Response to Reviewer #3

Overall evaluations:

The research is highly relevant as it focuses on optimizing cloud optical parameterizations in RTTOV for satellite visible reflectance data assimilation. With the increasing importance of satellite - based data in weather forecasting and climate studies, improving the accuracy of radiative transfer models like RTTOV is crucial. The use of data from recent geostationary meteorological satellites (FY - 4B and Himawari - 9) makes the study timely. The authors conducted four different experiments, covering two observing systems, two radiative solvers, and two atmospheric fields. A wide range of data was used, including forecasts from the CMA - MESO model, ERA5 reanalysis data, and observations from FY - 4B and Himawari - 9 satellites. The data was carefully processed, and multiple statistical methods were employed, such as analyzing O - B biases, standard deviations, and probability density functions. These analyses provided in - depth insights into the performance of different cloud optical parameterizations. The study identified the optimal cloud optical parameterization suite ("Deff" + "SSEC" + B02), which can significantly reduce the O - B biases. This finding has practical implications for improving the accuracy of radiative transfer simulations and data assimilation in weather prediction models.

Our response:

We would like to extend our sincere gratitude for your time and effort in reviewing our manuscript. We have carefully considered all your comments and suggestions and have made significant revisions to the manuscript accordingly. A point-by-point response addressing each of your concerns is attached below.

Major issue 1:

The number concentration in Eq. (1) was set to 300 cm^{-3}. Is this generally applicable for all types of clouds? If not, what is the sensitivity of the simulated reflectivity to the other number concentration?

Our response:

The number concentration of cloud droplets was set to 300 cm^{-3} mainly because we want to maintain consistency with the commonly used microphysical schemes. On one hand, the default physic scheme of the CMA-MESO model for operational forecasting is the single-moment six-class (WSM6) microphysical scheme. The default number concentration of cloud droplets for the WSM6 scheme was set to 300 cm^{-3}. On the other hand, we have conducted the data assimilation of FY-4A visible reflectance under a framework of Observing System Simulation Experiments (OSSEs) (Zhou et al., 2022; 2023). In the OSSEs, the microphysical scheme was set to the Thompson scheme. The default number concentration of cloud droplets for the Thompson scheme was also 300 cm^{-3}.

The number concentration of cloud droplets are determined by the pre-assumed Cloud Condensation Nuclei (CCN). An increase in CCN number concentration distributes available water vapour among a greater number of aerosol particles, resulting in the formation of smaller cloud hydrometeors. Conversely, a reduction in CCN leads to fewer but larger hydrometeors, and vice versa. According to Thompson et al. (2024), the typical CCN number concentration varies from 50, 100, 200, to 500 cm^{-3}. Therefore, we conducted two additional experiments to explore the sensitivity of the simulated reflectivity to the CCN number concentration. The two experiments were performed by configuring the CCN number concentration in Equation (1) as 100 cm^{-3} and 500 cm^{-3}. The results are consistent with these with the CCN number concentration of 300 cm^{-3}. This is because although the reflectance shows some sensitivity to the pre-assumed CCN number concentration, the impact of the CCN number concentration is less pronounced in synthetizing visible images due to the radiative effects of the upper-layer ice clouds. (Line: 97-104; 402-428)

Major issue 2:

For cloud ice, is the effective diameter in Eq. (2) independent of cloud ice content and number concentration? What is the number concentration assumed for cloud ice?

Our response:

This is an interesting question actually. We checked the paper by Ou and Liou (1994). The ice crystal size distribution is determined by Equation (R1),

$$\mathrm{n(L)} = AL^B \cdot IWC \tag{R1}$$

where A and B are empirical coefficients determined from measured data, and IWC denotes the Ice Water Content with a unit of g m^{-3}.

Ou and Liou (1994) conclude that A, B, and IWC depend on temperature. Therefore, $\mathrm{n(L)}$ and the effective diameter (Deff) of ice clouds are also functions of temperature. By theory, the number concentration of cloud ice, denotes by N, can be calculated by Equation (R2),

$$\mathrm{N} = \int_{L_{min}}^{L_{max}} \mathrm{n(L)}dL \tag{2}$$

Therefore, Deff and IWC (or number concentration) are interrelated, with their relationship being temperature-dependent.

The authors explicitly give the formula to calculate Deff, which is the Equation (2) in our manuscript. Unfortunately, they do not provide an explicit formulate to describe $\mathrm{n(L)}$. Therefore, we cannot calculate the number concentration of cloud ice.

Major issue 3:

In CMA-MESO, there are six types of hydrometeors. How is the scattering from rain, snow and graupel is treated in this study?

Our response:

The operational configuration of the microphysical scheme for the CMA-MESO model is the single-moment six-class microphysical scheme (Hong and Lim, 2006). The model configuration generates five types of cloud hydrometeors, including cloud droplet, raindrop, ice, snow, and graupel.

RTTOV treats liquid water cloud and ice cloud with different methods. For liquid water clouds, cloud droplets and raindrops impact the radiative transfer simulations by tuning the extinction and scattering coefficients. This is done by multiplying the per-concentration (1 g m^{-3}) extinction and scattering coefficients for selected liquid water cloud parameterization by the total liquid cloud concentration (the sum of cloud droplets and raindrops). For ice clouds, ice, snow, and graupel impact the radiative transfer simulation in a similar way to the liquid water clouds. To be specific, the extinction and scattering coefficients are the product of per-concentration (1 g m^{-3}) extinction and scattering coefficients for selected ice cloud parameterization and the total ice cloud concentration (the sum of ice, snow, and graupel). (Line: 79-83; 101-104; 126-128)

Major issue 4:

Since FY-4B AGRI has an aerosol AOD product, it is better to use AOD to quantify the contribution from aerosol? Eq. (8) and (9) seems to be too objective.

Our response:

It true that Equations (8) and (9) in the manuscript are too objective since no observed aerosol information was considered. Following your guidance, we conducted an extra experiment to account for aerosol impact on the evaluation results. The experiment settings were similar to the CM-FY-DM experiment, except that the aerosol optical properties were included in the RTTOV inputs when synthesizing visible satellite images.

For a certain atmosphere column, the aerosol-related inputs to RTTOV include the extinction coefficient profile, the scattering coefficient profile, and the phase function at specified scattering angles. The aerosol extinction coefficient profile was derived from FY-4B aerosol optical depth (AOD) products at 650 nm (data quality flag = 3), assuming an exponential decrease in aerosol concentration with a scale height of 3 km. The assumption was based on the aerosol climatology over China (Zhou et al., 2017), which revealed that the vertical distribution of aerosols commonly conforms to an exponential function and the typical value of scale height is around 3 km. In addition, sand dust is the most predominant aerosol type. Therefore, we used the phase function of sand dust aerosol type. The per-layer scattering coefficient was calculated by multiplying the extinction coefficient by the single scattering albedo of sand dust aerosol. The optical properties of the dust aerosol at the central wavelength of FY-4B AGRI band 2 were calculated by a logarithmic interpolation of the optical properties at 0.532 and 1.064 μm provided by Zhou et al. (2017).

It is noted that the radiative transfer simulations are rather time-consuming when the aerosol impact is included. For the results shown in Section 5.6 of the revised manuscript, it took about 15 days to complete the RTTOV simulations on our Linux cluster. Therefore, the aerosol impact was only discussed for the CMA-MESO 3-h forecasts, the RTTOV-DOM solver, and for the FY-4B visible band. Considering that the results for CM-FY-DM, E5-FY-DM, CM-HW-DM, and CM-HW-MF experiments are similar, the optimized cloud optical parameterizations derived from the aerosol-related experiment remain consistent with those shown the original manuscript. (Line:243-247; 429-460)

Major issue 5:

Captions for Figure 7b do not make sense. What is Fig 7c? Also, it is strange to show O-B bias from one month data.

Our response:

We are sorry for made a mistake here. Figure 7(a) denotes the spatial distribution of the one-month biases of O-B departure for the CM-FY-DM experiment. Figure 7(b) denotes the spatial distribution of the one-month standard deviation of O-B departure. Figure 7(c) denotes the spatial distribution of the one-month correlation coefficient between O and B.

We add the spatial distribution of one-month O-B statistics mainly to give some explanations to the discrepancies between O and B, which should be helpful to potential readers to better understand the errors in B. From the results shown by Figure 7, we conclude that the accuracy of B is not only determined by the cloud optical parameterizations, but also by the deficiencies of the CMA-MESO model in complex terrain areas and the inaccuracy of surface albedo of the RTTOV BRDF atlas in snow-covered areas.

We are uncertain whether it would be better to delete this section or retain it, so we would like to follow your recommendation in making the final decision. (Line: 302-317)

Major issue 5:

The DOM solver simplified the scattering interactions between clouds and gaseous molecules into single - scattering processes in non - cloudy layers. This simplification may lead to inaccuracies in the simulated reflectance, especially in areas with complex cloud - gas interactions. Although the MFASIS solver has some improvements in this regard, the overall treatment of scattering in the study could be more refined.

Our response:

We fully agree that accounting for multiple scattering interactions between clouds and gaseous molecules would further improve the accuracy of RTTOV simulations. However, we must acknowledge that addressing this issue currently lies beyond the scope of our expertise.

While these simplifications may introduce systematic errors in the simulated reflectance, previous studies (e.g., Scheck et al., 2020) have demonstrated that the current RTTOV framework still provides valuable contributions to the data assimilation of satellite visible reflectance data. Should this limitation be resolved in future developments, we would be eager to re-examine its impact on our evaluation results.