Improved cloud scattering parameterization for Mid and Far-IR in RTTOV

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Abstract

The fast radiative transfer model RTTOV (Saunders et al., 2018) has been developed for decades for satellite data assimilation in Numerical Weather Prediction (NWP) models and is increasingly used for direct retrieval of atmospheric parameters from satellite data. In the thermal infrared, the scattering by clouds or aerosols is modelled by the Chou parameterization (Chou et al., 1999), which allows a very fast simulation of the scattering contribution to the total signal. By using a large dataset of realistic cloud profiles from the ECMWF NWP model, we have shown that in the mid-infrared, the Chou parameterization gave very good results for ice clouds and poorer results for liquid or mixed phase clouds. With the recent selection of the FORUM mission as part of the ESA Earth Explorer 9 programme, we also tested the Chou parameterization in the far-infrared (wavelengths > 18 microns) and were able to show that the results were degraded in this spectral range for ice clouds. A recent paper by Tang et al. (2018) showed that an adjustment of the Chou parameterization improves the simulation of cloud scattering in the infrared. We implemented this in the latest version of RTTOV and compared the simulations to the full scattering model LIDORT. This study shows the performance of the new parameterization on total cloudy radiances as well as on sensitivities (Jacobians) to cloud parameters for both the mid and far-infrared.

Chou et al. (1999) approximation and the Tang et al. (2018) adjustment

The Chou scaling approximation

The treatment of the multiple scattering in RTTOV is based on the approach of Chou et al. (1999) (called **Chou99** hereafter). In this approach the effect of scattering by clouds and aerosols is parameterized 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) as to be solved by replacing the diffuse radiance field *I(τ,μ')* by the layer Planck function *B(τ)* when the incident and scattered radiances are in different hemispheres, and by the incident radiance *I(τ,μ)* otherwise.

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

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

$$\int_{-1}^{1} I(\tau,\mu')P(\mu,\mu')d\mu' \approx 2[(1-b)I(\tau,\mu) + bB(\tau)] \quad (2)$$

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

$$b = \frac{1}{2}\int_0^1 d\mu\int_{-1}^{0}\bar{P}(\mu,\mu')d\mu' = \frac{1}{2}\int_{-1}^{0} d\mu\int_{0}^{1}\bar{P}(\mu,\mu')d\mu' \qquad \text{Where} \qquad \bar{P}(\mu,\mu') = \frac{1}{2\pi}\int_0^{2\pi}P(\mu,\mu',\varphi)d\varphi$$

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

$$\mu\frac{\partial I(\tau,\mu)}{[1-\omega(\tau)(1-b)]\partial\tau} = I(\tau,\mu) - B(\tau) \quad (3)$$

In this equation the term [1-ω(τ)(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 $\tau=\tau_a+b\tau_s$, with τ_a and τ_s the layer's absorption and scattering optical depth respectively.

It has been shown that this approximation lead to pretty good result in the thermal Infrared when the scattering process are not to prominent. However it is now well established that in the far infrared (between 300 and 550 cm^{-1}) there is an enhancement of the scattering leading to a degradation of the Chou99 approximation. These poorer results can be seen in Figure 1 which shows (in blue) the spectral variation of the difference between the brightness temperature calculated exactly with the DOM (Discrete Ordinate Method) radiative transfer code and the Chou99 approximation. This difference can, on average, be greater than 0.2K.

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

The study of Tang et al. (2018) (referred as **Tang18** hereafter) 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 **T**ang **A**djustment **S**cheme* (**TAS**).

Tang Adjustment scheme (TAS)

Tang18 has proposed to replace the Planck function term in (2) by the radiance travelling in the opposite direction. In this case one can rewrite equation (2), for each hemisphere (two different expressions must be treated now), as:

$$\int_{-1}^{1} I(\tau,\mu')P(\mu,\mu')d\mu' \approx \begin{cases} 2[(1-b)I(\tau,\mu)+bB(\tau)] & \mu<0 \\ 2[(1-b)I(\tau,\mu)+bI(\tau,-\mu)] & \mu>0 \end{cases} \quad (4)$$

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:

$$\begin{cases} \mu\dfrac{\partial I(\tau,\mu)}{[1-\omega(1-b)]\partial\tau} = I(\tau,\mu) - B(\tau) & \mu<0 \quad (5a) \\ \mu\dfrac{\partial I(\tau,\mu)}{[1-\omega(1-b)]\partial\tau} = I(\tau,\mu) - B(\tau) - \dfrac{\omega b}{1-\omega(1-b)}[I(\tau,-\mu)-B(\tau)] & \mu>0 \quad (5b) \end{cases}$$

The last term on the right-hand side of equation (5b) 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.

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. Equation (5a) is therefore a first order differential equation with non-constant right hand side term, and the solution can be expressed as :

$$I(\tau,\mu) - B(\tau) = [I(\tau_{n+1},\mu) - B(\tau_{n+1})]e^{\frac{\tau-\tau_{n+1}}{A_d}} + \alpha A_d\left(1-e^{\frac{\tau-\tau_{n+1}}{A_d}}\right) \qquad \mu<0 \qquad (6a) \qquad \text{with} \quad A_d = \frac{\mu}{1-\omega(1-b)} < 0$$

This expression is therefore used in the right-hand side of equation (5b) but adapted to $\mu>0$. This Equation 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 Tang et al. (2018)), which treats the correction term introduce by Tang18, and labelled as "sp".

$$\begin{cases} \mu\dfrac{\partial I_{st}(\tau,\mu)}{[1-\omega(1-b)]\partial\tau} = I_{st}(\tau,\mu) - B(\tau) & (6b1) \\ \mu\dfrac{\partial I_{sp}(\tau,\mu)}{[1-\omega(1-b)]\partial\tau} = I_{sp}(\tau,\mu) - \dfrac{\omega b}{1-\omega(1-b)}\left[[I(\tau_{n+1},-\mu)-B(\tau_{n+1})]e^{-\frac{\tau-\tau_{n+1}}{A_u}} - \alpha A_u\left(1-e^{-\frac{\tau-\tau_{n+1}}{A_u}}\right)\right] & (6b2) \end{cases} \quad \mu>0$$

The final solution for upwelling radiation will therefore be the sum of the *standard* and *specific* solutions (note that we only deal with the specific solution below). As for equation (5a and 6b1) the differential equation (6b2) 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:

$$I_{sp}(\tau_{n+1},\mu) = \frac{1}{2}\frac{\omega b}{1-\omega(1-b)}\left\{[I(\tau_{n+1},-\mu)-B(\tau_{n+1})] - [I(\tau_n,-\mu)-B(\tau_n)]e^{-\frac{\tau_n-\tau_{n+1}}{A_u}} - \alpha A_u\left(1-e^{-\frac{\tau_n-\tau_{n+1}}{A_u}}\right)\right\} \quad \mu>0 \quad (7)$$

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.

Results: Exact versus the Chou99 approximation and Tang18 adjustment

The **adjustment** proposed by Tang et al. (2018) is sometime **too large**

→ **Play on the coefficient ½** (red color in 7), called hereafter *Tang Factor* and labelled as **TF** to reduce the contribution

Comparison with the Discrete Ordinate Method (DOM) (Hocking 2015)

- Use a set of more than 1000 realistic profiles over land and ocean from the realistics NWP SAF profiles database (Eresmaa and McNally, 2014)
- Ice cloud model → Baran (2018)
- Simulation over the Far InfraRed (FORUM like between 100 and 1600 cm^{-1})

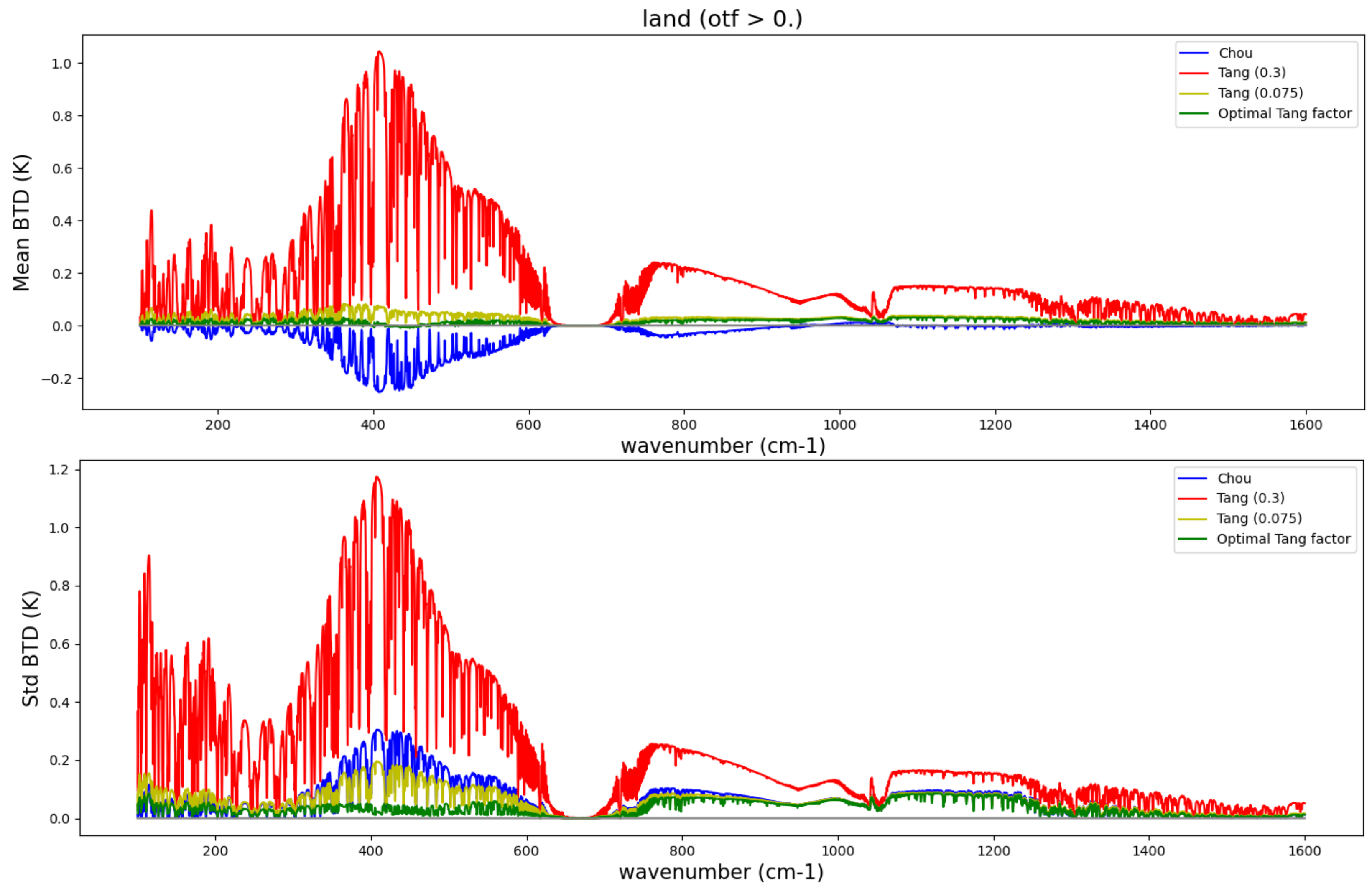


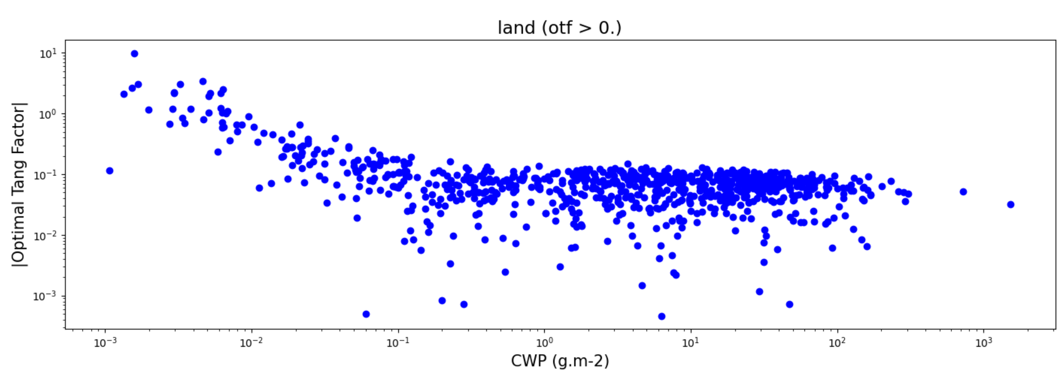
Figure 1: Mean (top) and standard deviation (bottom) of the difference between DOM computation and the Chou99 scaling approximation (blue line), the Tang18 correction with TF = 0.3 (red line), the Tang correction with TF = 0.075 (yellow line) and the optimal Tang factor (green line).

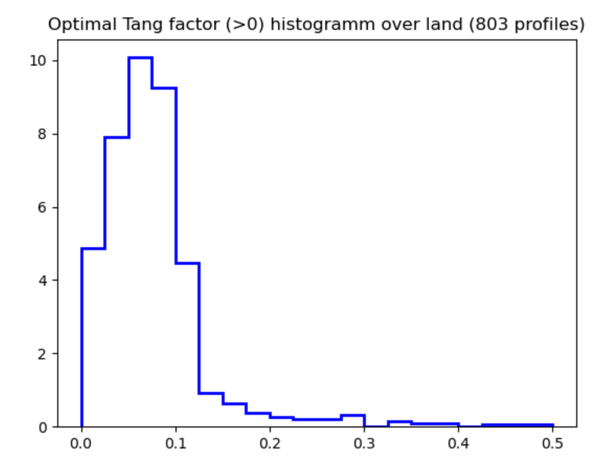
→ The **Adjustment** of the Chou99 approximation proposed by Tang18 (called TAS), even with a TF = 0.3, **does not improve the results** compare to the Chou99 approximation, especially in the far IR.

An optimal search algorithm have been developed to find the **Optimal Tang Factor (OTF)** that minimize the RMS difference between DOM and TAS in a given spectral range (here in the FIR between 400 and 500 cm^{-1}).

Results are shown on figure 1 (green line). As one can see there is a real improvement compared to both Chou99 and TAS (TF = 0.3). The maximum mean difference (or bias) now falls below 0.05 K in the far IR.

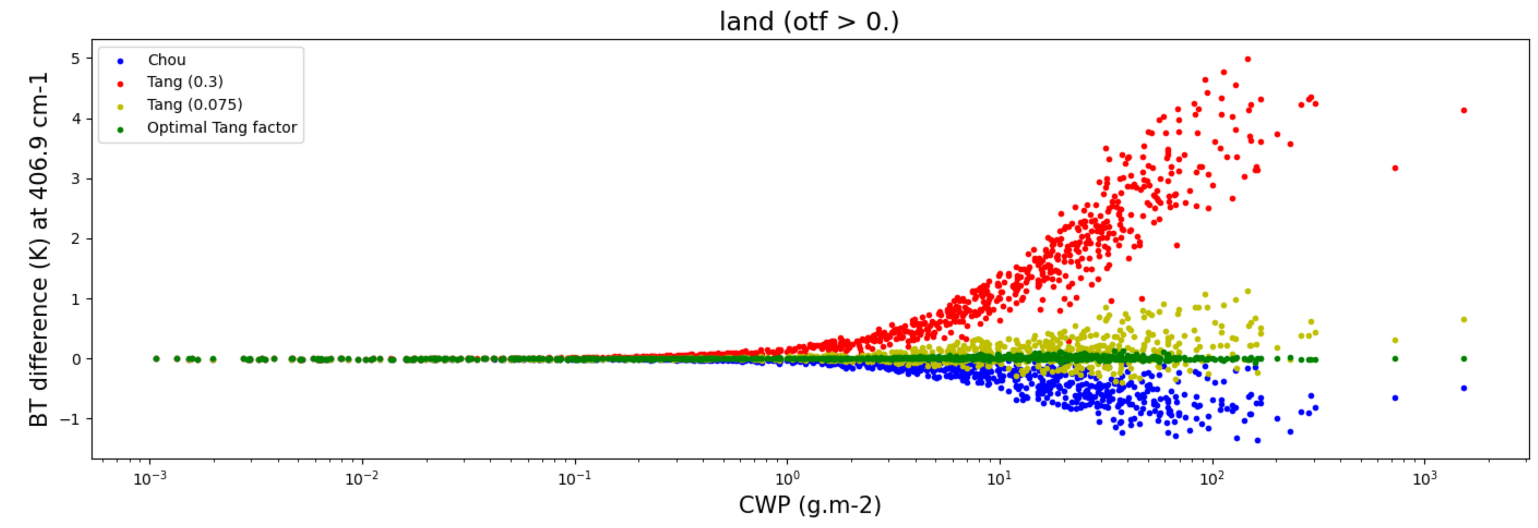
The OTF seems to tend to a fix value for CWC > 1 gm^{-3}



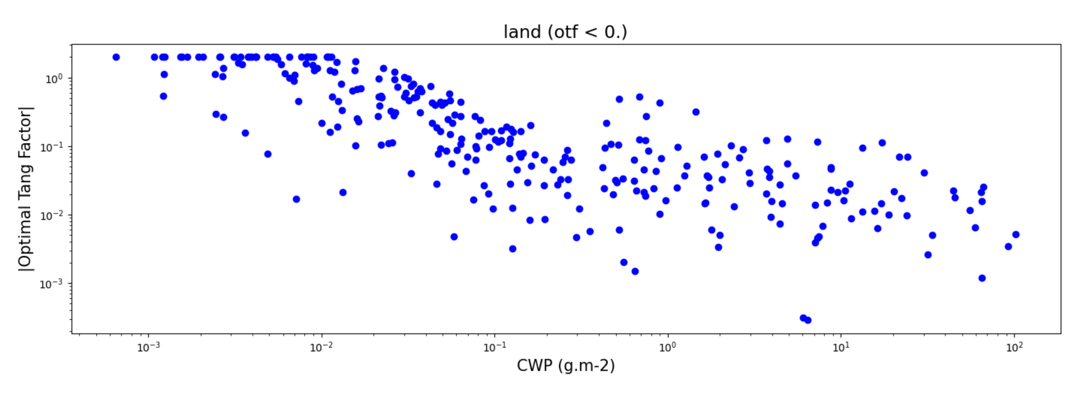


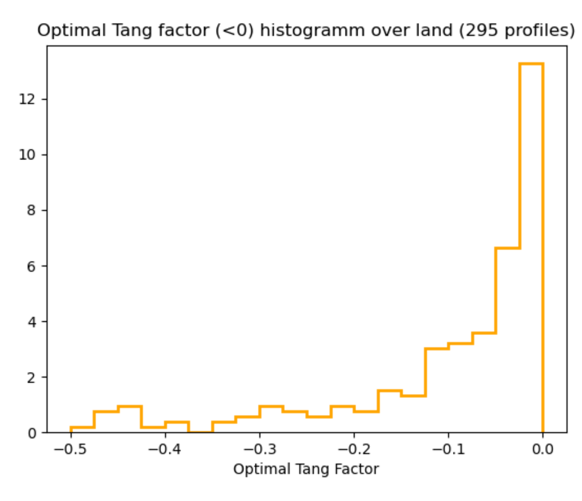
Run the TAS for TF = 0.075 → good results (yellow line on Fig 1) with a mean BTD < 0.1 K

BTD between DOM and the various approximation **at 406.9 cm^{-1}** as a function of CWP (Cloud Water Path in gm^{-2}) for the land database clearly show the goodness of the Optimal Tang Factor search in the FIR, as well as the good behavior of TAS with the fix TF = 0.075

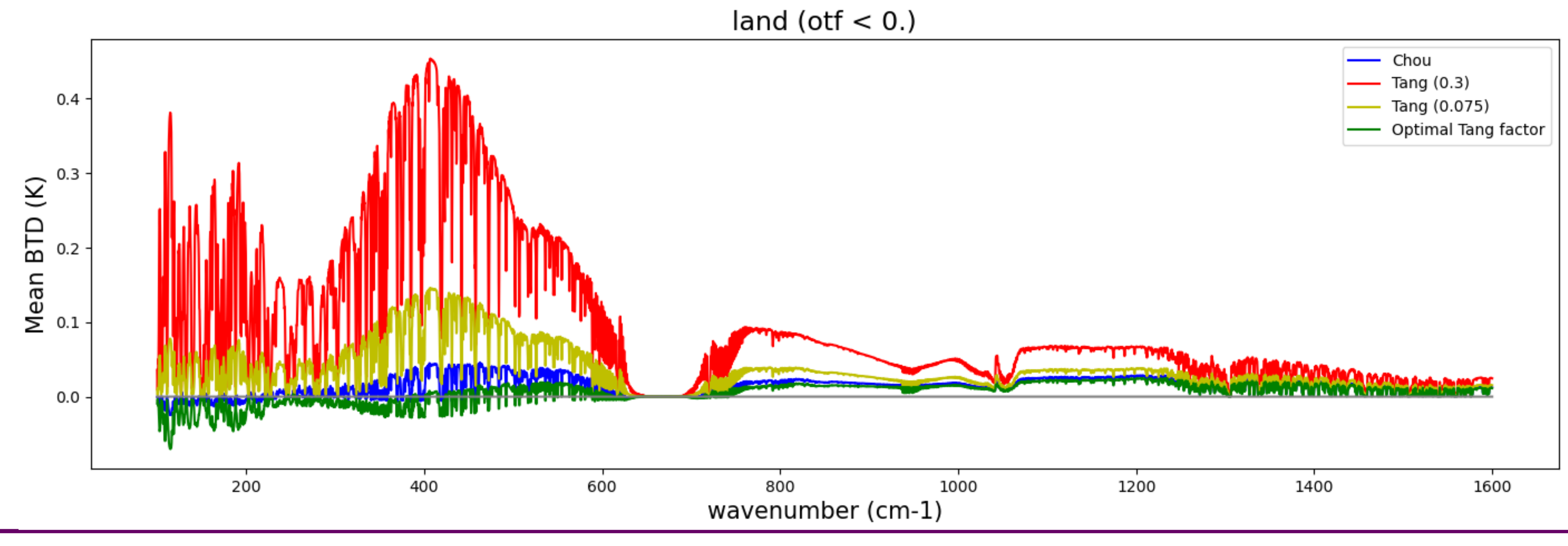


Interestingly there is a non-negligeable number of profiles for which the **OTF is < 0**





For these profiles the **Chou99 approximation is working well** but the optimal search still gives better results. Need to find out the reason why the Chou99 approximation underestimate the radiance for these profiles whereas it usually overestimate it.



Conclusion and perspectives

In this work we have implemented a correction of the Chou et al. (1999) approximation introduced by Tang et al. (2018), called adjustment scheme, in the RTTOV radiative transfer code. We have first expressed this adjustment theoretically by considering a linear variation of the Planck function between two levels. Secondly, we have tested this adjustment on a set of realistic atmospheric profiles obtained from ECMWF reanalyses, by comparing it with the exact simulations perform with the DOM simulator. These comparisons have shown that using the expression introduced by Tang et al. (2018) does not significantly improve (or even degrade) the Chou et al. (1999) 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 0.075 allowed to reach an average bias smaller than 0.05 K (in the FIR compare to more than 0.2 K with the Chou99 approximation) with a standard deviation of less than 0.2 K (compare to 0.3 K with Chou99).