Visiting Scientist mission report NWP_VS20_03

Document NWPSAF-MO_VS-059

Version 0.2

05 September 2022

Improvement of the scattering parameterisation in RTTOV

Laurent C.-Labonnote[1], James Hocking[2] and Jérôme Vidot[3]

1 - University of Lille, Laboratoire d'Optique Atmosphérique (LOA), Lille, France

2 – Met Office, Exeter, United Kingdom

3 – CNRM, University of Toulouse, Météo-France, Lannion, France

Improvement of the scattering parameterisation in RTTOV

Laurent C.-Labonnote[1], James Hocking[2] and Jérôme Vidot[3]

1 - University of Lille, Laboratoire d'Optique Atmosphérique (LOA), Lille, France
2 – Met Office, Exeter, United Kingdom
3 – CNRM, University of Toulouse, Météo-France, Lannion, France

This documentation was developed within the context of the EUMETSAT Satellite Application Facility on Numerical Weather Prediction (NWP SAF), under the Cooperation Agreement dated 7 September 2021, between EUMETSAT and the Met Office, UK, by one or more partners within the NWP SAF. The partners in the NWP SAF are the Met Office, ECMWF, DWD and Météo France.

Change record			
Version	Date	Author / changed by	Remarks
0.1	31.08.22	L Labonnote	First draf
0.2	05.09.22	F Carminati	Minor update from FC and J Hocking
0.3	11.10.22	L. C.-Labonnote	Add a conclusion to the report

1 The Chou scaling approximation

The treatment of the multiple scattering in RTTOV is based on the approach of Chou et al. (1999), referenced in the following as Chou99. In this approach the effect of scattering by clouds and aerosols is parametrised by scaling the optical depth by a factor which depend of the backward scattering properties of the particles that composed the layer. The main hypothesis rely on the representation of the diffuse radiance as an isotropic function equal to the Planck function of the layer.
To derive the Chou scaling factor, the radiative transfer equation (RTE) for azimuthally independent radiance (1) is solved by replacing the diffuse radiance field $I(\tau,\mu')$ by the layer Planck function $B(\tau)$ when the incident and scattered radiances are in different hemispheres, and by the incident radiance $I(\tau,\mu)$ otherwise. Here τ,μ (μ') stand respectively for the layer optical depth and the cosine of the incident zenith angle θ (cosine of the zenith angle θ' which define the direction of the diffuse field).

$$\mu\frac{\partial I(\tau,\mu)}{\partial\tau} = I(\tau,\mu) - \big(1-\omega(\tau)\big)B(\tau) - \frac{\omega(\tau)}{2}\int_{-1}^{1} I(\tau,\mu')P(\mu,\mu')d\mu' \quad (1)$$

Where $P(\mu,\mu')$ refer to the particle azimuthally independent phase function. In the Chou99 scheme $I(\tau,\mu')$ is approximated by:

$$I(\tau,\mu') \approx \begin{cases} I(\tau,\mu) & \text{if } \mu\mu' > 0 \\ B(\tau) & \text{if } \mu\mu' < 0 \end{cases} \quad (2)$$

This approximation led to a single expression, whatever the hemisphere, for the diffuse source term:

$$\int_{-1}^{1} I(\tau,\mu')P(\mu,\mu')d\mu' \approx \omega(\tau)[(1-b)I(\tau,\mu) + bB(\tau)] \quad (3)$$

With b, the integrated fraction of energy scattered backward compared to the incident radiation, given by:

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

In this expression $\bar{P}(\mu,\mu')$ is the particle's azimuthally averaged phase function

$$\bar{P}(\mu,\mu') = \frac{1}{2\pi}\int_{0}^{2\pi} P(\mu,\mu',\varphi)d\varphi \quad \text{where } \varphi \text{ is the relative azimuth}$$

From (1), (2) and (3), the RTE can be rewritten as follow:

$$\mu\frac{\partial I(\tau,\mu)}{\partial\tau} = I(\tau,\mu) - \big(1-\omega(\tau)\big)B(\tau) - \omega(\tau)[(1-b)I(\tau,\mu) + bB(\tau)]$$

Which gives :

$$\mu \frac{\partial I(\tau,\mu)}{[1-\omega(\tau)(1-b)]\partial\tau} = I(\tau,\mu) - B(\tau) \quad (4)$$

In this equation the term $[1-\omega(\tau)(1-b)]$ is known as the Chou scaling factor and allows to resolve the RTE as in clear sky condition by introducing the apparent optical depth $\tilde{\tau} = \tau_a + b\tau_s$, with τ_a and τ_s the layer's absorption and scattering optical depth respectively.

2 Correction of the Chou scaling introduced by Tang et al. (2018)

The study of Tang et al. (2018), referenced in the following as Tang18, has shown that the approximation proposed by Chou99 can some times lead to large error especially when the incident and scattered radiation occur in two different hemispheres. In that case the Planck function used to approximate the diffuse radiation field can be too large. In their study Tang18 proposed a correction to the Chou99 approximation called *the adjustment scheme.*

2.1 Adjustment scheme

Tang18 has proposed to replace the Planck function term in (2) by the radiance travelling in the opposite direction. For example, in case of the upward radiance computation at a given level n, one would replace the Planck function by the descending radiance above that level, i.e., in the level n+1 (n=0 refers to the surface and n=N the top of atmosphere (TOA)). In this case one can rewrite equation (3), for each hemisphere (two different expressions must be treated now), as:

$$\int_{-1}^{1} I(\tau,\mu')P(\mu,\mu')d\mu' \approx \begin{cases} 2[(1-b)I(\tau,\mu) + bB(\tau)] & \mu < 0 \\ 2[(1-b)I(\tau,\mu) + bI(\tau,-\mu)] & \mu > 0 \end{cases} \quad (5)$$

The minus sign in $I(\tau,-\mu)$ appears because it is the radiance travelling in the opposite hemisphere in the opposite direction. Therefore, two different expressions have to be treated to solve the RTE, one for $\mu < 0$ (or $\mu\mu' > 0$, scattered and incident radiation in the same hemisphere) and one for $\mu > 0$ (or $\mu\mu' < 0$ scattered and incident radiation in different hemisphere), and can be written as:

$$\mu \frac{\partial I(\tau,\mu)}{[1-\omega(1-b)]\partial\tau} = I(\tau,\mu) - B(\tau) \qquad \mu < 0 \quad (6a)$$

and

$$\mu \frac{\partial I(\tau,\mu)}{[1-\omega(1-b)]\partial\tau} = I(\tau,\mu) - B(\tau) - \frac{\omega b}{1-\omega(1-b)}[I(\tau,-\mu) - B(\tau)] \qquad \mu > 0 \quad (6b)$$

For the sake of clarity, we intentionally removed the dependence of ω with τ. The last term on the right-hand side of equation (6b) can be seen as the correction term of the Chou99 approximation proposed by Tang18.

In this formulation we first need to resolve the downward radiation at each level with the Chou99 approximation and resolve afterward the upward radiation by applying the Tang18 correction. Of course, once the upward radiation has been computed at each level, one could reprocess the downward radiation by applying the Tang18 correction and reprocess the upward direction once again. In order to reduce the impact on run-time performance, this iterative process will not be implemented here and a numerical correction will be explored.

2.2 Backward and upward expression of the radiation field

In this resolution we consider a linear variation of the Planck function with τ between two level (n, n+1) where τ_n (τ_{n+1}) refer to the optical depth between the TOA and level n (n+1). We can therefore write the Planck function $B(\tau)$, where $\tau \in [\tau_{n+1}, \tau_n]$, as:

$$B(\tau) = \alpha\tau + \beta$$

with

$$\alpha = \frac{B(\tau_n) - B(\tau_{n+1})}{\tau_n - \tau_{n+1}} \quad \text{and} \quad \beta = \frac{\tau_n B(\tau_{n+1}) - \tau_{n+1} B(\tau_n)}{\tau_n - \tau_{n+1}}$$

Equation (6a) is therefore a first order differential equation with non-constant right hand side term, and the solution can be expressed as:

$$I(\tau,\mu) = [I(\tau_{n+1},\mu) - B(\tau_{n+1}) - \alpha A_d] e^{\frac{\tau-\tau_{n+1}}{A_d}} + B(\tau) + \alpha A_d \qquad \mu < 0$$

Or

$$I(\tau,\mu) - B(\tau) = [I(\tau_{n+1},\mu) - B(\tau_{n+1})] e^{\frac{\tau-\tau_{n+1}}{A_d}} + \alpha A_d \left(1 - e^{\frac{\tau-\tau_{n+1}}{A_d}}\right) \qquad \mu < 0 \qquad (7)$$

$$\text{with} \quad A_d = \frac{\mu}{1-\omega(1-b)} < 0$$

This expression is therefore used in the right-hand side of equation (6b) but adapted to $\mu > 0$:

$$I(\tau,-\mu) - B(\tau) = [I(\tau_{n+1},-\mu) - B(\tau_{n+1})] e^{-\frac{\tau-\tau_{n+1}}{A_u}} - \alpha A_u \left(1 - e^{-\frac{\tau-\tau_{n+1}}{A_u}}\right) \qquad \mu > 0$$

$$\text{with} \quad A_u = -A_d$$

Equation (6b) can therefore be rewritten and split in two different parts, one called *standard* solution, obtained from the Chou99 approximation, and labelled as "st", and the other one called *specific* solution (also called *the adjustment term* in Tang18), which treats the correction term introduce by Tang18, and labelled as "sp".

$$\begin{cases} \mu \dfrac{\partial I_{st}(\tau,\mu)}{[1-\omega(1-b)]\partial\tau} = I_{st}(\tau,\mu) - B(\tau) & (8a) \\ \mu \dfrac{\partial I_{sp}(\tau,\mu)}{[1-\omega(1-b)]\partial\tau} = I_{sp}(\tau,\mu) \\ \qquad - \dfrac{\omega b}{1-\omega(1-b)} \left[[I(\tau_{n+1},-\mu) - B(\tau_{n+1})] e^{-\frac{\tau-\tau_{n+1}}{A_u}} - \alpha A_u \left(1 - e^{-\frac{\tau-\tau_{n+1}}{A_u}}\right) \right] & (8b) \end{cases} \qquad \mu > 0$$

The final solution for upwelling radiation will therefore be the sum of the *standard* and *specific* solutions. Because the *standard* solution is already implemented in RTTOV we will only deal with the equation that treats the *specific* solution, known as the adjustment term, for which we need to know the downward radiance $I(\tau_{n+1}, -\mu)$. Note that we also consider a linear variation of the Planck function with τ, not considered in Tang18 (the latter have only treated the case with a constant Planck function).
As for equation (6a) the differential equation (8b) leading to the *specific* solution is a first order differential equation with non-constant right hand side term, and the solution at level n+1 can be expressed as follow:

$$I_{sp}(\tau_{n+1}, \mu) = \frac{1}{2}\frac{\omega b}{1-\omega(1-b)}\{[I(\tau_{n+1}, -\mu) - B(\tau_{n+1})] - [I(\tau_n, -\mu) - B(\tau_n)]e^{-\frac{\tau_n - \tau_{n+1}}{A_u}} - \alpha A_u\left(1 - e^{-\frac{\tau_n - \tau_{n+1}}{A_u}}\right)\} \qquad (9)$$

The *specific* solution I_{sp} is basically negative, leading to a reduction of the overestimates upward radiance, especially above ice cloud as shown by Tang18.

Actually, this reduction is sometime too large and does not always improve the Chou approximation (not shown). Thus, Tang18 introduced a scaling of the adjustment term given by equation (9) to minimize the error for a number of simulations and used only one iterative step as discussed previously.
For this purpose, Tang18 proposed to act on the coefficient 1/2 of equation (9), hereafter called *Tang factor* and denoted TangFact, in order to optimise the adjustment term. The authors suggest using a *Tang factor* of 0.3 instead of 1/2 (0.5). The authors justify the use of this factor as it allows the correction of a bad estimation of the downward radiance (which does not use any adjustment at first iteration) without the need to calculate the upward radiance in order to re-calculate the downward and so on.

2.3 Results: exact versus the Chou scaling-adjustment

In order to test the goodness of the adjustment to the Chou scaling we have compared the so-called *Chou Scaling-Adjustment* (CSA) with TangFact = 0.3 to an exact computation of the scattering process from the *Discrete Ordinate Method* (DOM) implemented in RTTOV (Hocking, 2015).
This comparison has been performed on a set of 784 realistic profiles over land and 206 over ocean from the NWP SAF profile database on 137 vertical pressure levels (Eresmaa and McNally, 2014). This database allows to represent the natural variability as well as extremes atmospheric conditions that we may encounter all over the globe. Note that only ice clouds are considered here (i.e. no liquid water clouds or clear-sky cases).
The ice cloud microphysical model used is that of Baran 2018, and the surface emissivity has been set to 1 in order to avoid the effects linked to different representation of the Lambertian albedo between the DOM version and the CSA in RTTOV. It has already been shown that the Chou parameterisation does not work well in the far IR, this comparison is therefore carried out considering the FORUM instrument which will perform high spectral resolution measurements in the far IR (100-1600 cm^{-1}).
Figure 1 shows the average of the differences between DOM and Chou (blue line), DOM and CSA (TangFact = 0.3 – red line) as well as the standard deviation, above land only (results over ocean are almost identical and will not be shown in the following).

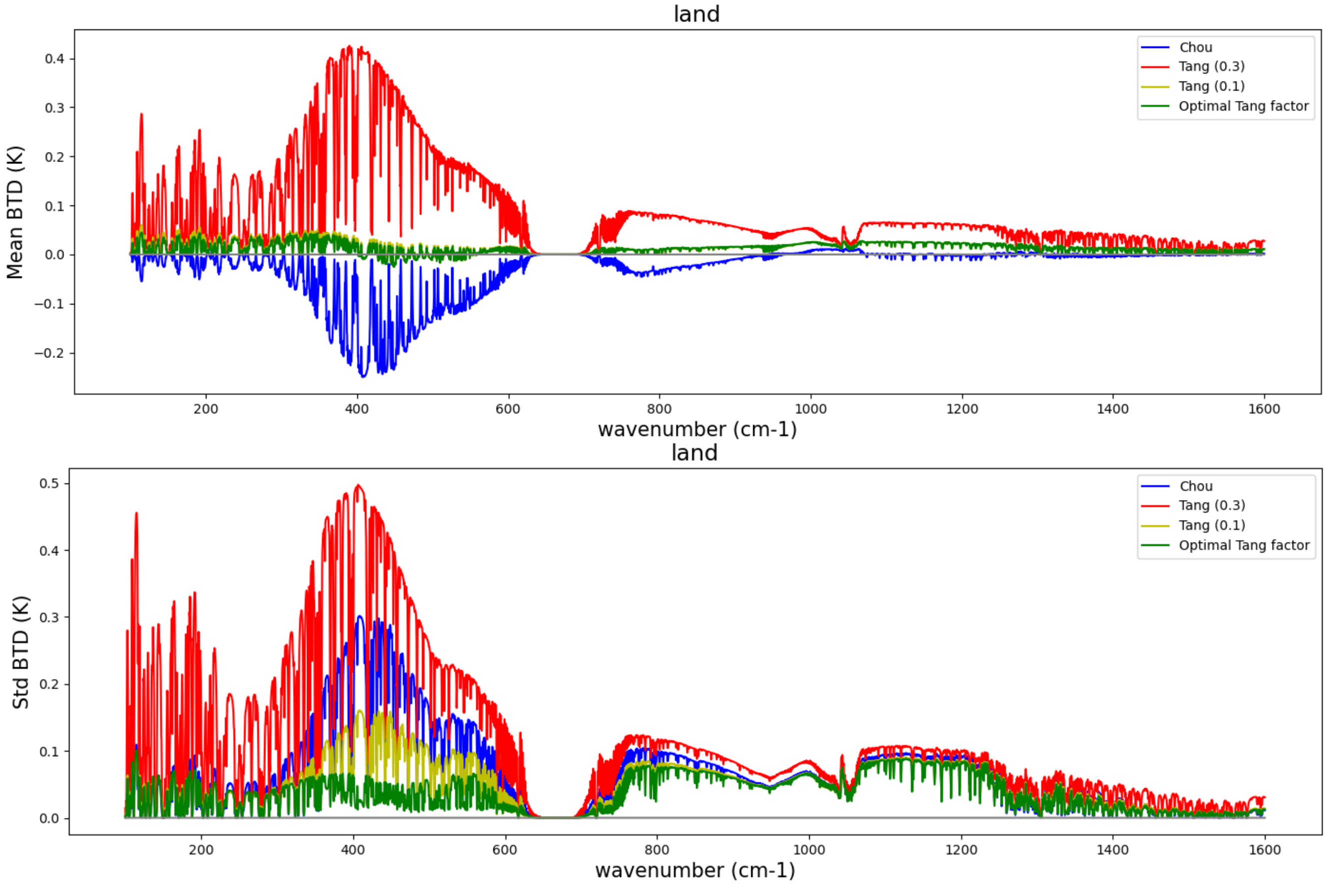

Figure 1: Mean (top) and standard deviation (bottom) of the difference between DOM computation and the Chou scaling approximation (blue line), the Tang correction with TangFact = 0.3 (red line), the Tang correction with TangFact = 0.1 (yellow line) and the optimal Tang factor (green line).

As one can see, the adjustment of the Chou approximation proposed by Tang18, even with a Tang factor of 0.3, does not improve the results compare to the Chou approximation, especially in the far IR where the mean bias can reach 0.4 K around 400 cm^{-1}. These contradictory results with Tang18 might be explained by the fact that the latter focused on fluxes and not on radiances where compensation effects related to the directional integration could reduce the differences between exact and approximated calculation. On the other hand, results presented by Tang18 have been obtained for a given Tang factor of 0.3 which might not be optimal, moreover in their study there are absolutely no explanation on how they get this factor.

We have therefore added the Tang factor as an input parameter in RTTOV in order to find an optimal factor which will help to reduce the bias between the exact DOM and CSA simulation.
An optimal search algorithm based on a brentq minimization method have been developed in order to find for each profile of the database the optimal tang factor that allow to minimize the radiance difference between DOM and CSA in a given spectral region. Here the spectral region has been defined in the far IR where the scattering process is predominant, i.e., between 400 and 500 cm^{-1}.
The results of this optimal search are shown on figure 1 (green line). As one can see there is a real improvement compared to both Chou and CSA (TangFact = 0.3). The maximum mean difference (or bias) now falls below 0.05 K in the far IR. It is interesting to point out that there is no improvement in

the mid IR where the Chou approximation was already very good. The standard deviation is also much lower with this optimal Tang factor.

One interesting thing is that this optimal Tang factor seems to tend to a fix value as can be seen on figure 2 which shows the value of TangFact as a function of the Cloud Water Path (CWP in $g.m^{-2}$). If the value of TangFact can be very high for very thin cloud (CWP<0.01 $g.m^{-2}$), it sems to tend to a constant value of 0.1, far from the value given by Tang18.

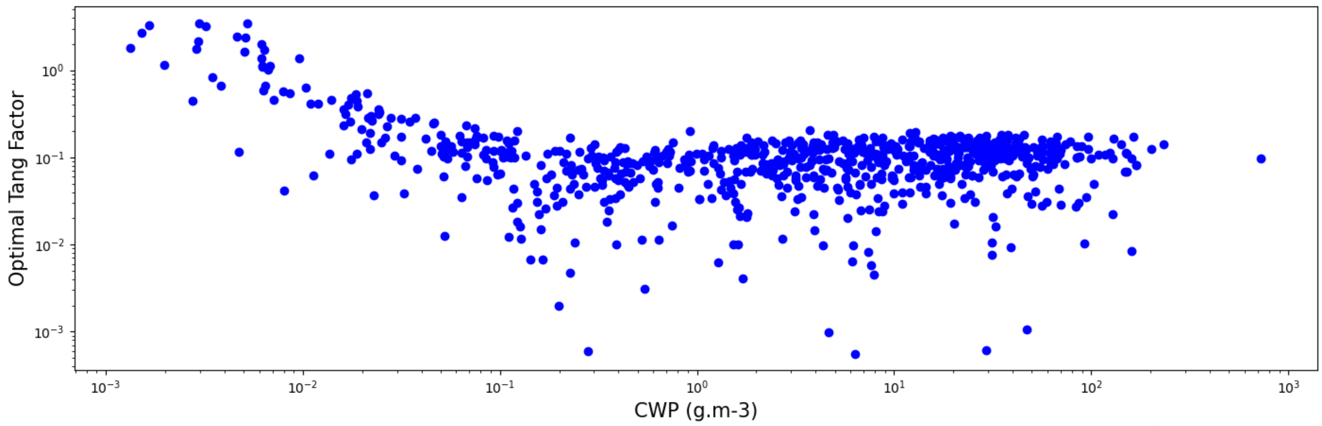

Figure 2: Optimal Tang factor as a function of the integrated cloud water content ($g.m^{-2}$), for all the profiles treated in this study over land.

Figure 3, which presents the histogram of this optimal tang factor for the 784 different profiles, clearly shows that **if we want to give a single value to TangFact, a value of 0.1 should be the optimal one.**

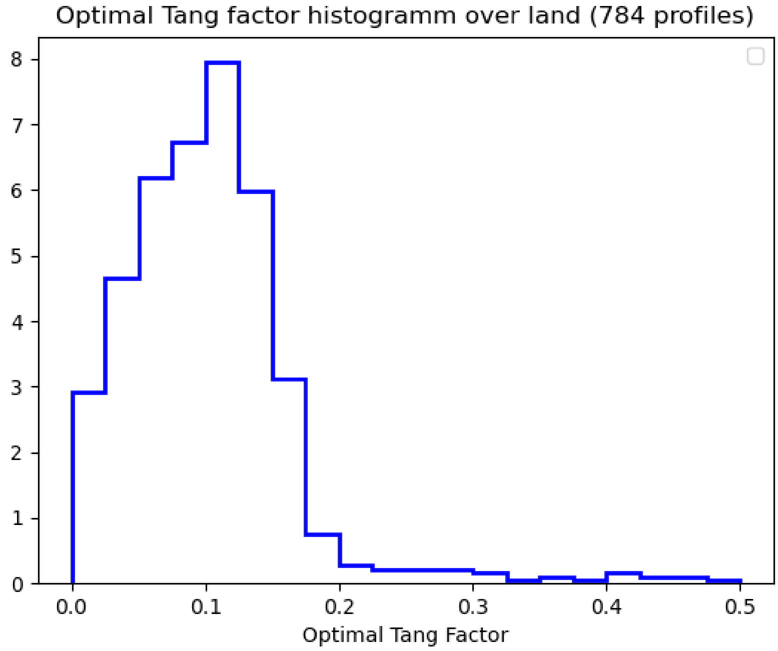

Figure 3: Histogram of the optimal Tang factor for profiles over land.

We finally re-run RTTOV on the entire database with a fix tang factor of 0.1. Results of these simulation are shown on figure 1 (yellow lines). As one can see by using a fix value of 0.1 the mean difference (with the DOM computation) is almost identical to that of the optimal tang factor (green line). Actually, it is only by looking at the figure representing the standard deviations that one can really see a difference. The last figure (figure 4) shows the brightness temperature difference with the DOM computation at 406.9 cm-1 in the spectral range of interest as a function of the integrated water content (g.m^{-2}), for the whole set of profiles. We clearly see that by using an optimal Tang factor this difference is very close to 0 for all the profiles and whatever the CWP. This figure also shows that the Chou or CSA (TangFact = 0.3) over and underestimate the radiance respectively (blue and red lines) by almost 2 K for large CWP, and that using a fixed value of the Tang factor of 0.1 (yellow line) gives reasonable results with a maximum difference with DOM of about 0.5K.

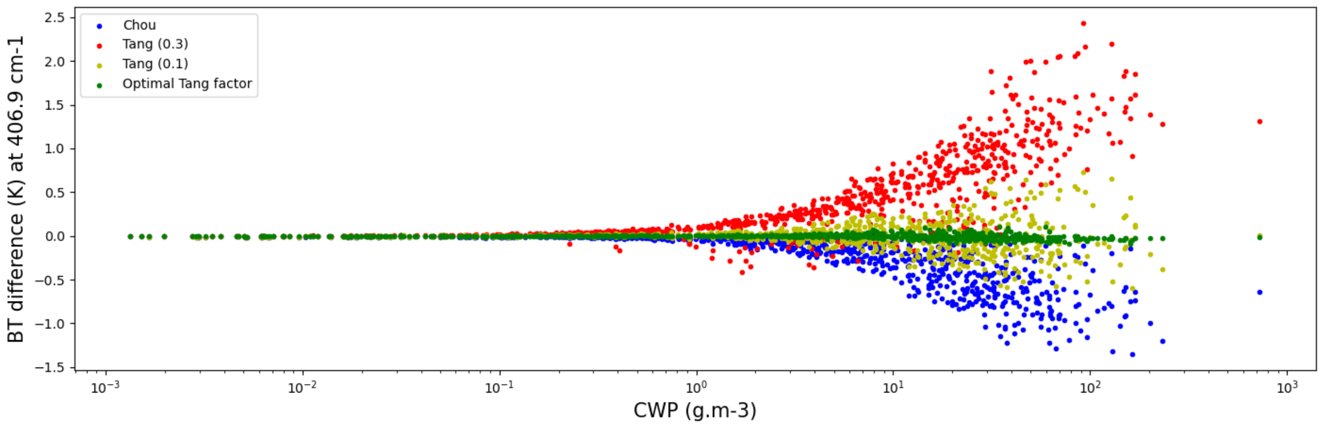

Figure 4: Brightness temperature difference at 406.9 cm^{-1} between the DOM computation and the Chou scaling approximation (blue dots), the Tang correction with TangFact = 0.3 (red dots), the Tang correction with TangFact = 0.1 (yellow dots) and the optimal Tang factor (green dots), as a function of the cloud water path (CWP)

Conclusion

In this work we have implemented a correction of the Chou et al. (1999) approximation introduced by Tang et al. (2018), called Tang18, in the RTTOV radiative transfer code. We have first expressed this correction theoretically by considering a linear variation of the Planck function between two levels. Secondly, we have tested this correction on a set of realistic atmospheric profiles obtained from ECMWF reanalyses, by comparing the exact simulations with those that consider the Tang18 correction. These comparisons have shown that using the expression introduced by Tang18 does not significantly improve (or even degrade) the Chou99 approximation. This work has therefore led us to introduce a factor, called the "Tang factor", which allows to optimise the amplitude of this correction in order to reduce the deviation from the exact simulations. It appeared that for the majority of the profiles tested, a Tang factor value of 0.1 allowed to reach an average bias smaller than 0.05K (in the FIR compare to more than 0.2K with the Chou99 approximation) with a standard deviation of less than 0.1K (compare to 0.3K with Chou99).

References

Eresmaa, R., and A. P. McNally: Diverse profile datasets from the ECMWF 137-level short-range forecasts, NWP SAF report, available at: https://nwp-saf.eumetsat.int/site/download/documentation/rtm/nwpsaf-ec-tr-017.pdf pdf (last access: 31 August 2022), 2014.

Hocking, J.: A visible/infrared multiple-scattering model or RTTOV, NWP SAF report, available at: https://nwp-saf.eumetsat.int/publications/tech_reports/nwpsaf-mo-tr-031.pdf (last access: 31 August 2022), 2015

Chou M.-D., K.-T. Lee, S.-C. Tsay and Q. Fu: Parameterization for Longwave Scattering for Use in Atmospheric Models, *J. of Clim*., **12**, 159-169, doi.org/10.1175/1520-0442-12.1.159.

Tang, G., P. Yang, G. W. Kattawar, X. Huang, E. J. Mlawer, B. A. Baum and M. King: Improvement of the simulation of Cloud Longwave Scattering in Broadband Radiative Transfer Models, J. of Atmos. Sci., 2217 – 2233, 2018, doi.org/10.1175/JAS-D-18-0014.1