errors are typically less than 1K in the thermal infrared and below 4 K in the short wave. It should be noted that for the cases considered here the presence of a water cloud in a tropical or arctic air mass can result in a reduction of the top of the atmosphere radiance by 30K in the thermal infrared and by up to 40K in the short wave. Results for a low level cloud (Stratus Continental) and for a middle level cloud (Cumulus Continental Clean) are shown in figures 6 and 7 respectively. Finally, for the cirrus cloud type we found a remarkable agreement between approximate and reference radiances. Some of the results are illustrated in figures 8 and 9 where it can be seen that for a tropical profile errors introduced by the scaling approximation never exceed 0.5 K whereas for an arctic profile errors are typically less than 0.1K. This can be explained in the light of the fact that the phase function for ice crystals is characterized by a narrow and sharp forward peak that results in a very small value of the b parameter and in the limit of $b \rightarrow 0$ we expect the reference and approximate radiances to converge since in this case the attenuation of the radiance is only due to absorption.

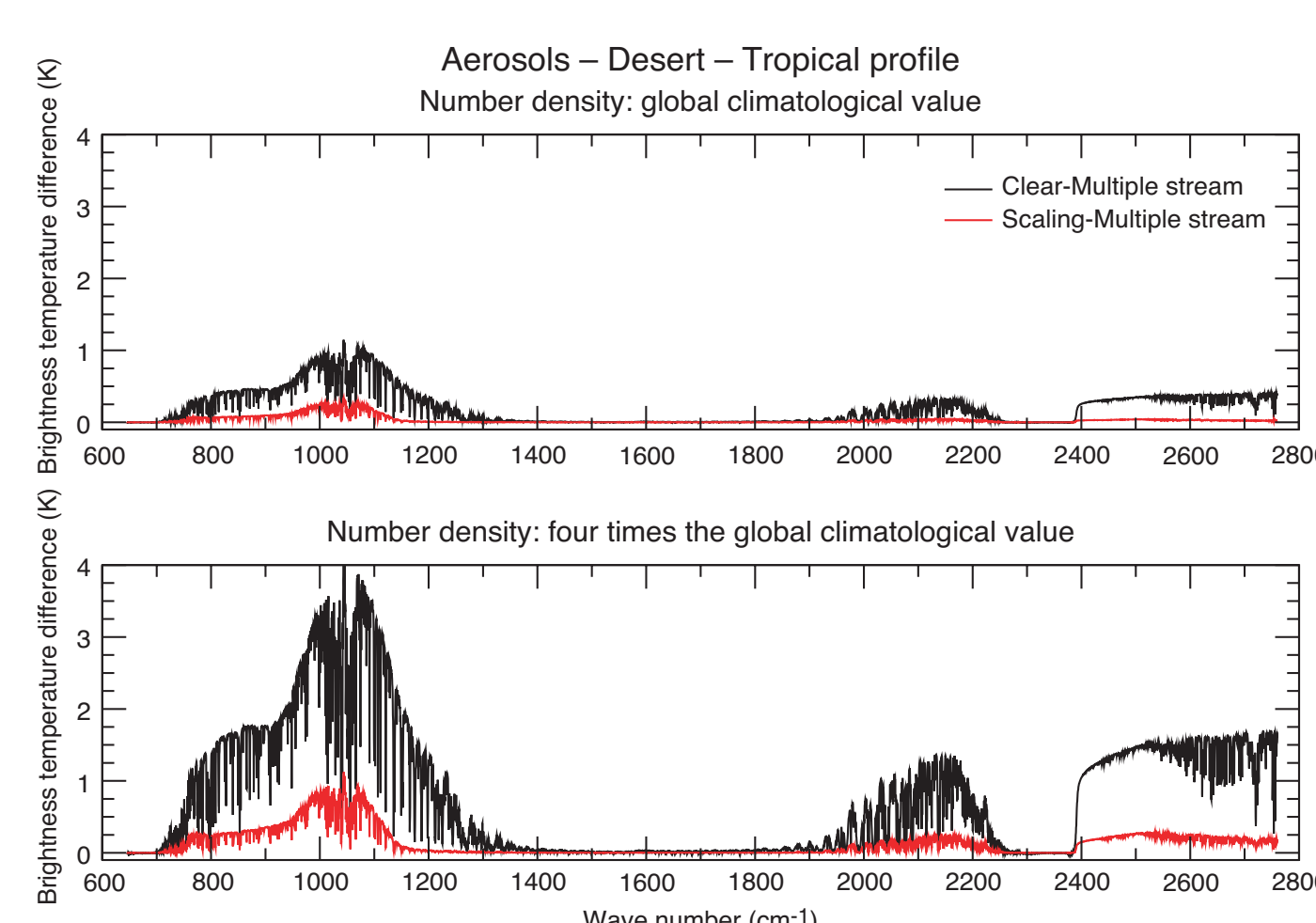


Figure 5 The radiative impact of the Desert aerosol type (black curve) and the error introduced by the scaling approximation (red curve) for the tropical profile for two different aerosol number densities.

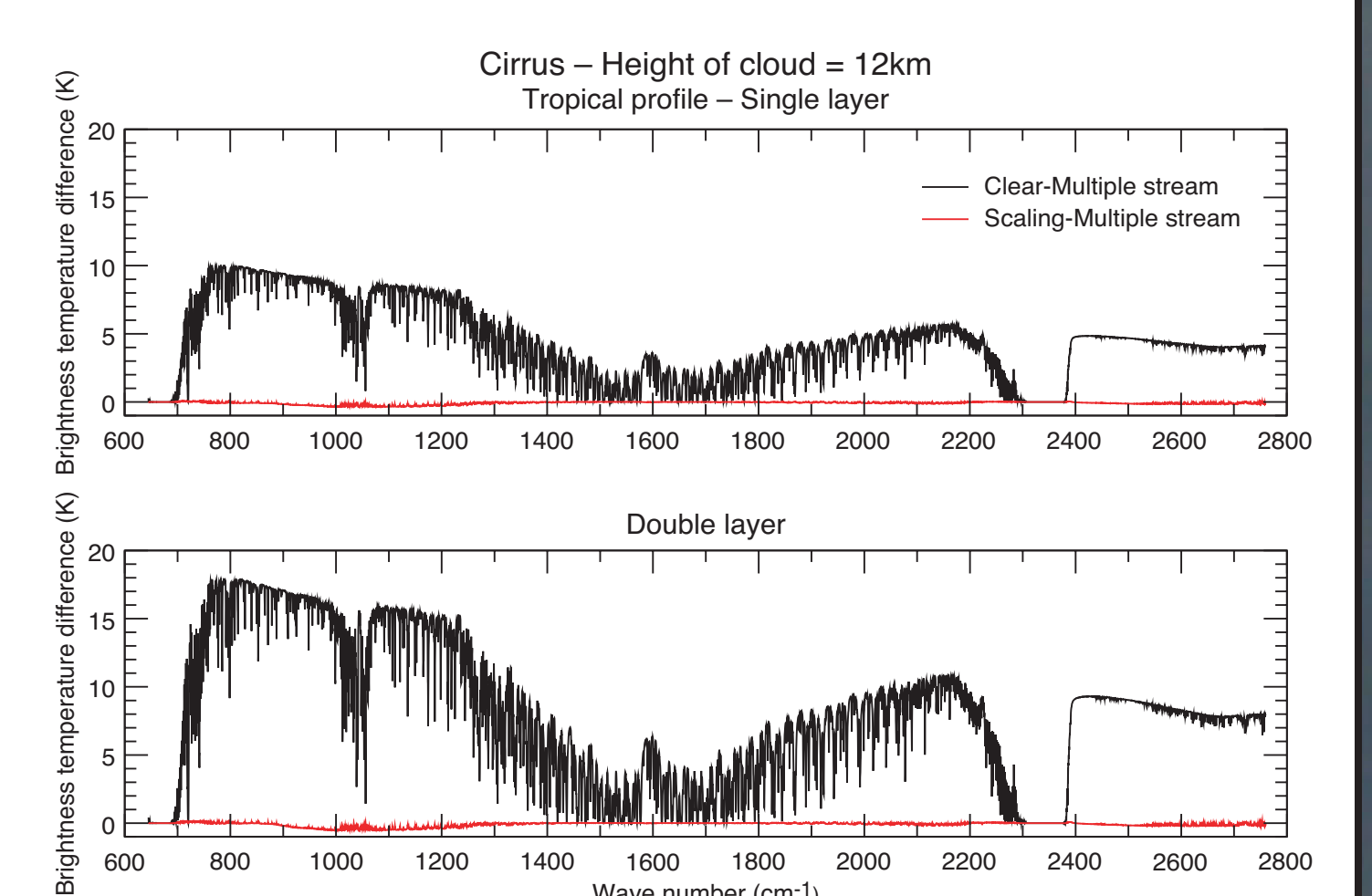


Figure 8 The radiative impact of the Cirrus cloud type (black curve) and the error introduced by the scaling approximation (red curve) for the tropical profile for two different values of the cloud thickness.

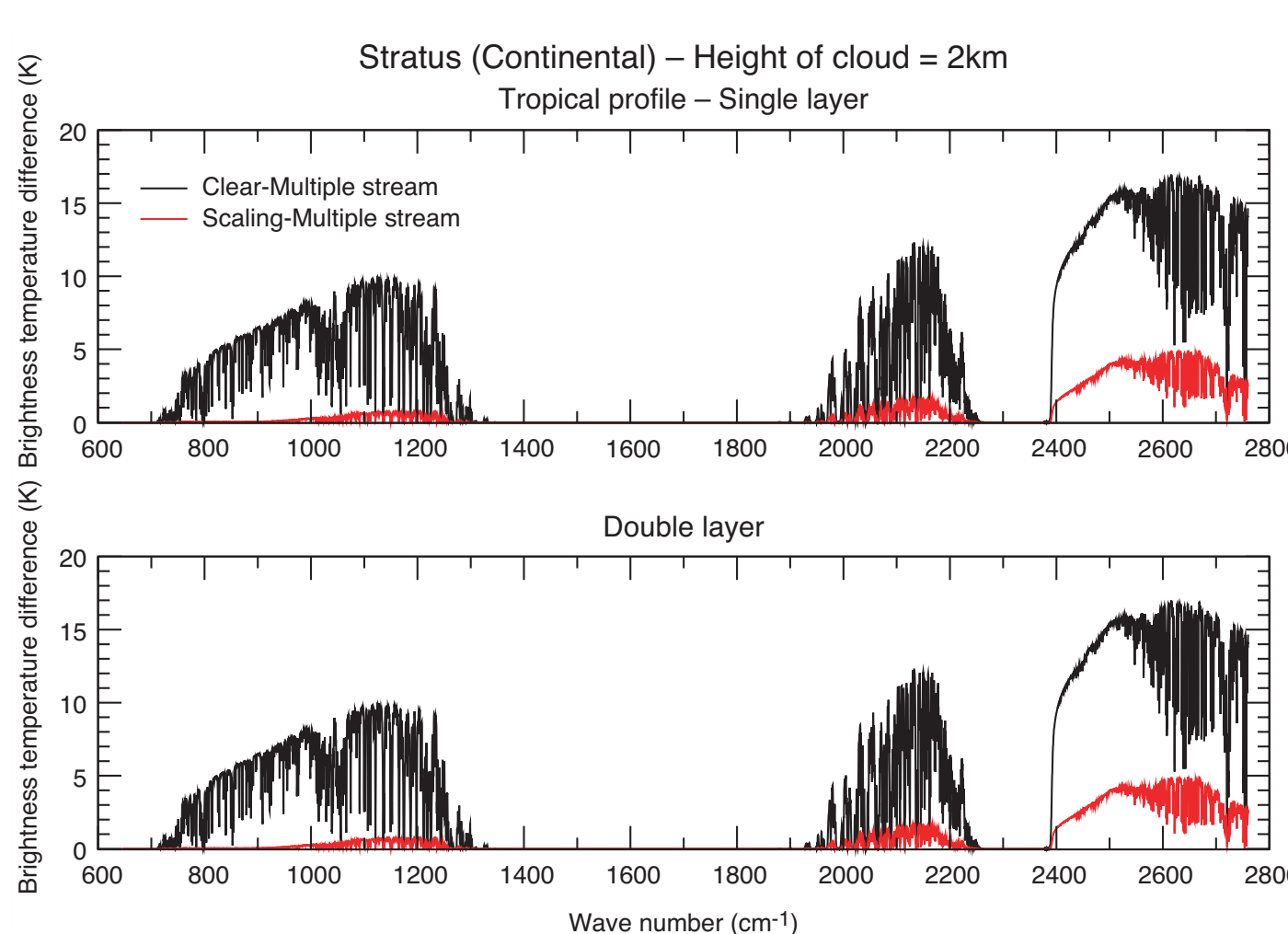


Figure 6 The radiative impact of the Stratus Continental cloud type (black curve) and the error introduced by the scaling approximation (red curve) for the tropical profile for two different values of the cloud thickness.

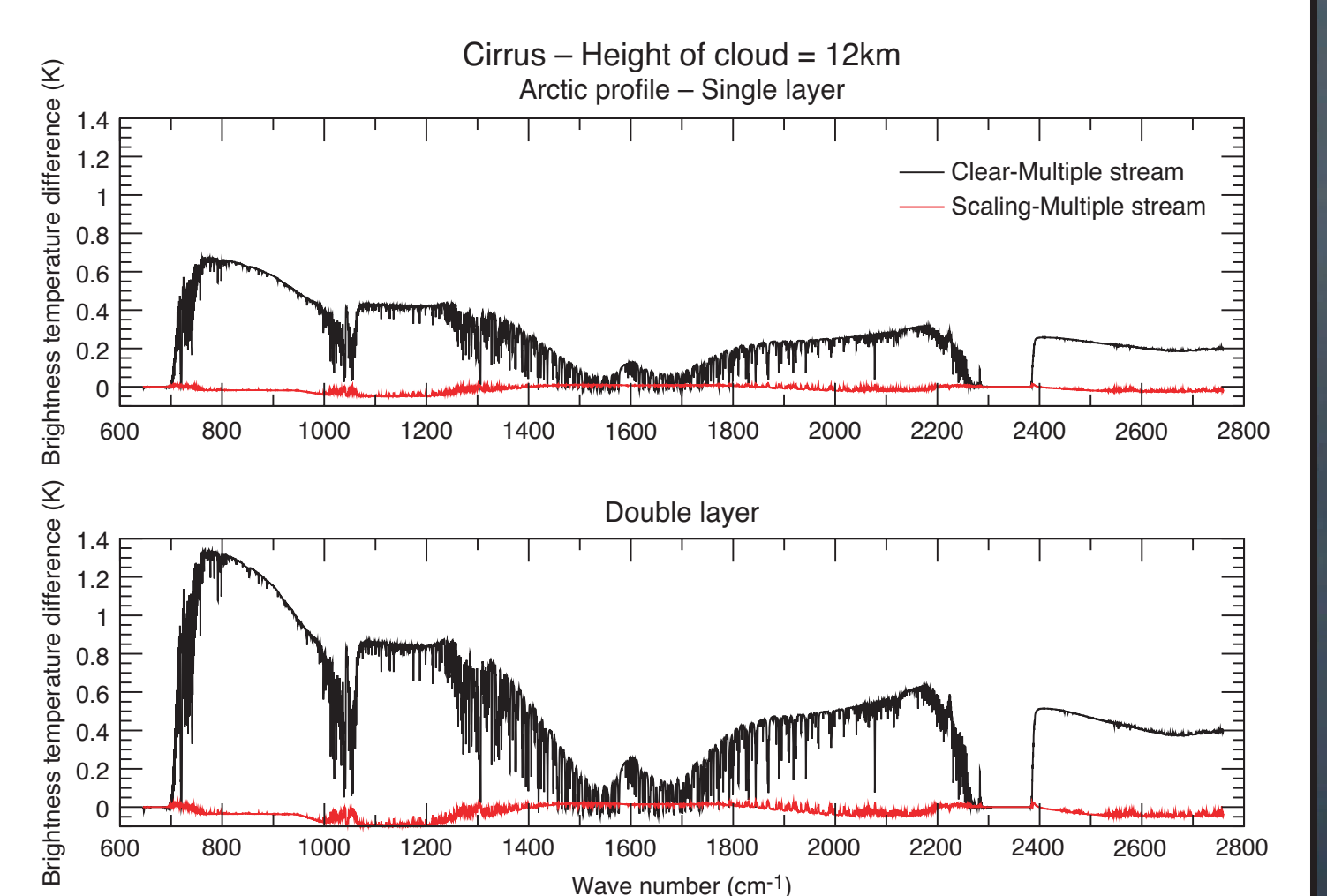


Figure 9 The radiative impact of the Cirrus cloud type (black curve) and the error introduced by the scaling approximation (red curve) for the arctic profile for two different values of the cloud thickness.

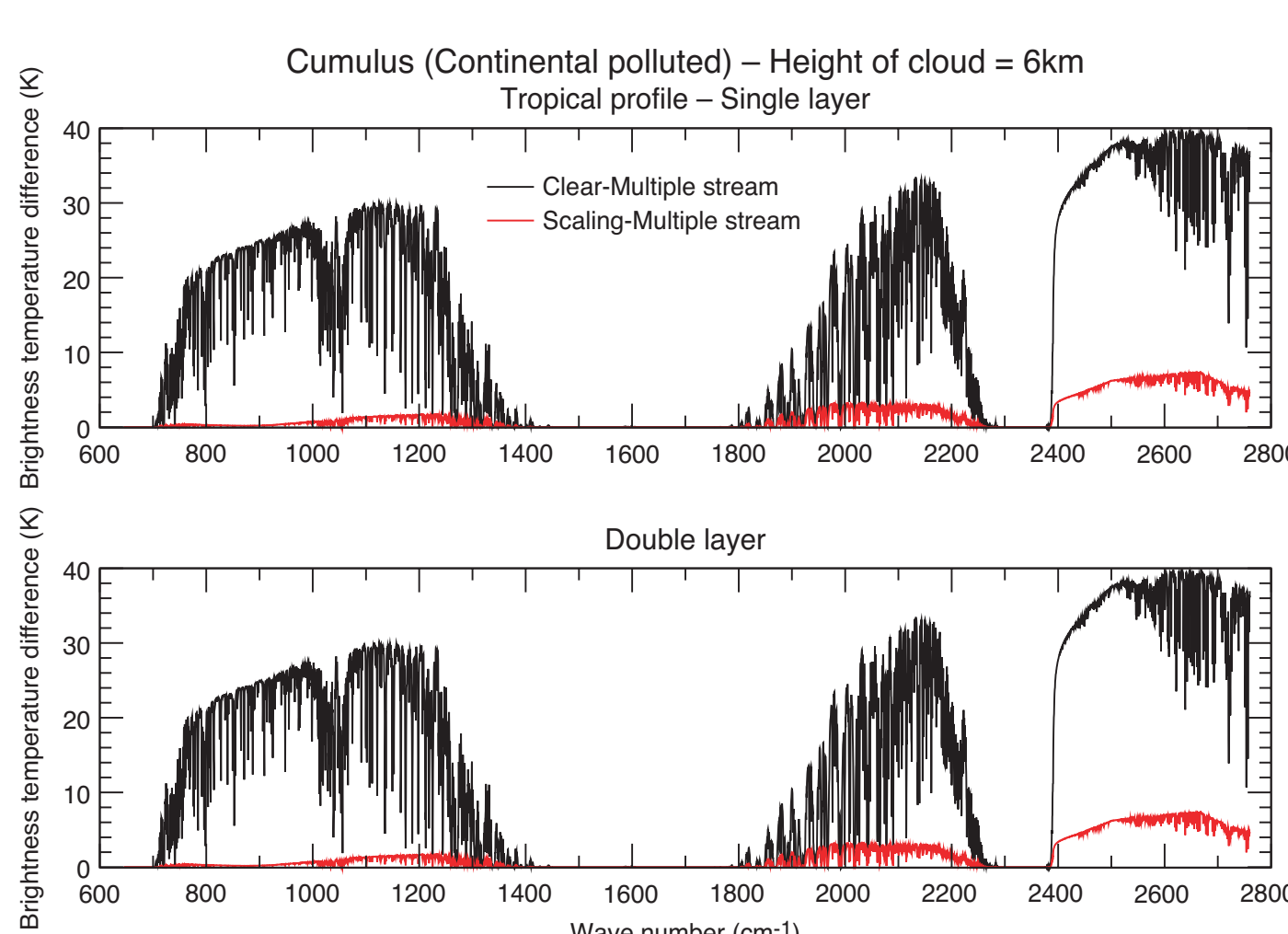


Figure 7 The radiative impact of the Cumulus Continental Clean cloud type (black curve) and the error introduced by the scaling approximation (red curve) for the tropical profile for two different values of the cloud thickness.